Electrical Power Cable Engineering

edited by
William A. Thue

Washington, D.C.

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SERIES INTRODUCTION

Power engineering is the oldest and most traditional of the various areas within electrical engineering, yet no other facet of modern technology is currently undergoing a more dramatic revolution in both technology and industry structure. Among the technologies of growing importance for the 21st century are high, medium, and low voltage power cables. They have become a staple of modern power systems engineering, in which underground transmission and distribution (T&D) systems–out of sight and out of the way–have become the only acceptable way of providing electrical service in urban areas that meets customer expectations for reliable service and low esthetic impact.

For a number of years there has been a surprising lack of good books on up-to-date cable engineering practices. William Thue's *Electrical Power Cable Engineering* certainly fills this gap, with a thorough, well-organized treatment of modern power cable technologies and practices. The book focuses particularly on the medium and low voltage cables, voltage levels that form the bulk of underground systems and which provide the reliable distribution link so necessary to the high quality service demanded by today's electric consumers. At both the introductory and advanced levels, this book provides an above-average level of insight into the materials, design, manufacturing, testing, and performance expectations of electric power cable.

As the editor of the Power Engineering Series, I am proud to include *Electrical Power Cable Engineering* in this important series of books. Like all the books planned for Marcel Dekker, Inc.'s Power Engineering Series, William Thue's book treats modern power technology in a context of proven, practical application and is useful as a reference book as well as for self-study and advanced classroom use. The Power Engineering Series will eventually include books covering the entire field of power engineering, in all of its specialties and sub-genres, all aimed at providing practicing power engineers with the knowledge and techniques they need to meet the electric industry's challenges in the 21st century.

H. Lee Willis

FOREWORD

Electrical cable can be considered as just a conductor with an overlying insulation or an exterior shield or jacket. Perhaps with this naive, simplistic concept is part of the reason that cable engineering, especially for power cable, has been largely neglected in current electrical engineering education in the United States with its emphasis on computers, electronics, and communication. But power cable does electrically connect the world! The history, so interestingly presented in Chapter 1 of this book, shows how the subject evolved with both great success and sometimes unexpected failure.

As this book emphasizes, cable engineering is technically very complex. Certainly electrical, mechanical, and even to some extent civil engineering are involved in interrelated ways. Many other disciplines—physics, inorganic chemistry, organic (primarily polymer) chemistry, physical chemistry, metallurgy, corrosion and with tests and standards in all of these areas—are concerns. Of course, it is impossible in one book to deal with all of these aspects in a completely comprehensive way. However, the various components of power cables are discusseded here with sufficient detail to provide an understanding of the basic considerations in each area. Reference to detailed sources provides a means for those with greater interest to pursue specific subjects.

The importance of factors involved in different types of cable installation is stressed. Long vertical cable runs have special problems. Installation in ducts may lead to problems with joints, terminations, elbows, and pulling stresses. At first, cable with extruded insulation was buried directly in trenches without recognition of the then unknown problem of "water treeing" in polyethylene, which was originally thought to be unaffected by moisture. After massive field failures, well over a thousand papers have been written on water treeing! Field failures can involve many factors, e.g., lightning, switching surges, repeated mechanical stressing, and swelling of voltage grading shields in contact with organic solvents such as oil and gasoline. It is important to recognize how such diverse factors can affect the performance of cable in the field.

Electrical Power Cable Engineering meets a need to consider its complex subject in a readable fashion, especially for those with limited background and experience. Yet sufficient detail is provided for those with greater need in evaluating different cables for specific applications. Most of all, the supplier of materials for cables can obtain a better understanding of overall problems. Also, the experienced cable engineer may come to recognize some of the parameters of materials with which he or she has not worked previously.

Kenneth N. Mathes
Consulting Engineer
Schenectady, New York

PREFACE

A course entitled Power Cable Engineering Clinic has been presented at the University of Wisconsin—Madison since the early 1970s. During the intervening years, there have been numerous lecturers and copious class notes that form the basis for much of the material that is contained in this volume. I have attempted to rearrange those notes into a book format. Many sections have been expanded or are entirely new so that the complete story of power cables can be obtained in one book. We hope that this team effort will be a useful addition to the library of all dedicated cable engineers.

The emphasis is on low and medium voltage cables since they comprise the bulk of the cables in service throughout the world. Transmission cables are the ones with greater sophistication from an engineering standpoint. However, all the basic principles that apply to transmission cables also apply to low and medium voltage cables and are therefore included in this book.

An unfortunate fact is that in the rapidly changing environment of power cables, the most recent book published in North America that covered medium voltage cables was the 1957 *Underground Systems Reference Book,* prepared by the Edison Electric Institute. Several excellent handbooks have been published by cable manufacturers and are current, but the broad scope of the 1957 textbook has not been updated since then.

The current volume covers the up-to-date methods of design, manufacture, installation, and operation of power cables that are widely used throughout the world. The audience that would benefit from the highly knowledgeable writings and wide backgrounds of the development team include:

> Cable engineers employed by investor-owned utilities, rural electric utilities, industrial users, and power plant personnel
>
> Universities that would like to offer electrical power cable courses

Cable manufacturers that need to provide new employees with an overall view of power cables as an introduction to their companies

This text provides the required information to understand the terminology and engineering characteristics and background of power cables and to make sound decisions for purchasing, installation, and operation of electrical power cables.

William A. Thue

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CONTRIBUTORS

Theodore A. Balaska Insulated Power Cable Services, Inc., Bradenton, Florida

Bruce S. Bernstein Electric Power Research Institute (EPRI), Washington, DC

Lawrence J. Kelly Kelly Cables, Montvale, New Jersey

Carl C. Landinger Hendrix Wire and Cable, Longview, Texas

James D. Medek JMed & Associates, Ltd., Palatine, Illinois

William A. Thue Consulting Electrical Engineer, Washington, DC

CHAPTER 1

HISTORICAL PERSPECTIVE OF ELECTRICAL CABLES

Bruce S. Bernstein and William A. Thue

1. DEVELOPMENT OF UNDERGROUND CABLES [1-1, 1-2]

In order to trace the history of underground cable systems, it is necessary to examine the early days of the telegraph. The telegraph was the first device utilizing electrical energy to become of any commercial importance and its development necessarily required the use of wires. Underground construction was advocated by the majority of the early experimenters. Experimentation with underground cables accordingly was carried on contemporaneously with the development of the apparatus for sending and receiving signals. Underground construction was planned for most of the earliest commercial lines. A number of these early installations are of considerable interest as marking steps in the development of the extensive underground power systems in operation around the world.

2. EARLY TELEGRAPH LINES

In 1812, Baron Schilling detonated a mine under the Neva River at St. Petersburg by using an electrical pulse sent through a cable insulated with strips of India rubber. This is probably the earliest use of a continuously insulated conductor on record.

One of the earliest experiments with an underground line was made by Francis Ronalds in 1816. This work was in conjunction with a system of telegraphy consisting of 500 feet of bare copper conductor drawn into glass tubes, joined together with sleeve joints and sealed with wax. The tubes were placed in a creosoted wooden trough buried in the ground. Ronalds was very enthusiastic over the success of this line, predicting that underground conductors would be widely used for electrical purposes, and outlining many of the essential characteristics of a modern distribution system.

The conductor in this case was first insulated with cotton saturated with shellac before being drawn into the tubes. Later, strips of India rubber were used. This installation had many insulation failures and was abandoned. No serious attempt was made to develop the idea commercially.

In 1837, W. R. Cooke and Charles Wheatstone laid an underground line along the railroad right-of-way between London's Euston and Camden stations for their five-wire system of telegraphy. The wires were insulated with cotton saturated in rosin and were installed in separate grooves in a piece of timber coated with pitch. This line operated satisfactorily for a short time, but a number of insulation failures due to the absorption of moisture led to its abandonment. The next year, Cooke and Wheatstone installed a line between Paddington and Drayton, but iron pipe was substituted for the timber to give better protection from moisture. Insulation failures also occurred on this line after a short time, and it was also abandoned.

In 1842, S. F. B. Morse laid a cable insulated with jute, saturated in pitch, and covered with strips of India rubber between Governor's Island and Castle Garden in New York harbor. The next year, a similar line was laid across a canal in Washington, D.C. The success of these experiments induced Morse to write to the Secretary of the Treasury that he believed "telegraphic communications on the electro-magnetic plan can with a certainty be established across the Atlantic Ocean."

In 1844, Morse obtained an appropriation from the U.S. Congress for a telegraph line between Washington and Baltimore. An underground conductor was planned and several miles were actually laid before the insulation was proved to be defective. The underground project was abandoned and an overhead line erected. The conductor was originally planned to be a #16 gage copper insulated with cotton and saturated in shellac. Four insulated wires were drawn into a close fitting lead pipe that was then passed between rollers and drawn down into close contact with the conductors. The cable was coiled on drums in 300 foot lengths and laid by means of a specially designed plow.

Thus, the first attempts at underground construction were unsuccessful, and overhead construction was necessary to assure the satisfactory performance of the lines. After the failure of Morse's line, no additional attempts were made to utilize underground construction in the United States until Thomas A. Edison's time.

Gutta-percha was introduced into Europe in 1842 by Dr. W. Montgomery, and in 1846 was adopted on the recommendation of Dr. Werner Siemens for the telegraph line that the Prussian government was installing.

Approximately 3,000 miles of such wire were laid from 1847 to 1852. Unfortunately, the perishable nature of the material was not known at the time, and no adequate means of protecting it from oxidation was provided. Insulation troubles soon began to develop and eventually became so serious that the entire installation was abandoned.

However, gutta-percha provided a very satisfactory material for insulating telegraph cables when properly protected from oxidation. It was used extensively for both underground and submarine installations.

In 1860, vulcanized rubber was used for the first time as an insulation for wires. Unvulcanized rubber had been used on several of the very early lines in strips applied over fibrous insulation for moisture protection. This system had generally been unsatisfactory because of difficulties in closing the seam. Vulcanized rubber proved a much better insulating material, but did not become a serious competitor of gutta-percha until some years later.

3. ELECTRIC LIGHTING

While early telegraph systems were being developed, other experimenters were solving the problems connected with the commercial development of electric lighting. An electric light required a steady flow of a considerable amount of energy, and was consequently dependent upon the development of the dynamo. The first lamps were designed to utilize the electric arc that had been demonstrated by Sir Humphry Davy as early as 1810. Arc lights were brought to a high state of development by Paul Jablochkoff in 1876 and C. R. Brush in 1879. Both men developed systems for lighting streets by arc lamps connected in series supplied from a single generating station

Lighting by incandescence was principally the result of the work of Edison, who developed a complete system of such lighting in 1879. His lights were designed to operate in parallel instead of series as had been the case with the previously developed arc-lighting systems. This radical departure from precedent permitted the use of low voltage, and greatly simplified the distribution problems.

4. DISTRIBUTION OF ENERGY FOR LIGHTING

Edison planned his first installation for New York City, and decided that an underground system of distribution would be necessary. This took the form of a network supplied by feeders radiating from a centrally located dc-generating station to various feed points in the network. Pilot wires were taken back to the generating station from the feed points in order to give the operator an indication of voltage conditions on the system. Regulation was controlled by cutting feeders in, or out, as needed. At a later date, a battery was connected in parallel with the generator to guard against a station outage.

Gutta-percha, which had proved a satisfactory material for insulating the telegraph cables, was not suitable for the lighting feeders because of the softening of the material (a natural thermoplastic) at the relatively high operating temperature. Experience with other types of insulation had not been sufficient to provide any degree of satisfaction with their use. The development of a cable sufficiently flexible to be drawn into ducts was accordingly considered a rather remote possibility. Therefore, Edison designed a rigid, buried system consisting of copper rods insulated with a wrapping of jute. Two or three insulated rods were drawn into iron pipes and a heavy bituminous compound was forced in around them. They were then laid in 20-foot sections and joined together with specially designed tube joints from which taps could be taken if desired. The Edison tube gave remarkably satisfactory performance for this class of low voltage service.

The low voltage and heavy current characteristics of dc distribution were limited to the area capable of being supplied from one source if the regulation was to be kept within reasonable bounds. The high first cost and heavy losses made such systems uneconomical for general distribution. Accordingly, they were developed in limited areas of high-load density such as the business districts of large cities.

In the outlying districts, ac distribution was universally employed. This type of distribution was developed largely as a result of the work, in 1882, of L. Gaulard and J. D. Gibbs, who designed a crude alternating current system using induction coils as transformers. The coils were first connected in series, but satisfactory performance could not be obtained. However, they were able to distribute electrical energy at a voltage considerably higher than that required for lighting, and to demonstrate the economics of the ac system. This system was introduced into the United States in 1885 by George Westinghouse, and served as the basis for the development of workable systems. An experimental installation went in service at Great Barrington, Massachusetts, early in 1886. The first large scale commercial installation was built in Buffalo, New York, the same year.

The early installations operated at 1,000 volts. Overhead construction was considered essential for their satisfactory performance and almost universally employed. This was also true of the street-lighting feeders, which operated at about 2,000 volts. In Washington and Chicago, overhead wires were prohibited, so a number of underground lines were installed. Many different types of insulation and methods of installation were tried with little success. Experiments with underground conductors were also carried out in Philadelphia. The 1884 enactment of a law forcing the removal of all overhead wires from the streets of New York mandated the development of a type of construction that could withstand such voltages. It was some time, however, before the high-voltage wires disappeared. In 1888, the situation was summarized in a paper before the National Electric Light Association as follows:

> "No arc wires had been placed underground in either New York or Brooklyn. The experience in Washington led to the statement that no insulation could be found that would operate two years at 2,000 volts. In Chicago, all installations failed with the exception of lead covered cables which appeared to be operating successfully. In Milwaukee, three different systems had been tried and abandoned. In Detroit, a cable had been installed in Dorsett conduit, but later abandoned. In many of the larger cities, low voltage cables were operating

> satisfactorily and in Pittsburgh, Denver and Springfield, Mass., some 1,000 volt circuits were in operation."

5. PAPER INSULATED CABLES [1-3]

The first important lines insulated with paper were installed by Ferranti in 1890 between Deptford and London for operation at 10,000 volts. Some of these mains were still in use at the original voltage after more than 50 years. The cables consisted of two concentric conductors insulated with wide strips of paper applied helically around the conductor and saturated with a rosin based oil. The insulated conductors were forced into a lead pipe and installed in 20 foot lengths. These mains were not flexible and were directly buried in the ground.

Soon after, cables insulated with narrow paper strips saturated in a rosin compound and covered with a lead sheath (very similar in design to those in use at the present time) were manufactured in the United States by the Norwich Wire Company. These were the first flexible paper-insulated cables, and all subsequent progress has been made through improvements in the general design.

Paper insulated cables were improved considerably with:

(a) Introduction of the shielded design of multiple conductor cables by Martin Hochstadter in 1914. This cable is still known as Type H.

(b) Luigi Emanueli's demonstration that voids due to expansion and contraction could be controlled by the use of a thin oil with reservoirs. This permitted the voltages to be raised to 69 kV and higher.

(c) The 1927 patent by H. W. Fisher and R. W. Atkinson revealed that the dielectric strength of impregnated paper-insulated cable could be greatly increased by maintaining it under pressure. This system was not used until the 1932 commercial installation of a 200 psi cable in London.

Impregnated paper became the most common form of insulation for cables used for bulk transmission and distribution of electrical power, particularly for operating voltages of 12.5 kV and above, where low dielectric loss, a low dissipation factor, and a high ionization level are important factors in determining cable life.

Impregnated paper insulation consists of multiple layers of paper tapes, each tape from 2.5 to 7.5 mils in thickness, wrapped helically around the conductor to be insulated. The total wall of paper tapes is then heated, vacuum dried, and impregnated with an insulating fluid. The quality of the impregnated paper insulation depends not only on the properties and characteristics of the paper and impregnating fluid, but also on the mechanical application of the paper tapes over the conductor, the thoroughness of the vacuum drying, and the control of the saturating and cooling cycles during the manufacturing.

Originally, most of the paper used was made from Manila-rope fiber. This was erratic in its physical properties and not always susceptible to adequate oil penetration. Increased knowledge of the chemical treatment of the wood (in order to obtain pure cellulose by the adjustment of the fiber content and removal of lignin), the control of tear resistance, and the availability of long fiber stock resulted in the almost universal use of wood pulp paper in cables after 1900.

The impregnating compound was changed from a rosin-based compound to a pure mineral oil circa 1925, or oil blended to obtain higher viscosity, until polybutene replaced oil circa 1983.

Paper insulated, lead-covered cables were the predominant primary cables of all the large, metropolitan distribution systems in the United States, and the rest of the world, throughout the twentieth century. Their reliability was excellent. It was, however, necessary to have a high degree of skill for proper splicing and terminating. A shift towards extruded dielectric cables began about 1975 in those metropolitan areas, but the majority of the distribution cables of the large cities remain paper insulated, lead-covered cables as the century ends.

Considerable research has been carried out by the utilities, technical organizations, and manufacturer's of cables to obtain improved paper and laminated PPP (polypropylene-paper-polypropylene, now used in transmission cables) tapes and insulating fluids able to withstand high, continuous operating temperatures, etc.

Impregnated paper insulation has excellent electrical properties, such as high dielectric strength, low dissipation factor, and dielectric loss. Because of these properties, the thickness of impregnated paper insulation was considerably less than for rubber or varnished cambric insulations for the same working voltages. Polyethylene and crosslinked polyethylene cables in the distribution classes are frequently made with the same wall thickness as today's impregnated paper cables

6. EXTRUDED DIELECTRIC POWER CABLES

The development of polyethylene in 1941 triggered a dramatic change in the insulation of cables for the transmission and distribution of electrical energy. There are two major types of extruded dielectric insulation in wide use today for medium voltage cables:

(a) Crosslinked polyethylene or tree-retardant crosslinked polyethylene.

(b) Ethylene propylene rubber.

Thermoplastic polyethylene (PE), which was widely used through the 1970s, was introduced during World War II for high-frequency cable insulation. PE was furnished as 15 kV cable insulation by 1947. Large usage began with the advent of Underground Residential Distribution (URD) systems early in the 1960s.

7.0 URD SYSTEMS

The development of modern URD systems may be viewed as the result of drastically lowering first costs through technology.

Post-war URD systems were basically the same as the earlier systems except that there were two directions of feed (the loop system.) System voltages rose from 2400/4160 to 7620/13,200 volts. The pre-1950 systems were very expensive because they utilized such items as paper insulated cables, vaults, and submersible transformers. Those systems had an installed cost of $1,000 to $1,500 per lot. Expressed in terms of buying power at that time, you could buy a luxury car for the same price! Underground service was, therefore, limited to the most exclusive housing developments.

But for three developments in the 1960s, the underground distribution systems that exist today might not be in place. First, in 1958-59, a large midwestern utility inspired the development of the pad-mounted transformer; the vault was no longer necessary nor was the submersible transformer. Second, the polyethylene cable with its concentric neutral did not require cable splicers, and the cable could be directly buried. While possibly not as revolutionary, the load-break elbow (separable connector) allowed the transformer to be built with a lower, more pleasing appearance.

The booming American economy and the environmental concerns of the nation made underground power systems the watchword of the Great Society. In a decade, URD had changed from a luxury to a necessity. The goal for the utility engineer was to design a URD system at about the same cost as the equivalent overhead system. There was little or no concern about costs over the system's life because that PE cable was expected to last 100 years!

8.0 TROUBLE IN PARADISE

During the early part of the 1970s, isolated reports of early cable failures on extruded dielectric systems began to be documented in many parts of the world. "Treeing" was re-introduced to the cable engineer's vocabulary. This time it did not have the same meaning as with paper insulated cables. See Chapter 16 for additional information on treeing.

By 1976, reports from utilities [1-4] and results of EPRI research [1-5] confirmed the fact that thermoplastic polyethylene insulated cables were failing in service at a rapidly increasing rate. Crosslinked polyethylene exhibited a much lower failure rate that was not escalating nearly as rapidly. Data from Europe confirmed the same facts [1-6].

The realization of the magnitude and significance of the problem led to a series of changes and improvements to the primary voltage cables:

- ☐ Research work was initiated to concentrate on solutions to the problem
- ☐ Utilities began replacing the poorest performing cables
- ☐ Suppliers of component materials improved their products
- ☐ Cable manufacturers improved their handling and processing techniques

9. MEDIUM VOLTAGE CABLE DEVELOPMENT [1-7]

In the mid 1960s, conventional polyethylene became the material of choice for the rapidly expanding URD systems in the United States. It was known to be superior to butyl rubber for moisture resistance, and could be readily extruded. It was used with tape shields, which achieved their semiconducting properties because of carbon black. By 1968, virtually all of the URD installations consisted of polyethylene-insulated medium voltage cables. The polyethylene was referred to as "high molecular weight" (HMWPE); this simply meant that the insulation used had a very high "average" molecular weight. The higher the molecular weight, the better the electrical properties. The highest molecular weight PE that could be readily extruded was adopted. Jacketed construction was seldom employed at that time.

Extruded thermoplastic shields were introduced between 1965 and 1975 leading both to easier processing and better reliability of the cable

Crosslinked polyethylene (XLPE) was first patented in 1959 for a filled compound and in 1963 for unfilled by Dr. Frank Precopio. It was not widely used because of the tremendous pressure to keep the cost of URD down near the cost of an overhead system. This higher cost was caused by the need for additives (crosslinking agents) and the cost of manufacturing based on the need for massive, continuous vulcanizing (CV) tubes. EPR (ethylene propylene rubber) was introduced at about the same time. The significantly higher initial cost of these cables slowed their acceptance for utility purposes until the 1980s.

The superior operating and allowable emergency temperatures of XLPE and EPR made them the choice for feeder cables in commercial and industrial applications. These materials did not melt and flow as did the HMWPE material.

In order to facilitate removal for splicing and terminating, those early 1970-era XLPE cables were manufactured with thermoplastic insulation shields as had been used over the HMWPE cables. A reduction in ampacity was required until deformation resistant and then crosslinkable insulation shields became available during the later part of the 1970s.

A two-pass extrusion process was also used where the conductor shield and the insulation were extruded in one pass. The unfinished cable was taken up on a reel and then sent through another extruder to install the insulation shield layer. This resulted in possible contamination in a very critical zone. When crosslinked insulation shield materials became available, cables could be made in one pass utilizing "triple" extrusion of those three layers. "True triple" soon followed where all layers were extruded in a single head fed by three extruders.

In the mid 1970s, a grade of tree-retardant polyethylene (TR-HMWPE) was introduced. This had limited commercial application and never became a major factor in the market.

Around 1976 another option became available -- suppliers provided a grade of "deformation resistant" thermoplastic insulation shield material. This was an attempt to provide a material with "thermoset properties" and thus elevate the allowable temperature rating of the cable. This approach was abandoned when a true thermosetting shield material became available.

By 1976 the market consisted of approximately 45% XLPE, 30% HMWPE, 20% TR-HMWPE and 5% EPR.

In the late 1970's, a strippable thermosetting insulation shield material was introduced. This allowed the user to install a "high temperature" XLPE that could be spliced with less effort than the earlier, inconsistent materials.

Jackets became increasingly popular by 1980. Since 1972-73, there had been increasing recognition of the fact that water presence under voltage stress was causing premature loss of cable life due to "water treeing." Having a jacket reduced the amount of water penetration. This led to the understanding that water treeing could be "finessed" or delayed by utilizing a jacket. By 1980, 40 percent of the cables sold had a jacket.

EPR cables became more popular in the 1980s. A breakthrough had occurred in the mid-1970s with the introduction of a grade of EPR that could be extruded on the same type of equipment as XLPE insulation. The higher cost of EPR cables, as compared with XLPE, was a deterrent to early acceptance even with this new capability.

In 1981, another significant change took place: the introduction of "dry cure" cables. Until this time, the curing, or cross-linking, process was performed by using high-pressure steam. Because water was a problem for long cable life, the ability to virtually eliminate water became imperative. It was eventually recognized that the "dry cure" process provided faster processing speeds as well as elimination of the steam process for XLPE production.

Another major turning point occurred in 1982 with the introduction of tree-resistant crosslinked polyethylene (TR-XLPE). This product, which has supplanted conventional XLPE in market volume today, shows superior water tree resistance as compared with conventional XLPE. HMWPE and TR-HMWPE were virtually off the market by 1983.

By 1984, the market was approximately 65 percent XLPE, 25 percent TR-XLPE and 10 percent EPR. Half the cable sold had a jacket by that time.

During the second half of the 1980s, a major change in the use of filled strands took place. Although the process had been known for about ten years, the control of the extruded "jelly-like" material was better understood by a large group of manufacturers. This material prevents water movement between the strands along the cable length and eliminates most of the conductor's air space, which can be a water reservoir.

In the late 1980s, another significant improvement in the materials used in these cables became available for smoother and cleaner conductor shields. Vast improvements in the materials and processing of extruded, medium voltage power cables in the 1980s has led to cables that can be expected to function for 30, 40, or perhaps even 60 years when all of the proper choices are utilized. In 1995, the market was approximately 45 percent TR-XLPE, 35 percent XLPE, and 20 percent EPR.

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CHAPTER 2

BASIC DIELECTRIC THEORY OF CABLE

Theodore A. Balaska and Carl C. Landinger [2-1, 2-2]

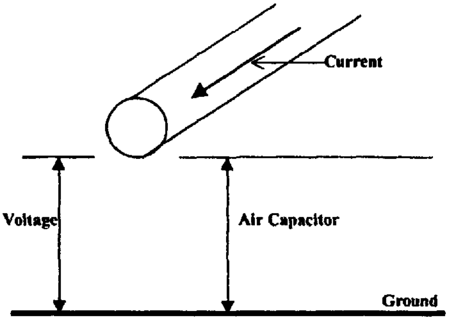
1. INTRODUCTION

Whether being used to convey electric power or signals, it is the purpose of a wire or cable to convey the electric current to the intended device or location. In order to accomplish this, a conductor is provided which is adequate to convey the electric current imposed. Equally important is the need to keep the current from flowing in unintended paths rather than the conductor provided. Insulation is provided to largely isolate the conductor from other paths or surfaces through which the current might flow. Therefore, it may be said that any conductor conveying electric signals or power is an insulated conductor.

2. AIR INSULATED CONDUCTORS

A metallic conductor suspended from insulating supports, surrounded by air, and carrying electric signals or power may be considered as the simplest case of an insulated conductor. It also presents an opportunity to easily visualize the parameters involved.

Figure 2-1
Location of Voltage and Current



In Figure 2-1, clearly the voltage is between the conductor and the ground [2-3, 2-4]. Also, because of the charge separation, there is a capacitor and a large resistance between conductor and ground. Finally, as long as ground is well away from the conductor, the electric field lines leave the conductor as reasonably straight lines emanating from the center of the conductor. We know that all bend to ultimately terminate at ground.

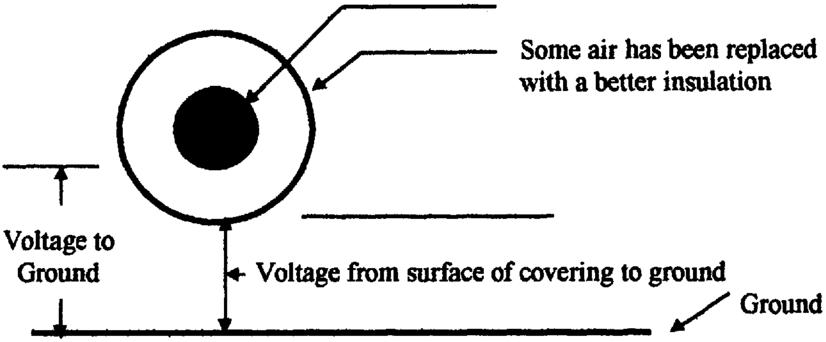
Air is not a very good insulating material since it has a lower voltage breakdown strength than many other insulating materials. It is low in cost if space is not a constraint. As the voltage between the conductor and ground is increased, a point is reached where the electric stress at the conductor exceeds the breakdown strength or air. At this point, the air literally breaks down producing a layer of ionized, conducting air surrounding the conductor. The term for this is corona (crown). It represents power loss and can cause interference to radio, TV, and other signals. It is not uncommon for this condition to appear at isolated spots where a rough burr appears on the conductor or at a connector. This is simply because the electric stress is locally increased by the sharpness of the irregularity or protrusion from the conductor. In air or other gasses, the effect of the ionized gas layer surrounding the conductor is to increase the electrical diameter of the conductor to a point where the air beyond the ionized boundary is no longer stressed to breakdown for the prevailing temperature, pressure, and humidity. The unlimited supply of fresh air and the conditions just mentioned, precludes the progression of the ionization of air all the way to ground. It is possible that the stress level is so high that an ionized channel can breach the entire gap from conductor to earth, but this generally requires a very high voltage source such as lightning.

3. INSULATING TO SAVE SPACE

Space is a common constraint that precludes the use of air as an insulator. Imagine the space requirements to wire a house or apartment using bare conductors on supports with air as the insulation. Let's consider the next step where some of the air surrounding the previous conductor is replaced with a better insulating material -- also known as a dielectric.

In Figure 2-2, we see that the voltage from conductor to ground is the same as before. A voltage divider has been created that is made up the impedance from the covering surface to ground. The distribution of voltage from conductor to the surface of the covering and from the covering surface to ground will be in proportion to these impedances. It is important to note that with ground relatively far away from the covered conductor, the majority of the voltage exists from the covering surface to ground. Putting this another way, the outer surface of the covering has a voltage that is within a few percent of the voltage on the conductor (95 to 97% is a common value).

Figure 2-2
"Covered" Conductor



The amount of current that can flow from an intact covering to ground in the event of contact is limited by the impedance of the covering. If the covering is made of an excellent insulation, the majority of the current will be due to capacitive charging current that can be released from the covering surface by the contacting object.

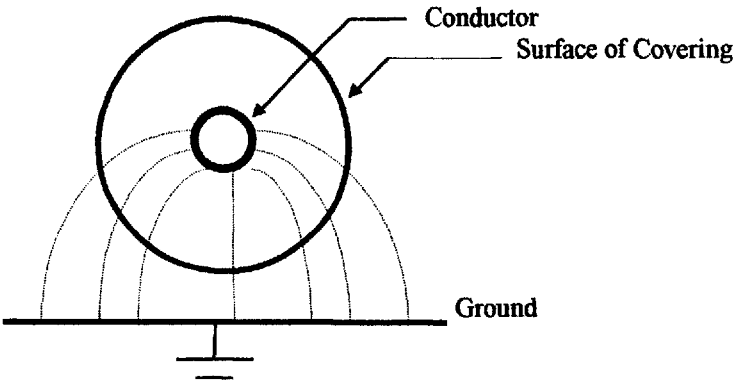
So little current is available at the covering surface from a low voltage covering (600 volts or less), that it is imperceptible. When this condition exists with some level of confidence, the "covering" is then considered to be "insulation" and suitable for continuous contact by a grounded surface as long as such contact does not result in chemical or thermal degradation. The question arises as to what is considered to be low voltage. The voltage rating of insulated cables is based on the phase-to-phase voltage. Low voltage is generally considered to be less than 600 volts phase-to-phase. See Chapters 4 and 9 for additional information.

Because of the proximity and contact with other objects, the thickness of insulating materials used for low voltage cables is generally based on mechanical requirements rather than electrical. The surrounding environment, the need for special properties such as sunlight, or flame resistance, and rigors of installation often make it difficult for a single material satisfy all related requirements. Designs involving two or more layers are commonly used in low voltage cable designs.

4. AS THE VOLTAGE RISES

Return to the metallic conductor that is covered with an insulating material and suspended in air. When the ground plane is brought close or touches the covering, the electric field lines become increasingly distorted.

Figure 2-3
Electric Field Lines Bend to Terminate at Ground Plane



In Figure 2-3, we see considerable bending of the electric field lines. Recognizing that equipotential lines are perpendicular to the field lines, the bending results in potential difference on the covering surface. At low voltages, the effect is negligible. As the voltage increases, the point is reached where the potential gradients are sufficient to cause current to flow across the surface of the covering. This is commonly known as "tracking." Even though the currents are small, the high surface resistance causes heating to take place which ultimately damages the covering. If this condition is allowed to continue, eventually the erosion may progress to failure.

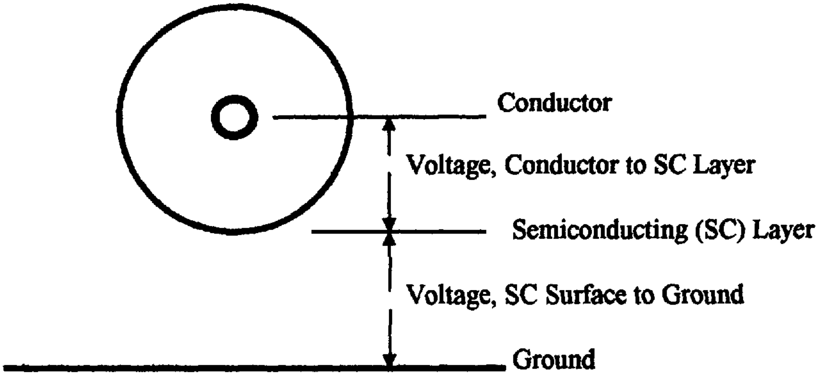
It is important to note that the utilization of spacer cable systems and heavy walled tree wires depend on this ability of the covering to reduce current flow to a minimum. When sustained contact with branches, limbs, or other objects occurs, damage may result -- hence such contacts may not be left permanently.

At first, it might be thought that the solution is to continue to add insulating covering thickness as the operating voltage increases. Cost and complications involved in overcoming this difficulty would make this a desirable first choice. Unfortunately, surface erosion and personnel hazards are not linear functions of voltage versus thickness and this approach becomes impractical.

4.1 The Insulation Shield

In order to make permanent ground contact possible, a semiconducting or resistive layer may be place over the insulation surface. This material forces the ending of the field lines to occur in the semiconducting layer. This layer creates some complications, however.

Figure 2-4



In Figure 2-4, it is clear that a capacitor has been created from the conductor to the surface of semiconducting layer. A great deal of charge can be contained in this capacitor. This charging current must be controlled so that a path to ground is not established along the surface of the semiconducting layer. This path can lead to burning and ultimate failure of that layer. Accidental human contact would be a very serious alternative. It is clearly necessary to provide a continuous contact with ground that provides an adequate path to drain the capacitive charging current to ground without damage to the cable. This is done by adding a metallic path in contact with the semiconducting shield.

Once a metallic member has been added to the shield system, there is simply no way to avoid its presence under ground fault conditions. This must be considered by either providing adequate conductive capacity in the shield to handle the fault currents or to provide supplemental means to accomplish this. This is a critical factor in cable design.

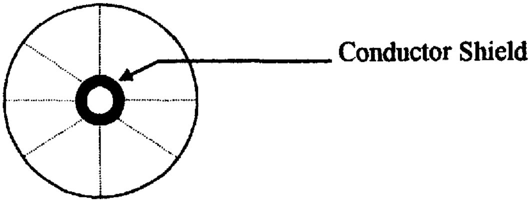
Electric utility cables have fault current requirements that are sufficiently large that it is common to provide for a neutral in the design of the metallic shield. These cables have become known as Underground Residential Distribution (URD) and Underground Distribution (UD) style cables. It is important that the functions of the metallic shield system are understood since many serious errors and accidents have occurred because the functions were misunderstood. The maximum stress occurs at the conductor.

4.2 A Conductor Shield is Needed

The presence of an insulation shield creates another complication. The grounded insulation shield results in the entire voltage stress being placed across the insulation.

Just as in the case of the air insulated conductor, there is concern about exceeding maximum stress that the insulating layer can withstand. The problem is magnified by stranded conductors or burrs and scratches that may be present in both stranded and solid conductors.

Figure 2-5
A Conductor Shield is Added to Provide a Smooth Inner Electrode



In Figure 2-5, a semiconducting layer has been added over the conductor to smooth out any irregularities. This reduces the probability of protrusions into the insulating layer. Protrusions into the insulation or into the semiconducting layer increase the localized stress (stress enhancement) that may exceed the long term breakdown strength of the insulation. This is especially critical in the case of extruded dielectric insulations. Unlike air, there can be no fresh supply of insulation. Any damage will be progressive and lead to total breakdown of the insulating layer. There will be more discussion about "treeing" in Chapter 16.

4.3 Shielding Layer Requirements

There are certain requirements inherent in shielding layers to reduce stress enhancement. First, protrusions, whether by material smoothness or manufacturing, must be minimized. Such protrusions defeat the very purpose of a shield by enhancing electrical stress. The insulations shield layer has a further complication in that it is desirable to have it easily removable to facilitate splicing and terminating. This certainly is the case in the medium voltage (5 to 35 kV). At higher voltages, the inconveniences of a bonded insulation shield can be tolerated to gain the additional probability of a smooth, void-free insulation-insulation shield interface for cable with a bonded shield.

4.4 Insulation Layer Requirements

At medium and higher voltages, it is critical that both the insulation and insulation-shield interfaces be contamination free. Contamination results in stress enhancement that can increase the probability of breakdown. Voids can do the same with the additional possibility of capacitive-resistive (CR) discharges in the gas-filled void as voltage gradients appear across the void. Such discharges can be destructive of the surrounding insulating material and lead to progressive deterioration and breakdown.

4.5 Jackets

In low voltage applications, jackets are commonly used to protect underlying layers from physical abuse, sunlight, flame or chemical attack. Chemical attack includes corrosion of underlying metallic layers for shielding and armoring. In multi-conductor designs, overall jackets are common for the same purposes. For medium and high voltage cables, jackets have been almost universally used throughout the history of cable designs. They are used for the same purposes as for low voltage cables with special emphasis on protecting underlying metallic components from corrosion. The only exceptions were paper-insulated, lead-covered cables and early URD/UD designs that were widely used by the electric utility industry. Both "experiments" were based on the assumption that lead, and subsequently copper wires, were not subject to significant corrosion. Both experiments resulted in elevated failure rates for these designs. Jackets are presently used for these designs.

5. TERMINOLOGY [2-1]

To better understand the terminology that will be used throughout this book, a brief introduction of the terms follows.

5.1 Medium Voltage Shielded Cables

Medium voltage (5 kV to 46 kV) shielded cable appears to be a relatively simple electrical machine. It does electrical work but there are no parts that move, at least no discernible movement to the naked eye. Do not be misled. This cable is a sophisticated electrical machine, even though it looks commonplace. To know why it is constructed the way it is, let us first look at a relatively simple cable, a low voltage non-shielded cable. For simplicity, we shall confine this discussion to single conductor cable.

5.1.1 Basic Components of Non-Shielded Power Cable. There are only two components in this cable, a conductor and its overlying insulation.

5.1.2 Conductor. The conductor may be solid or stranded and its metal usually is either copper or aluminum. An attempt to use sodium was short-lived. The strand can be concentric, compressed, compacted, segmental, or annular to achieve desired properties of flexibility, diameter, and current density.

Assuming the same cross-sectional area of conductor, there is a difference in diameters between solid and the various stranded conductors. This diameter differential is an important consideration in selecting methods to effect joints, terminations, and fill of conduits.

5.1.3 Electrical Insulation (Dielectric). This provides sufficient separation between the conductor and the nearest electrical ground to preclude dielectric failure. For low voltage cables, (2,000 volts and below), the required thickness of insulation to physically protect the conductor is more than adequate for required dielectric strength.

5.1.4 Dielectric Field. The conductor and the insulation are visible to the unaided eye. However, there is a third component in this cable. It is invisible to the unaided eye. This third component is what contributes to sophistication of the electrical machine known as cable. Alternating current fields will be discussed, not direct current

In all cables, regardless of their kV ratings, there exists a dielectric field whenever the conductor is energized. This dielectric field can be visualized by lines of electrostatic flux and equi-potentials. Electrostatic flux lines represent the boundaries of dielectric flux between electrodes having different electrical potentials. Equi-potential lines represent points of equal potential difference between electrodes having different electrical potentials. They represent the radial voltage stresses in the insulation and their relative spacing indicates the magnitude of the voltage stress. The closer the lines, the higher the stress. See Figures 2-1, 2-2, and 2-3.

If the cable is at an infinite distance from electrical ground (ideal situation), there will be no distortion of this dielectric field. The electrostatic flux lines will radiate between the conductor and the surface of the cable insulation with symmetrical spacing between them. The lines of equi-potential will be concentric with relation to the conductor and the surface of the cable insulation. However, in actual practice this ideal situation does not exist.

In actual practice, the surface of the cable insulation is expected to be in contact with an electrical ground. This actual operating condition creates distortion in the dielectric field. The lines of electrostatic flux are crowded in the area of the insulation closest to ground.

The lines of equi-potential are eccentric with respect to the conductor and the surface of the cable insulation. This situation is tolerated if the dielectric strength of the cable insulation is sufficient to resist the flow of electrons (lines of electrostatic flux), and the surface discharges and internal voltage stresses that are due to concentrated voltage gradients (stresses) that are represented by lines of equi-potential. Low voltage, non-shielded cables are designed to withstand this condition. Service performance of non-shielded cables is generally considered acceptable. Thus one may ask "Why not extrapolate non-shielded cable wall thickness for increasing voltages?" There are very practical limits, economics being paramount, to such an approach.

5.1.5 Extrapolation of 600 Volt and 5 kV Cable Walls. If we use the same volts per mil wall thickness of 600 volt cable to determine higher voltage walls, we achieve a wall of at least 4.6 inches (117 mm) for a 35 kV cable.

A similar approach using 5 kV cable voltage stress as the basis for extrapolation provides at least a 0.63 inch (16 mm) wall for a 35 kV cable.

5.1.6 Summary of Limitation. It is apparent that the bulk dimensions created by extrapolation of non-shielded cable walls are unacceptable. To overcome this situation of bulk dimensions, generally shielded cable is used.

5.2 Basic Components of a Shielded Power Cable

The essential additional component is shielding. However, where is it placed, what materials are used, and what does it do to the dielectric field? Let us start from the conductor again and move outward from the center of the cable.

5.2.1 Conductor. Nothing unusual as compared to a non-shielded cable.

5.2.2 Conductor Shield. A conducting material is placed over the conductor circumference to screen (shield) out irregularities of the conductor contours. The dielectric field will not be affected or "see" the shape of the outer strands (or other conductor contours) due to the presence of the conductor shield (screen).

5.2.3 Electrical Insulation (Dielectric). The differences between insulation for a non-shielded cable as compared to a shielded cable are in material, quality, cleanliness, and application. The thickness applied is primarily influenced by considerations of electrical stress (voltage gradients).

5.2.4 Insulation Shield. This is a two-part system, consisting of an auxiliary shield and a primary shield.

5.2.5 Auxiliary Shield. A conducting material that is placed over the outer diameter of the cable insulation. This material must be capable of conducting "leakage" current radially through its wall without creating an abnormal voltage drop.

5.2.6 Primary Shield. A metallic layer of tapes, wires, or a tube that is placed over the circumference of the underlying auxiliary shield. This must be capable of conducting the summation of "leakage" currents and carry them to the nearest ground without creation of an abnormal voltage drop.

5.2.7 Dielectric Field. A dielectric field, composed of electrostatic flux and equi-potential lines, exists when the conductor is energized. There is no distortion in this dielectric field because of the shielding of insulation and conductor. Electrostatic flux lines are symmetrically spaced and equi-potential lines are concentric. See Figure 2-3.

However, observe features not previously noted; the electrostatic flux and equi-potential lines are spaced closer together near the conductor shield as compared to their spacing near the insulation shield. This is why we are cognizant of maximum stresses at areas of minimum radii (and diameters). Insulation voids at the conductor shield are more critical than voids at the insulation shield. Also these lines are spaced closer together at the minimum diameter (or radii). This substantiates the maximum radial stress theory.

5.2.8 Insulation Thickness. The use of shielded cable permits using cables that are more economic to manufacture and install as compared to non-shielded cables that would require very heavy insulation thickness. Table 2-2 provides a comparison.

5.2.9 Jacket or Outer Coverings. Over the insulation shielding system, the cable contains components that provide environmental protection for the cable.

This can be extruded jacket (of synthetic material), metal sheath or wires, armoring, or a combination of these items.

6. REFERENCES

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[2-2] Landinger, Carl, adapted from class notes for "Power Cable Engineering Clinic," University of Wisconsin – Madison, 1997.

[2-3] A. Clapp, C. C. Landinger, and W. A. Thue, "Design and Application of Aerial Systems Using Insulating and Covered Wire and Cable," *Proceedings of the 1996 IEEE/PES Transmission and Distribution Conference,* 96CH35968, Los Angeles, CA, Sept. 15-20, 1996.

[2-4] A. Clapp, C. C. Landinger, and W. A. Thue, "Safety Considerations of Aerial Systems Using Insulating and Covered Wire and Cable," *Proceedings of the 1996 IEEE/PES Transmission and Distribution Conference,* 96CH35968, Los Angeles, CA, Sept. 15-20, 1996.

CHAPTER 3

CONDUCTORS

Lawrence J. Kelly and Carl C. Landinger

1. INTRODUCTION

The fundamental concern of power cable engineering is to transmit current (power) economically and efficiently. The choice of the conductor material, size, and design must take into consideration such items as:

☐ Ampacity (current carrying capacity)
☐ Voltage stress at the conductor
☐ Voltage regulation
☐ Conductor losses
☐ Bending radius and flexibility
☐ Overall economics
☐ Material considerations
☐ Mechanical properties

2. MATERIAL CONSIDERATIONS [3-1]

There are several low resistivity (or high conductivity) metals that may be used as conductors for power cables. Examples of these as ranked by low resistivity at 20 °C are shown in Table 3-1.

Table 3-1
Resistivity of Metals at 20 °C

Metal	**Ohm-mm^2/m × 10^{-8}**	**Ohm-cmil/ft × 10^{-6}**
Silver	1.629	9.80
Copper, annealed	1.724	10.371
Copper, hard drawn	1.777	10.69
Copper, tinned	1.741–1.814	10.47–10.91
Aluminum, soft, 61.2% cond.	2.803	16.82
Aluminum, 1/2 hard to full hard	2.828	16.946
Sodium	4.3	25.87
Nickel	7.8	46.9

Considering these resistivity figures and cost of each of these materials, copper and aluminum become the logical choices. As such, they are the dominant metals used in the power cable industry today.

The choice between copper and aluminum conductors should carefully compare the properties of the two metals, as each has advantages that outweigh the other under certain conditions. The properties most important to the cable designer are shown below.

2.1 DC Resistance

The conductivity of aluminum is about 61.2 to 62 percent that of copper. Therefore, an aluminum conductor must have a cross-sectional area about 1.6 times that of a copper conductor to have the equivalent dc resistance. This difference in area is approximately equal to two AWG sizes.

2.2 Weight

One of the most important advantages of aluminum, other than economics, is its low density. A unit length of bare aluminum wire weighs only 48 percent as much as the same length of copper wire having an equivalent dc resistance. However, some of this weight advantage is lost when the conductor is insulated, because more insulation volume is required over the equivalent aluminum wire to cover the greater circumference.

2.3 Ampacity

The ampacity of aluminum versus copper conductors can be compared by the use of many documents. See Chapter 9 for details and references, but obviously more aluminum cross-sectional area is required to carry the same current as a copper conductor as can be seen from Table 3-1.

2.4 Voltage Regulation

In ac circuits having small (up to #2/0 AWG) conductors, and in all dc circuits, the effect of reactance is negligible. Equivalent voltage drops result with an aluminum conductor that has about 1.6 times the cross-sectional area of a copper conductor.

In ac circuits having larger conductors, however, skin and proximity effects influence the resistance value (ac to dc ratio, later written as ac/dc ratio), and the effect of reactance becomes important. Under these conditions, the conversion factor drops slightly, reaching a value of approximately 1.4.

2.5 Short Circuits

Give consideration to possible short circuit conditions, since copper conductors have higher capabilities in short circuit operation.

2.6 Other Important Factors

Additional care must be taken when making connections with aluminum conductors. Not only do they tend to creep, but they also oxidize rapidly. When aluminum is exposed to air, a thin, corrosion-resistant, high dielectric strength film quickly forms.

When copper and aluminum conductors are connected together, special techniques are required in order to make a satisfactory connection. See the discussion in Chapter 12.

Aluminum is not used extensively in generating station, substation, or portable cables because the lower bending life of small strands of aluminum does not always meet the mechanical requirements of those cables. However, it is the overwhelming choice for aerial conductors because of its high conductivity to weight ratio and for underground distribution for economy where space is not a consideration.

Economics of the cost of the two metals must, of course, be considered, but always weighed after the cost of the overlying materials.

3. CONDUCTOR SIZES

3.1 American Wire Gauge

Just as in any industry, a standard unit must be established for measuring conductor sizes. In the United States and Canada, electrical conductors are sized using the American Wire Gauge (AWG) system. This system is based on the following definitions:

- The diameter of size #0000 AWG (usually written #4/0 AWG and said as "four ought") is 0.4600 inches.
- The diameter of size #36 AWG is 0.0050 inches.
- There are 38 intermediate sizes governed by a geometric progression.

The ratio of any diameter to that of the next smaller size is:

$$\sqrt[39]{\frac{0.4600}{0.0050}} = 1.122932 \qquad (3.1)$$

3.1.1 Short Cuts for Estimations. The square of the above ratio (the ratio of diameters of successive sizes) is 1.2610. Thus, an increase of one AWG size yields a 12.3 % increase in diameter and an increase of 26.1 % in area. An increase of two AWG sizes results in a change of 1.261 (or 26.1 %) in diameter and 59 % increase in area.

The sixth power of 1.122932 is 2.0050, or very nearly 2. Therefore, changing six AWG sizes will approximately double (or halve) the diameter. Another useful short cut is that a #10 AWG wire has a diameter of roughly 0.1 inch, for copper a resistance of one ohm per 1000 feet and a weight of about 10 π, or 31.4 pounds per 1000 feet.

Another convenient rule is based on the fact that the tenth power of 1.2610 is 10.164, or approximately 10. Thus, for every increase or decrease of ten gage numbers (starting anywhere in the table) the cross-sectional area, resistance, and weight are divided or multiplied by about ten.

From a manufacturing standpoint, the AWG sizes have the convenient property that successive sizes represent approximately one reduction in die size in the wire drawing operation.

The AWG sizes were originally known as the Brown and Sharpe Gage (B & S). The Birmingham Wire Gage (BWG) is used for steel armor wires. In Britain, wire sizes were specified by the Standard Wire Gage (SWG), and was also known as the New British Standard (NBS).

3.2 Circular Mil Sizes

Sizes larger than #4/0 AWG are specified in terms of the total cross-sectional area of the conductor and are expressed in circular mils. This method uses an arbitrary area of a conductor that is achieved by *squaring the diameter* of a solid conductor. This drops the π/4 multiplier required for the actual area of a round conductor. A circular mil is a unit of area equal to the area of a circle having a diameter of one mil (one mil equals 0.001 inch). Such a circle has an area of 0.7854 (or π/4) square mils. Thus, a wire ten mils in diameter has a cross-sectional area of 100 circular mils. Likewise, one square inch equals π/4 times

1,000,000 = 1,273,000 circular mils. For convenience, this is usually expressed in thousands of circular mils and abbreviated kcmil. Thus, one square inch equals 1,273 kcmils.

The abbreviation used in the past for thousand circular mils was MCM. The SI abbreviations for million, M, and for coulombs, C, is easily confused with the older term. The preferred abbreviation is kcmil for "thousand circular mils."

3.3 Metric Designations

All the world, except for North America, uses the SI unit of square millimeters (mm^2) to designate conductor size. The International Electrotechnical Commission has adopted IEC 280 to define these sizes. An important consideration is that these are not *precise* sizes. For instance, their 50 mm^2 conductor is actually 47 mm^2. To accommodate everyone, the IEC standard allows as much as a 20% variation in conductor area from the size designated.

A comparison of the two systems can be seen in the tables in Chapter 21. Compression connectors, especially for aluminum, are sensitive to size variations. A #1/0 AWG is not close enough to any of the SI sizes so that a direct substitution is possible without changing the necessary connector and dies for either the 50 or 70 mm^2 sizes. Even the 1000 kcmil (1974 mm^2) size is slightly smaller than the standard SI size of 2000 mm^2.

In Canada, metric designations are used for all cable dimensions *except for the conductor size*! The variations in the two systems are too great to use any of the SI sizes as a direct substitution for standard sizes.

4. STRANDING

Larger sizes of solid conductors become too rigid to install, form and terminate. Stranding becomes the solution to these difficulties. The point at which stranding should be used is dependent on the type of metal as well as the temper of that metal. Copper conductors are frequently stranded at #6 AWG and greater. Aluminum, in the half-hard temper, can be readily used as a solid conductor up to a #2/0 AWG conductor.

4.1 Concentric Stranding

This is the typical choice for power cable conductors. This consists of a central wire or core surrounded by one or more layers of helically applied wires. Each additional layer has six more wires than the preceding layer. Except in unilay construction, each layer is applied in a direction opposite to that of the layer underneath. In the case of power cable conductors, the core is a single wire and all of the strands have the same diameter. The first layer over the core contains six wires; the second, twelve; the third, eighteen; etc. The distance that it takes for one strand of the conductor to make one complete revolution of the layer is called the length of lay. The requirement for the length of lay is set forth in ASTM specifications, [3-5], to be not less than 8 times nor more than 16 times the overall diameter (OD) of that layer.

In power cables, the standard stranding is Class B. Specifications require that the outermost layer be of a left hand lay. This means that as you look along the axis of the conductor, the outermost layer of strands roll towards the left as they recede from the observer. More flexibility is achieved by increasing the number of wires in the conductor. Class C has one more layer than Class B; Class D one more layer than C. The Class designation goes up to M (normally used for welding cables, etc.). These are covered by ASTM specifications [3-2, 3-3, 3-4].

Classes C and D have approximately the same weight as Class B and an OD within 3 mils of Class B conductors. Examples of Class B (standard), Class C (flexible) and Class D (extra flexible) are shown below with the number of strands and diameter of each strand:

Table 3-2
Examples of Class B, C, and D Stranding

Size	**Class B**	**Class C**	**Class D**
#2 AWG	7 × 0.0974	19 × 0.0591	37 × 0.0424
#4/0 AWG	19 × 0.1055	37 × 0.0756	61 × 0.0589
500 kcmil	37 × 0.1162	61 × 0.0905	91 × 0.0741
750 kcmil	61 × 0.1109	91 × 0.0908	127 × 0.0768

The following formula may be used to calculate the number of wires in a concentric stranded conductor:

$$n = 1 + 3\,N\,(N + 1) \tag{3.2}$$

where n = total number of wires in stranded conductor
N = number of layers around the center wire

4.2 Compressed Stranding

This is the term that is used to describe a slight deformation of the layers to allow the layer being applied to close tightly. There is no reduction in conductor area. The diameter of the finished cable can be reduced no more 3 % of the equivalent concentric strand. A typical reduction is about 2.5 %. Examples of gaps in the outer layer for concentric stranded cables are shown in Table 3-3.

Table 3-3
Gaps in Outer Layer of a Stranded Conductor

Total Number of Strands	Angle of Gap at 16 × OD
19	8.3^{0}
37	10^{0}
61	10^{0}

Shortening the length of lay on the outer layers could solve the problem but would result in higher resistance and would require more conductor material.

The reason that compressed stranding is an excellent construction is that concentric stranding with its designated lay length creates a slight gap between the outer strands of such a conductor. Lower viscosity materials that are extruded over such a conductor tend to "fall in" to any gap that forms. This results in surface irregularities that create increased voltage stresses and makes it more difficult to strip off that layer.

4.3 Compact Stranding

This is similar to compressed stranding except that additional forming is given to the conductor so that the reduction in diameter is typically 9% less than the concentric stranded conductor. This results in a diameter nearing that of a solid conductor. Some air spaces are still present that can serve as channels for moisture migration.

4.4 Bunch Stranding

This term is applied to a collection of strands twisted together in the same direction without regard to the geometric arrangement. This construction is used when extreme flexibility is required for small AWG sizes, such as portable cables. Examples of bunch stranded conductors are cords for vacuum cleaners, extension cords for lawn mowers, etc. Examples are:

Table 3-4
Examples of Class K and M Stranding

Conductor Size	Class K	Class M
#16 AWG	26 × 0.0100	65 × 0.0063
#14 AWG	41 × 0.0100	104 × 0.0063
#12 AWG	65 × 0.0100	168 × 0.0063

Note in Class K and M that the individual wire diameters are constant and area is developed by adding a sufficient number of wires to provide the total conductor area required.

4.5 Rope Stranding

This term is applied to a concentric-stranded conductor, each of whose component strands is itself stranded. This is a combination of the concentric conductor and a bunch stranded conductor. The finished conductor is made up of a number of groups of bunched or concentric stranded conductors assembled concentrically together. The individual groups are made up of a number of wires rather than a single, individual strand. A rope-stranded conductor is described by giving the number of groups laid together to form the rope and the number of wires in each group.

Classes G and H are generally used on portable cables for mining applications. Classes I, L, and M utilize bunch stranded members assembled into a concentric arrangement. The individual wire size is the same with more wires added as necessary to provide the area. Class I uses #24 AWG (0.020 inch) individual wires, Class L uses #30 AWG (0.010 inch) individual wires, and Class M uses #34 AWG (0.0063 inch) individual wires. Class I stranding is generally used for railroad applications and Classes L and M are used for extreme portability such as welding cable and portable cords.

4.6 Sector Conductors

They have a cross-section approximately the shape of a sector of a circle. A typical three-conductor cable has three 120° segments that combine to form the basic circle of the finished cable. Such cables have a smaller diameter than the corresponding cable with round conductors.

For paper-insulated cables, the sector conductor was almost always stranded and then compacted in order to achieve the highest possible ratio of conductor area to cable area. The precise shape and dimensions varied somewhat between manufacturers.

Sector conductors that are solid rather than stranded have been used for low-voltage cables on a limited basis. There is interest in utilizing this type of conductor for medium voltage cables, but they are not available on a commercial basis at this time.

4.7 Segmental Conductors

They are round, stranded conductors composed of three or more sectors that are electrically separated from each other by a thin layer of insulation around every other segment. Each segment carries less current than the total conductor and the current is transposed between inner and outer positions in the completed cable. This construction has the advantage of lowering the ac resistance by having less skin effect than a conventionally stranded conductor. This type of conductor should be considered for large sizes such as 1000 kcmil and above.

4.8 Annular Conductors

These are round, stranded conductors whose strands are laid around a core of rope, fibrous material, helical metal tube, or a twisted I-beam. This construction has the advantage of lowering the total ac resistance for a given cross-sectional area of conductor by eliminating the greater skin effect at the center of the completed cable. Where space is available, annular conductors may be economical to use for 1000 kcmil cables and above at 60 hertz and for 1500 kcmil cables and above for lower frequencies such as 25 hertz.

4.9 Unilay Conductors

Unilay has, as the name implies, all of its strands applied with the same direction of lay. A design frequently used for low-voltage power cables is the combination unilay where the outer layer of strands are partially composed of strands having a smaller diameter than the other strands. This makes it possible to attain the same diameter of a compact stranded conductor. The most common unilay conductor is a compact, 8000 series aluminum alloy.

5. PHYSICAL AND MECHANICAL PROPERTIES

5.1 Properties

Table 3-5

Property	Unit	Copper, Annealed	Alum, Hard Drawn
Density at 20°C	Pounds/in^3 Grams/cm^3	0.32117 8.890	0.0975 2.705
Linear Temp. Coeff. of Expansion	per °F per °C	9.4×10^{-6} 17.0×10^{-6}	12.8×10^{-6} 23.0×10^{-6}
Melting Point	per °F	1981	1205–1215
Melting Point	per °C	1083	652–657

5.2 Conductor Properties

Although high conductivity is one of the important features of a good conductor material, other factors must be taken into account. Silver is an interesting possibility for a cable conductor. Its high cost is certainly one of the reasons to look for other candidates. Silver has another disadvantage of lack of physical strength that is necessary for pulling cables into conduits.

5.2.1 Copper. Impurities have a very deleterious effect on the conductivity of copper. The specified purity of copper for conductors is 100%. Small amounts of impurities, such as phosphorous or arsenic, can reduce the conductivity to a value as low as 80% of pure copper.

5.2.2 Aluminum. Electrical conductor (EC) grade aluminum is also low in impurities—99.5% purity or better. ASTM B 233 specifies the permissible impurity levels for aluminum [3-5].

5.3 Temper

Drawing metal rod into wire results in work hardening of the wire. This causes the soft temper metal to have a slightly lower conductivity as well as a higher temper. Stranding and compacting also increases the temper of the metal. If a more flexible conductor is required, annealing the metal may be desirable. This can be done while the strand is being drawn or the finished conductor may be annealed by placing a reel of the finished conductor in an oven at an elevated temperature for a specified period of time.

5.3.1 Copper. ASTM specifications cover three tempers for copper conductors: soft (annealed), medium-hard-drawn, and hard-drawn. Soft-drawn is usually specified for insulated conductors because of its flexibility. Medium-hard-drawn and hard-drawn are usually specified for overhead conductors, but for long or difficult pulls of underground cable, it may be desirable to use a temper greater than soft-drawn.

5.3.2 Aluminum. ASTM has five specifications for aluminum tempers as shown below. Note that some of the values overlap. Half-hard aluminum is usually specified for solid and for 8000 series alloy conductors because of the need for greater flexibility. Three-quarter and full-hard are usually specified for stranded cables.

Table 3-6
Aluminum Temper

1350 Aluminum Tempers	**PSI × 10^3**
Full Soft (H-0)	8.5 to 14.0
1/4 Hard (H-12 or -22)	12.0 to 17.0
1/2 Hard (H-14 or -24)	15.0 to 20.0
3/4 Hard (H-16 or -26)	17.0 to 22.0
Full Hard (H-19)	22.5 to 29.0

It is important to consider two facts before deciding what temper should be specified:

☐ It costs money to provide the energy and equipment to anneal conductors.

☐ The stiffness of the rest of the insulated cable may overwhelm the flexibility issue.

6. STRAND BLOCKING

Moisture in the conductor of an insulated conductor has been shown to cause several problems. Aluminum, in the presence of water and in the absence of oxygen, will hydrolyze. Thus, if water enters an insulated cable having an aluminum conductor, the aluminum and water combine chemically to form aluminum hydroxide and hydrogen gas. This condition is aggravated by a deficiency in oxygen in the insulated conductor. The chemical reaction is:

$$2\,Al + 6\,H_2O \rightarrow Al(OH)_3 + 3\,H_2 \uparrow$$

Aluminum hydroxide is a white, powdery material that is a good insulator. Many users of stranded aluminum conductors are now requiring filled conductors for this reason. Filled conductors prevent the passage of moisture along the conductor and thus help to retard this form of deterioration.

Regardless of the degree of compaction of a stranded conductor, there is some air space remaining. This space can be a reservoir for moisture to collect and hence a source of water for water treeing. Water blocked stranded conductors are frequently specified for underground cables to reduce the possibility of this happening. (Solid conductors, of course, are specified for the same reason for #2/0 AWG aluminum and smaller cables.)

7. ELECTRICAL CALCULATIONS

7.1 Conductor dc Resistance

$$R_{dc} \text{ at } 25\ °C = 1000\,\rho / A \tag{3.3}$$

where R_{dc} = direct current resistance of the conductor in ohms per 1000 feet at 25 °C

ρ = resistivity of metal in ohms per circular mil foot

ρ for copper = 10.575 ohms/cmil-foot at 25 °C

ρ for aluminum = 17.345 ohms/cmil-foot at 25 °C

A = conductor area in circular mils

The resistance of a stranded conductor is more difficult to calculate. It is generally assumed that the current is evenly divided among the strands and does not transfer from one strand to the next one. For that reason, the dc resistance is based on:

☐ Multiply the number of strands by the cross-sectional area taken perpendicular to the axis of that strand. The product is then the cross-sectional area of the conductor.

☐ Compare the length of each strand to the axial length of the conductor. This increased length is arithmetically averaged.

☐ The dc resistance of a solid conductor having the same effective cross-sectional area is multiplied by the average increase in length of the strand. The result is the calculated resistance of the stranded conductor.

Since resistance is based on temperature, the following formulas correct for other temperatures in the range most commonly encountered:

Copper: $$R_2 = R_1 \frac{234.5 + T_2}{234.5 + T_1} \tag{3.4}$$

Aluminum: $$R_2 = R_1 \frac{228.1 + T_2}{228.1 + T_1} \tag{3.5}$$

where

R_2 = Conductor resistance at temperature T_2 in °C
R_1 = Conductor resistance at temperature T_1 in °C

These formulas are based on the resistance coefficient of copper having 100% conductivity and of aluminum having 61.2% conductivity (international annealed copper standard).

7.2 Conductor ac Resistance

A conductor offers a greater resistance to a flow of alternating current than it does to direct current. This increased resistance is generally expressed as the ac/dc resistance ratio. The two major factors for this increase are the skin effect and the proximity effect of closely spaced current carrying conductors. Other magnetic effects can also cause an additional increase in ac/dc resistance ratios.

$$R_{ac} = ac\,/\,dc \text{ ratio} \times R_{dc} \tag{3.6}$$

The ac/dc resistance ratio is increased by larger conductor sizes and higher ac frequencies.

7.3 Skin Effect

In ac circuits, the current density is greater near the outer surface of the conductor. The current tends to crowd toward the outer surface. This is called skin effect. A longitudinal element of the conductor near the center of the axis is surrounded by more lines of magnetic force than near the rim. This results in an increase in inductance toward the center. The decreased area of conductance causes an apparent increase in resistance. At 60 hertz, the phenomenon is negligible in copper sizes of #2 AWG and smaller and aluminum sizes #1/0 AWG and smaller. As conductor sizes increase, the effect becomes more significant.

The following formula can be used to give a good approximation of skin effect for round conductors at 60 hertz:

$$Y_{CS} = \frac{11.18}{R_{dc}^2 + 8.8} \qquad (3.7)$$

where Y_{CS} = Skin effect expressed as a number to be added to the dc resistance

R_{dc} = DC resistance of the conductor in micro-ohms per foot at operating temperature

7.4 Proximity Effect

In closely spaced ac conductors, there is a tendency for the current to shift to the portion of the conductor that is away from the other conductors of that cable. This is called proximity effect. The flux linking the conductor current in one conductor is distorted by the current in a nearby conductor which in turn causes a distortion of the cross-sectional current distribution.

Since skin and proximity effects are cumbersome to calculate, tables have been established to give these values for common modes of operation [3-4].

7.5 Cables in Magnetic Metal Conduit

Due to excessive hysteresis and eddy current losses, individual phases of an ac circuit should not be installed in separate magnetic metal conduits under any circumstances. This is because of the high inductance of such an installation. In fact, separate phases should not pass through magnetic structures since overheating can occur in such a situation. All phases should pass through any magnetic enclosure simultaneously so that maximum cancellation occurs of the resultant magnetic field. This greatly reduces the magnetic effect. However, even under these conditions, an increase in skin and proximity effect will occur because of the proximity of the magnetic material. There can be significant losses when large conductors are simply placed near magnetic materials.

Cables in 50 or 60 hertz ac circuits should not be installed with each phase in a separate non-magnetic metal conduit when their size is #4/0 AWG or larger due to high circulating currents in the conduit. This causes a significant derating of the cable ampacity.

7.6 Resistance at Higher Frequencies

Cables operating at frequencies higher than 60 hertz may need to be evaluated for ampacity and ac/dc ratios because they can cause higher voltage drops than might be anticipated. Also at higher frequencies, an increase in the inductive reactance may affect voltage drops. Insulated conductors should not be installed in metallic conduits nor should they be run close to magnetic materials.

For frequencies other than 60 hertz, a correction factor is provided by:

$$x = 0.027678\sqrt{f/R_{dc}} \qquad (3.8)$$

where f = frequency in hertz
R_{dc} = conductor dc resistance at operating temperature, in ohms per 1000 feet

For additional information on the effects of higher frequency, see the ICEA Report in reference [3-3] and cable manufacture's manuals [3-4 and 3-5].

8. REFERENCES

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CHAPTER 4

CABLE CHARACTERISTICS: ELECTRICAL

Lawrence J. Kelly and William A. Thue

1. VOLTAGE RATINGS OF CABLES

The rating, or voltage class, of a cable is based on the phase-to-phase voltage of the system even though the cable is single, two, or three phase. For example, a 15 kV rated cable (or a higher value) must be specified on a system that operates at 7,200 or 7,620 volts to ground on a grounded wye 12,500 or 13,200 volt system. This is based on the fact that the phase-to-phase voltage on a wye system is 1.732 (the square root of 3) times the phase-to-ground voltage. Another example is that a cable for operation at 14.4 kV to ground *must* be rated at 25 kV or higher since 14.4 times 1.732 is 24.94 kV.

The wye systems described above are usually protected by fuses or fast-acting relays. This is generally known as the 100 % voltage level and was previously known as a "grounded" circuit. Additional insulation thickness is required for systems that are not grounded, such as found in some delta systems, impedance or resistance grounded systems, or systems that have slow-acting isolation schemes. The following voltage levels are found in AEIC specifications [4-1 and 4-2].

1.1 100 Percent Level

Cables in this category may be applied where the system is provided with relay protection such that ground faults will be cleared as rapidly as possible, but in any case within 1 minute. While these cables are applicable to the great majority of cable installations that are on grounded systems, they may also be used on other systems for which the application of cables is acceptable provided the above clearing requirements are met in completely de-energizing the faulted section.

1.2 133 Percent Level

This insulation level corresponds to that formerly designated for "ungrounded" systems. Cables in this category may be applied in situations where the clearing time requirements of the 100 percent category cannot be met and yet there is adequate assurance that the faulted section will be de-energized in a time not exceeding one hour. Also, they may be used when additional insulation strength over the 100 percent level category is desirable.

1.3 173 Percent Level

Cables in this category should be applied on systems where the time required to de-energize a section is indefinite. Their use is recommended also for resonant grounded systems. Consult the (cable) manufacturer for insulation thickness.

1.4 Cables Not Recommended

Cables are not recommended for use on systems where the ratio of the zero to positive phase reactance of the system at the point of cable application lies between -1 and -40 since excessively high voltages may be encountered in the case of ground faults.

1.5 Ratings of Low Voltage Cables

Low voltage cable ratings follow the same general rules as for the medium voltage cables previously discussed in that they are also based on phase-to-phase operation. The practical point here is that a cable that operates at say 480 volts from phase-to-ground on a grounded wye system requires an insulation thickness applicable to 480 x 1.732 or 831.38 volts phase-to-phase. This, of course, means that a 1,000 volt level of insulation thickness should be selected.

There are no categories for low voltage cables that address the 100, 133 and 173 percent levels. One of the main reasons for the thickness of insulation walls for these low voltage cables in the applicable Standards is that mechanical requirements of these cables dictate the insulation thickness. As a practical matter, all these cables are over-insulated for the actual voltages involved.

2. CABLE CALCULATION CONSTANTS

There are four main calculation constants that affect how a cable functions on an electric system: resistance, capacitance, inductance, and conductance. Conductor resistance has been addressed in Chapter 3.

2.1 Cable Insulation Resistance

The resistance to flow on a direct current through an insulating material (dielectric) is known as insulation resistance. There are two possible paths for current to flow when measuring insulation resistance:

(a) Through the body of the insulation (volume insulation resistance)

(b) Over the surface of the insulation system (surface resistivity)

2.1.1 Volume Insulation Resistance. The volume insulation resistance of a cable is the direct current resistance offered by the insulation to an impressed dc voltage tending to produce a radial flow of leakage through that insulation material. This is expressed as a resistance value in megohms for 1000 feet of cable for a given conductor diameter and insulation thickness. Note that this is *for* 1000 feet, not *per* 1000 feet! This means that the longer the cable, the lower the resistance value that is read on a meter since there are more parallel paths for current to flow to ground. The basic formula for the insulation resistance of a single conductor cable of cylindrical geometry is:

$$IR = \mathrm{K} \log_{10} D/d \qquad (4.1)$$

where IR = Megohms for 1000 feet of cable
K = Insulation resistance constant
D = Diameter over the insulation (under the insulation shield)
d = Diameter under the insulation (over the conductor shield)

Note: Both D and d must be expressed in the same units.

In order to measure the insulation resistance of a cable, the insulation must be either enclosed in a grounded metallic shield or immersed in water. Resistance measurements are greatly influenced by temperature—the higher the temperature, the lower the insulation resistance. The cable manufacturer should be contacted for the temperature correction factor for the specific insulation. Equation 4.1 is based on values at 60 °F.

The values shown in Table 4-1 are also based on this temperature. The ICEA minimum requirements of IR (sometimes referred to as "guaranteed values") are shown as well to represent values that may be measured in the field. The actual value of IR that would be read in a laboratory environment are many times higher than these "minimum" values and approaches the "typical" values shown below.

Table 4-1
Insulation Resistance

Insulation	ICEA Minimum	Typical
HMWPE	50,000	1,000,000
XLPE & EPR, 600 V	10,000	100,000
XLPE & EPR, Med. V	20,000	200,000
PVC at 60 °C	2,000	20,000
PVC at 75 °C	500	5,000

2.1.2 Surface Resistivity. One of our contributors often states that "all cables have two ends." These terminations or ends, when voltage is applied to the conductor, can have current flow over the surface of that material. This current adds to the current that flows through the volume of insulation which lowers the *apparent* volume insulation resistance unless measures are taken to eliminate that current flow while the measurements described above are being made. This same situation can occur when samples of insulation are measured in the laboratory. A "guard" circuit is used to eliminate the surface leakage currents from the volume resistivity measurement.

2.1.3 dc Charging Current. The current generated when a cable is energized from a dc source is somewhat complicated because there are several currents that combine to form the total leakage current. These currents are:

I_L = Leakage current
I_G = Charging current
I_A = Absorption current

The dc charging current behaves differently than the ac in that the dc value rises dramatically during the initial inrush. It decreases rather quickly with time, however. The magnitude of the charging and absorption currents is not usually very important except that it may distort the true leakage current reading. The longer the length and the larger the cable size, the greater the inrush current and the longer it will take for the current to recede. This initial current decays exponentially to zero in accordance with the following equation:

$$I_G = (E/R)\,\varepsilon^{-t/RC} \qquad (4.2)$$

where
I_G = Charging current in microamperes per 1000 feet
E = Voltage from conductor to ground in volts
R = dc resistance of cable in megohms for 1000 feet
ε = Base of natural logarithm (2.718281...)

t = Time in seconds
C = Capacitance of circuit in microfarads per 1000 feet

The absorption current is caused by the polarization and accumulation of electric charges that accumulate in a dielectric under applied voltage stress. The absorption current normally is relatively small and decreases with time. Absorption current represents the stored energy in the dielectric. Short-term grounding of the conductor may not give a sufficient amount of time for that energy to flow to ground. Removing the ground too quickly can result in the charge reappearing as a voltage on the conductor. The general rule is that the ground should be left on for one to four times the time period that the dc source was applied to the cable. The absorption current is:

$$I_A = A\,V\,C\,t^{-B} \tag{4.3}$$

where
I_A = Absorption current in microamperes per 1000 feet
V = Incremental voltage change in volts
C = Capacitance in microfarads per 1000 feet
t = Time in seconds

A and B are constants depending on the insulation.

A and B are constants that differ with the specific cable since they are dependent on the type and condition of the insulation. They generally vary in a range that limits the absorption current to a small value compared to the other dc currents. This current decays rather rapidly when a steady-state voltage level is reached.

The current that is of the most importance is the leakage or conduction current. The leakage current is dependent on the applied voltage, the insulation resistance of the cable insulation, and any other series resistance in the circuit. This value becomes very difficult to read accurately at high voltages because of the possibility of end leakage currents as well as the transient currents. The formula for leakage current is:

$$I_L = E / R_I \tag{4.4}$$

where
I_L = Leakage current in microamperes per 1000 feet
E = Voltage between conductor and ground in volts
R_I = Insulation resistance in megohms for 1000 feet

The total current is:

$$I_T = I_G + I_A + I_L \tag{4.5}$$

The voltage must be raised slowly and gradually because of the rapid rise of I_G and I_A with time. Also, since both of these values are a function of cable length, the longer the cable length, the slower the rise of voltage is allowable. Equation (7-11) demonstrates the reason for taking a reading of leakage current after a specified period of time so that the actual leakage current can be recorded.

2.2 Dielectric Constant

Dielectric constant, relative permittivity, and specific inductive capacitance all mean the same. They are the ratio of the absolute permittivity of a given dielectric material and the absolute permittivity of free space (vacuum). The symbol for permittivity is ε (epsilon). To put this another way, these terms refer to the ratio of the capacitance of a given thickness of insulation to the capacitance of the same capacitor insulated with vacuum. (This is occasionally referred to as air rather than vacuum, but the dielectric constant of air is 1.0006). Since the calculations are usually not taken out to more than two decimal points, it is practical to use air for the comparison. The value of permittivity, dielectric constant, and SIC are expressed simply as a number since the dielectric constant of a vacuum is taken as 1.0000.

2.3 Cable Capacitance

The property of a cable system that permits the conductor to maintain a potential across the insulation is known as capacitance. Its value is dependent on the permittivity (dielectric constant) of the insulation and the diameters of the conductor and the insulation. A cable is a distributed capacitor. Capacitance is important in cable applications since charging current is proportional to the capacitance as well as to the system voltage and frequency. Since the charging current is also proportional to length, the required current will increase with cable length.

The capacitance of a single conductor cable having an overall grounded shield or immersed in water to provide a ground plane may be calculated from the following formula:

$$C = \frac{0.00736\,\varepsilon}{\log_{10} D/d} \tag{4.6}$$

where C = Capacitance in microfarads per 1000 feet

ε = Permittivity of the insulating material. The terms permittivity (ε, epsilon), dielectric constant (K), and specific inductive capacitance (SIC) are used interchangeably. The term permittivity is preferred. See Table 4-2.
D = Diameter over the insulation (under the insulation shield)
d = Diameter under the insulation (over the conductor shield)

Note: Both *D* and *d* must be expressed in the same units.

Table 4-2
Permittivity, Dielectric Constant, and SIC

Material	Range	Typical
Butyl Rubber	3.0–4.5	3.2
PVC	3.4–10	6.0
Varnished Cambric	4–6	4.5
Impregnated Paper	3.3–3.7	3.5
Rubber-GRS or Natural	2.7–7.0	3.5
HMWPE	2.1–2.6	2.2
XLPE or TR-XLPE	2.1–2.6	2.3
XLPE, filled	3.5–6.0	4.5
EPR	2.5–3.5	3.0
Silicone Rubber	2.9–6.0	4.0

In single conductor, low-voltage cables where there is no semiconducting layer over the conductor, a correction factor must be used to compensate for the irregularities of the stranded conductor surface as shown in Table 4-3.

$$C = \frac{0.00736\,\varepsilon}{\log_{10} D/kd} \tag{4.7}$$

Table 4-3
Correction Factors for Irregularities

Number of Strands	Factor k
1 (solid)	1.0
7	0.94
19	0.97
37	0.98
61 & 91	0.985

2.4 Capacitive Reactance

The capacitive reactance of a cable is inversely dependent on the capacitance of the cable and the frequency at which it operates.

$$X_C = \frac{1}{2\pi f C} \tag{4.8}$$

where X_C = Ohms per foot
f = Frequency in hertz
C = Capacitance in picofarads per foot

2.5 Charging Current for Alternating Current Operation

For a single conductor cable, the current may be calculated from the formula:

$$I_C = 2\pi f C E \times 10^{-3} \tag{4.9}$$

where I_C = Charging current in milliamperes per 1000 feet
f = Frequency in hertz
C = Capacitance in picofarads per foot
E = Voltage from conductor to neutral in kilovolts

Other leakage currents are also present, but the capacitive current has the largest magnitude. In addition, the capacitive charging current flows as long as the system is energized. The resistive component of the charging current is also dependent on the same factors as the capacitive current and is given by the formula:

$$I_R = 2\pi f C E \tan\delta \tag{4.10}$$

where I_R = Resistive component of the charging current
$\tan\delta$ = Dissipation factor of the insulation

The tan δ of medium voltage insulation, such as crosslinked polyethylene and ethylene propylene, has values that are generally below 0.02 so the resistive component of the charging current is only a small fraction of the total charging current. The tan δ is sometimes referred to as the insulation power factor since at the small angles these values are approximately equal. since the capacitive charging current is 90° out of phase with the resistive charging current, the total charging current is generally given as the capacitive component and leads any resistive current flowing in the circuit by 90°. The result of these ac currents generated put demands on power required for test equipment.

2.6 Cable Inductive Reactance

The inductive reactance of an electrical circuit is based on Faraday's law. That law states that the induced voltage appearing in a circuit is proportional to the rate of change of the magnetic flux that links it. The inductance of an electrical circuit consisting of parallel conductors, such as a single-phase concentric neutral cable may be calculated from the following equation:

$$X_L = 2\pi f\,(0.1404 \log_{10} S/r + 0.153) \times 10^{-3} \qquad (4.11)$$

where X_L = Ohms per 1000 feet
S = Distance from the center of the cable conductor to the center of the neutral
r = Radius of the center conductor

S and r must be expressed in the same unit, such as inches.

The inductance of a multi-conductor cable mainly depends on the thickness of the insulation over the conductor.

2.6.1 Cable Inductive Reactance at Higher Frequencies. Since the inductive reactance of an insulated conductor is directly proportional to frequency, the inductive reactance is substantially increased in higher frequency applications. Conductors must be kept as close together as possible. Due to the severe increase in inductive reactance at high frequency, many applications will require using two conductors per phase to reduce the inductive reactance to approximately one-half that of using one conductor per phase. A six conductor installation should have the same phase conductors 180° apart.

2.7 Mutual Inductance in Cables

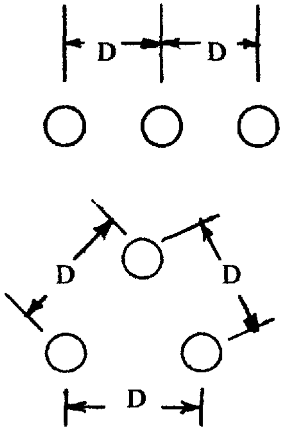
In single-conductor shielded or metallic-sheathed cables, current in the conductor will cause a voltage to be produced in the shield or sheath. If the shield or sheath forms part of a closed circuit, a current will flow. (Shield and sheath losses are described under Ampacity in Chapter 12).

The approximate mutual inductance between shields or sheaths is given by the following relation:

$$L_m = 0.1404 \log_{10} S/r_m \times 10^{-3} \qquad (4.12)$$

where L_m = Henries to neutral per 1000 feet
S = Geometric mean spacing between cable centerlines in inches
r_m = Mean shield or sheath radius in inches. See Fig. 4-1.

Figure 4-1
Geometric Spacing



$$S = \sqrt[3]{D \times D \times 2D} = \sqrt[3]{2D^3} = 1.26\,D$$

$$S = D$$

2.8 Cable Conductor Impedance

Conductor impedance of a cable may be calculated from the following equation:

$$Z = R_{ac} + \mathrm{j}X_L \tag{4.13}$$

where
Z = Conductor impedance in ohms per 1000 feet
R_{ac} = ac resistance in ohms per 1000 feet
X_L = Conductor reactance in ohms per 1000 feet

Conductor impedance becomes an important factor when calculating voltage drop. Since the power factor angle of the load and impedance angle are usually different, the voltage drop calculation can be cumbersome. The following voltage drop equation can be used for a close approximation:

$$V_D = R_{ac}\, I \cos\theta + X_L\, I \sin\theta \tag{4.14}$$

where
V_D = Voltage drop from phase to neutral in volts
R_{ac} = ac resistance of the length of cable in ohms
$\cos\theta$ = Power factor of the load
X_L = Inductive reactance of the length of cable in ohms

2.9 Total Cable Reactance

The total cable reactance (X) is the vector sum of the capacitive reactance and the inductive reactance of the cable in ohms per foot.

$$X = X_C + X_L \tag{4.15}$$

2.10 Cable Dissipation Factor

In cable engineering, the small amount of power consumed in the insulation (dielectric absorption) is due to losses. These losses are quite small in medium voltage cables, but can become more significant in systems operating above 25 kV. No insulating material is perfect.

In addition to the charging current flowing through the capacitive portion of the circuit, current also flows though the ac resistance portion of the circuit. This is the ac loss portion of the insulation circuit. The ratio of the ac resistance of the insulation to the capacitive reactance of the insulation is called the dissipation factor. This is equal to the tangent of the dissipation angle that is usually called tan δ. This tan δ is approximately equal to the power factor of the insulation which is the cos θ of the complimentary angle.

In practical cable insulations and at 50 to 60 hertz, high insulation resistance and a comparatively large amount of capacitive reactance is present. There is virtually no inductive reactance. Hence the current leads the voltage by almost 90°. Since the cosine of 90° is zero, the cosine of an angle approaching 90° is small and the dissipation factor (often referred to as power factor of the insulation) also is small. Typical values for insulation power factor are 0.005 to 0.02 or slightly higher for other materials.

Dissipation factor is used in cable engineering to determine the dielectric loss in the insulation, expressed as watts per foot of cable that is dissipated as heat. It is also used to some extent to describe the efficiency or perfection of the insulation as a dielectric. Hence the term δ (delta) was chosen to represent the defect angle of the material.

Figure 4-2
Cable Insulation Power Factor or Dissipation Factor

2.11 Insulation Parameters

2.11.1 Voltage Stress in Cables. Voltage stresses in shielded cable insulations with smooth, round conductors is defined as the electrical stress or voltage to which a unit thickness of insulation is subjected. The average stress in volts per mil is determined by dividing the voltage across the insulation by the insulation thickness in mils.

$$S_{avg} = 2V/(D-d) \tag{4.16}$$

where

S_{avg} = Average stress in volts per mil
V = Voltage across the insulation
D = Outer diameter of the insulation in mils
d = Inside diameter of the insulation in mils

The stress is not uniform throughout the wall. The stress at any point in insulation wall can be calculated by the formula:

$$S = V/2.303\, r \log_{10}(D/d) \tag{4.17}$$

where

S = Stress in volts per mil at a point in the insulation r mils from the cylindrical axis.

The maximum stress occurs at the surface of the conductor shield.

$$S_{max} = 0.868\, V/\, d \log_{10}(D/d) \tag{4.18}$$

where The units are the same as in (4.15, 4.16 and 4.17).

2.11.2 Dielectric Strength. Although maximum and average stress are important, dielectric strength is usually specified as the average stress at electrical breakdown. The dielectric strength of a material depends on the dimensions and the testing conditions, particularly the time duration of the test. A thin wall of material generally withstands a higher average stress before breaking down than a thicker wall.

2.11.2.1 ac Dielectric Strength. These measurements are made in two ways:

Quick-rise or
Step-rise.

In the quick-rise method, the voltage applied to the insulation is raised at a uniform rate until the insulation breaks down. As an example, a rate of rise of 500 volts per second is known as "quick-rise."

In the "step-rise" method, the voltage is raised to a predetermined level and held at that level for an amount of time, such as five or ten minutes at each level, until breakdown occurs. A relatively short time, say the five or ten minutes described above, has the advantage of reaching breakdown in a shorter amount of total test time. In the real world, the time at a voltage level is much longer, so some cable engineers prefer a longer step time such as 30 minutes or one hour at each step. With the longer step times, the breakdown voltage is lower than with the quick-rise or short step time methods.

2.11.2.2 Impulse Strength. Because cable insulation is frequently subjected to lightning or switching surges, it is often desirable to know the impulse strength of the cable. Surges of "standard" wave shape, such as eight seconds to reach 90% of crest value, and 40 microseconds to drop to one-half of crest value, are frequently used in the laboratory. The increasing voltages are applied to the insulation with several surges at a negative potential and then, at the same voltage level, the same number of surges are applied with positive pulses. The average stress in volts per mil is calculated from the crest voltage of the surge on which breakdown occurs.

3. REVIEW OF ELECTRICAL ENGINEERING TERMS

These terms apply to all electrical engineering circuits. The actual application of these terms to cables is covered in section 2.0 of this chapter.

3.1 Resistance

(R) is the scalar property of an electric circuit which determines, for a given current, the rate at which electric energy is converted into heat or radiant energy. Its value is such that the product of the resistance and the square of the current gives the rate of conversion of energy.

In a direct-current circuit,

$$R = E/I \tag{4.19}$$

and

$$P = I^2R \tag{4.20}$$

where R = Resistance in ohms
E = Electromotive force in volts

I = Current in amperes
P = Power in watts

3.2 Conductance

(G) is the property of an electric circuit which determines, for a given electromotive force in the circuit or for a given potential difference between the terminals of a part of a circuit, the rate at which energy is converted into heat or radiant energy. This value is such that the product of the conductance and the square of the electromotive force, or potential difference, gives the rate of conversion of energy.

$$P = E^2 G \qquad (4.21)$$

where P = Power in watts
E = Voltage, phase to ground, in kilovolts
G = Conductance in mhos

The unit of conductance is the mho. Conductance is the reciprocal of resistance.

$$G = 1/R \qquad (4.22)$$

where G = Conductance in mhos
R = Resistance in ohms

3.3 Volume Resistivity

Volume resistivity of a material is the reciprocal of conductivity. The unit for volume resistivity is ρ (rho). It is the resistance of a section of material of unit length and unit cross-section.

$$R = \rho l / a \qquad (4.23)$$

where R = Resistance
ρ = rho, volume resistivity
a = Area
l = Length

3.4 Conductivity

Conductivity of a material is the direct-current conductance between the opposite, parallel faces of a portion of the material having unit length and unit cross-section. The unit for this is γ (gamma). It is the reciprocal of resistivity.

$$G = \gamma a / l \tag{4.24}$$

where G = Conductance
a = Area
l = Length

3.5 Inductance

Unit L represents the scalar property of an electric circuit, or two neighboring circuits, which determines the electromotive force induced in one of the circuits by a change of current in either of them.

3.5.1. Self Inductance. This is the property of an electric circuit that determines, for a given rate of change of current in the circuit, the electromotive force induced in the same circuit.

The unit of inductance is one henry. One henry is the self inductance of a closed circuit in which an electromotive force of one volt is produced when the electric current transversing the circuit varies uniformly at the rate of one ampere per second.

$$e_1 = -L \, di_1 / dt \tag{4.25}$$

where e_1 and i_1 are in the same circuit and L is the coefficient of self inductance.

3.5.2. Mutual Inductance. (L_m) is the common property of two associated electric circuits that determines, for a given rate of change of current in one of the circuits, the electromotive force induced in the other.

3.6 Capacitance

This is the property of an electric system comprising insulated conductors and associated dielectric materials which determines, for a given time rate of change of potential difference between the conductors, the displacement currents in the system.

3.7 Reactance

Reactance is the product of the sine of the angular phase difference between the current and potential difference times the ratio of the effective potential difference to the effective current, there being no source of power in the portion of the circuit under consideration. The total reactance of a circuit is the sum of the inductive and capacitive reactance.

3.8 Impedance

Impedance is the ratio of the effective value of the potential difference between the terminals to the effective value of the current, there being no source of power in the portion of the circuit under consideration.

3.9 Admittance

(Y) is the reciprocal of impedance.

3.10 Power Factor

(F_p) is the ratio of active power to apparent power. Apparent power (S) consists of two components; active (in-phase) power P_a, which does useful work and reactive (out-of-phase) power P_r.

4. REFERENCES

[4-1] Association of Edison Illuminating Companies, *Specifications for Thermoplastic and Cross-Linked Polyethylene Insulated Shielded Power Cables Rated 5 Through 46 kV,* Specification CS5-94, 10th Ed., New York, NY, AEIC, 1994.

[4-2] Association of Edison Illuminating Companies, *Specifications for Ethylene Propylene Insulated Shielded Power Cables Rated 5 Through 69 kV,* Specification CS6-96, 6th Ed. New York, NY, AEIC, 1996.

CHAPTER 5

INSULATING MATERIALS FOR CABLES

Bruce S. Bernstein

1.0 INTRODUCTION

Electrical insulation materials are employed over the metallic conductors of underground cables at all voltage ratings. Polymeric materials are employed as the insulation, but the nature of the polymer may vary with the voltage class.

Transmission cables, which are defined as cables operating above 46 kV, have traditionally used paper / oil systems as the insulation. The paper is applied as a thin film wound over the cable core. Some years back, a variation of this paper insulation was developed, the material being a laminate of paper with polypropylene (PPP or PPLP). Since the advent of synthetic polymer development, polyethylene (PE) has been used as an insulation material, and in most countries (France being the exception) the use of polyethylene was limited to the crosslinked version (XLPE). XLPE is considered to be the material of choice due to its ease of processing and handling, although paper / oil systems have a much longer history of usage and much more information on reliability exists.

For distribution voltage classes (mostly 15 to 35 kV), the prime material used in the past was conventional PE; however, this was replaced by XLPE as the material of choice in the 1980s. The installed PE-insulated cables are gradually being replaced. In recent years, ethylene propylene co- or ter-polymers have been used (EPR or EPDM, respectively). The use of EPR, which is an elastomer, (XLPE is semi-crystalline) requires the incorporation of inorganic mineral fillers. The term EPR has been used to generically describe both EPR and EPDM cables and that terminology will be employed here.

At even lower voltages, the possible choices of polymeric materials widens. Here it is possible to use polyvinyl chloride (PVC), silicone rubber (SIR), or other polymers that are readily available and processable. PVC was used for a time in Europe for medium voltage cables in the 10 kV class, but that practice has been discontinued.

Many years ago, butyl rubber was used for distribution cables, but virtually all of this installed cable has been replaced at medium voltages.

Each insulation type has certain advantages and disadvantages. As an overview, some are noted below:

POLYMER TYPE	**PROPERTY**
Low Density Polyethylene	Low dielectric losses Moisture sensitive under voltage stress
Crosslinked polyethylene	Slightly higher losses vs. PE Ages better than PE
EPR / EPDM	Higher losses vs. XLPE or PE More flexible than XLPE or PE Requires inorganic filler
PVC	Must contain plasticizer for flexibility Higher losses

Polymers such as polyethylene, polypropylene, and ethylene propylene co- and ter-polymers are hydrocarbon polymers, and are known as polyolefins. Paper insulated cables were historically the first type of polymer used since paper was, and is, readily available from natural resources. Paper is derived from wood pulp and is a natural polymer comprised of cellulose. However, the polyolefins developed shortly after World War II are a preferred insulation because of their superior properties such as:

- ☐ Excellent electrical properties
    - - Low dielectric constant
    - - Low power factor
    - - High dielectric strength

- ☐ Excellent moisture resistance
- ☐ Extremely low moisture vapor transmission
- ☐ High resistance to chemicals and solvents

The electrical properties of polyolefins are superior to those of paper / oil insulation systems and the polymers are considerably more moisture resistant than paper. The reasons for preferred use of polyolefins for electrical insulations are clear.

In addition to the primary insulation, polymers are employed as conductor and insulation shields. These are essentially ethylene copolymers that possess quantities of carbon black to provide the conducting properties. The copolymer is considered a "carrier", but this carrier must possess the property of controlled adhesion to the insulation. The use of a conducting material dispersed throughout the polymer matrix makes the mixture semiconducting in nature; hence the term "semiconducting" is applied to the shield materials.

This chapter will focus on:

(a) Fundamental properties of polyethylene and crosslinked polyethylene from an electrical perspective.

(b) EPR and how it differs from PE and XLPE.

(c) Fundamentals of cellulosic insulation and how it differs from polyolefins.

2.0 FUNDAMENTALS OF EXTRUDED POLYMERS

2.1 Polyethylene

Polyethylene is a hydrocarbon polymer comprised exclusively of carbon and hydrogen. It is manufactured from the monomer ethylene, as shown in Figure 5-1. Note that the chemical structure is a series of repeating - CH_2 - units.

Figure 5-1

FUNDAMENTALS

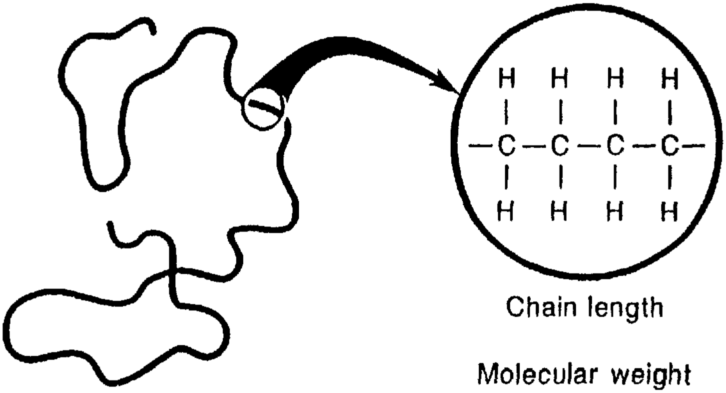
- Polyethylene
- Crosslinked polyethylene

Ethylene (gas) Polyethylene (solid)

$$\ldots CH_2 = CH_2 \ldots \longrightarrow CH_2 - CH_2 - CH_2 - CH_2 - CH_2 \ldots$$

Polyethylene falls into the class of polymers known as polyolefins (polypropylene is another example). The polymer is produced by one of several processes, the nature of which is beyond the scope of this book. What is important to note is that the method of manufacture controls the exact chemical structure, which in turn controls the properties. The carbon--hydrogen structure noted above is simplified; PE is actually more complex than is shown here. To understand this, and for simplicity, we will depict the polymer as a wavy line as shown below in Figure 5-2.

Figure 5-2
Depiction of Polyethylene Chemical Structure



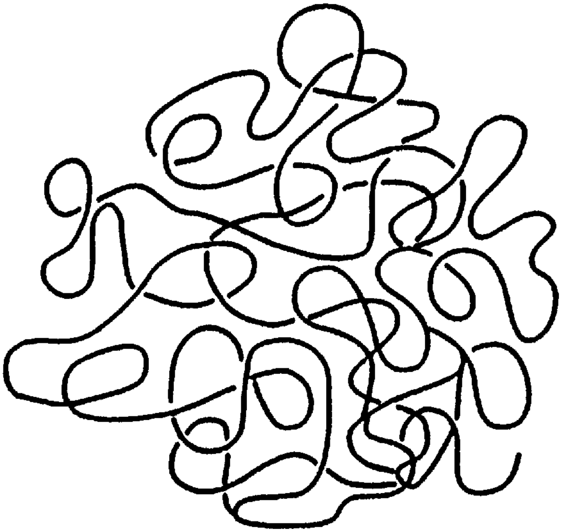
The wavy line is referred to as a "chain" and the length of the chain is significant. The chain length as depicted is related to the molecular weight. Hence, a longer chain is considered to have a higher molecular weight than a shorter chain. Molecular weight increases as the number of ethylene groups in the molecule increases. Conventional polyethylene is comprised of many chains of this type, and the chain lengths varies. Hence, PE is considered to be comprised of polymer chains that have a distribution of molecular weights. Indeed, the molecular weight distribution is a means of characterizing the polyethylene. For the PE insulation that was employed as insulation for medium voltage cables in the past, the polymeric material was described as "high molecular weight polyethylene." This merely means that the "average" chain length was considered to be high. Another generalization is that the higher the molecular weight, the better the overall properties. A typical polyethylene contains a variety of individual chains of different lengths (i. e., weights).

The average molecular weight can be described in several ways. The terms employed most often are "weight average" and "number average." These values arise from different mathematical methods of averaging the molecular weights in polymer samples possessing molecules of different sizes. The mathematical definitions of the number and weight averages are related to the smaller and larger sized molecules, respectively. Hence, the weight average molecule weight is always greater than the number average. When the polymer insulation is crosslinked (see below), the molecular weight determination becomes more complex since the crosslinked fraction can be considered to have an "infinite" molecular weight. From the perspective of the cable engineer, what is relevant to understand is that there is no single way of characterizing the polymer molecular weight. However, the higher molecular weight (average, of course) provides better overall properties in application.

The same principles apply to ethylene copolymers with propylene or other monomers such as vinyl acetate or ethyl acrylate. These latter copolymers are employed in shield compounds. The chain lengths may vary and their length influences properties. The relative amounts of the second (copolymerized) monomer must also be taken into consideration when evaluating properties.

Another point to note about the polyethylene chains is the fact that they have a tendency to coil. In other words, they are not exactly straight, but have a tendency to achieve random configuration like a bowl of spaghetti as shown in Figure 5-3. This tendency is independent of the molecular weight.

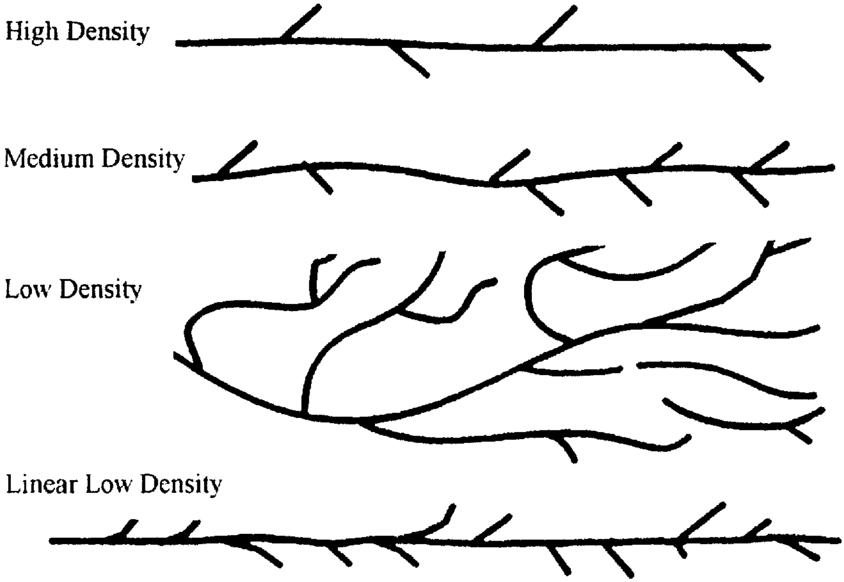
Figure 5-3
Simplified Description of Random Coiled Configuration



The tendency to coil means that the chains also have a tendency to entangle with each other. These entanglements mean that when the chains are pulled apart (as would occur in performing a tensile strength or elongation measurement), and there will be some resistance to movement. These entanglements contribute to the good properties of PE, but not to the qualities that make PE resistant to the penetration of water vapor.

In addition, the chains are not always as linear as shown in the figures. When polyethylene is manufactured, the process always leads to side chains coming off the main long chain. This is called chain branching, and is discussed below. These branches contribute to the molecular weight. It is possible to now visualize that two single molecules may have the same exact molecular weight, but one may have a longer main chain and the other a shorter main chain with a longer branch than the first. Two different polyethylene material batches having many molecules like the two described here (if it were possible to manufacture these) would have significantly different properties.

Figure 5-4
Structure of Polyethylenes

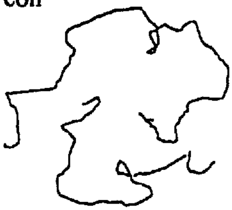


Molecular weight, or molecular weight distribution, is one way of describing the characteristics of polyethylene insulation, but it is not the only way. Other very important characteristics are branching and crystallinity. Crystallinity will be discussed first. Polyethylene and some other polyolefins are known as semicrystalline polymers. This characteristic results from the fact that the polymer chains have a tendency not only to coil, but to align relative to each other. Alignment means that there is short and long term order to the chain structure. While the nature of these alignments is quite complex, and the detailed structure is beyond the scope of this chapter, it is important to understand that the alignment contributes to the crystalline nature of the polyethylene, and therefore to the density.

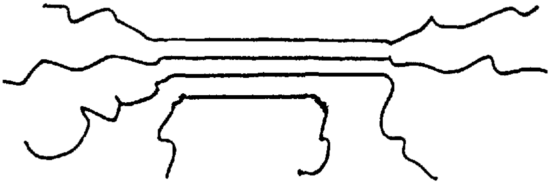
Figure 5-5

Conventional polyethylene has many chains

The chains have a tendency to coil



For polyethylene, different chain segments also have a tendency to align next to each other



The aligned portions cannot coil. The portions that are not aligned will coil. The chain portions that are aligned are said to be crystalline. The chain portions not aligned are said to be amorphous.

Figure 5-5 shows chains alignment where the polymer chain lengths differ. Some portions of the same chains align with adjacent chains, and some portions of the very same chains are not aligned. Those chain portions where alignment occurs are in regions called "crystalline." Figure 5-5 shows that such alignment is not related to molecular weight. It is possible to have low or high molecular weight polyethylene of the same, or different, degrees of alignment. Hence, in principle, it is possible to have many different types of polyethylenes: high density, high molecular weight; high density, low molecular weight; low density, high molecular weight; or low density, low molecular weight. Not all these types are of practical interest.

It is the crystalline regions that give polyethylene many good properties such as toughness, high modulus, moisture and gas permeation resistance. Those regions that are aligned also have increased density due to "tighter" chain packing. Hence, increased crystallinity also means higher density. The alignment process means less "free" (amorphous) regions in the polymer and more polymer per unit volume. The amorphous regions increase the ductility, flexibility, and facilitate processing.

Branching, referred to above, is a direct result of the polymerization process. The older high pressure process leads to a greater number of branches (and they are longer) than do the newer low pressure processes. Branching influences the crystallization process by interfering with the ability of the polyethylene chains to align with each other. For crystallinity to occur, non-branched regions must be able to approach each other closely. When branching is present, the ability of the main chain to come in close proximity to another main chain is inhibited. Hence, polyethylenes have historically been classified into three main categories due to this phenomenon:

Low density
Medium density
High density

As the density increases, the degree of chain alignment increases and the "volume" of aligned chains increases. The degree of branching is related to the polymerization process. It is affected since branching influences crystallinity, the latter is affected very little, if at all, by the conversion of polymer pellets into cable insulation.

Historically, low and medium density polyethylenes have been manufactured by a high pressure process, and high density polyethylene by a low pressure process using a different catalyst concept. Manufacturing technology is continuously changing. More recently, suppliers have been able to manufacture a low to medium density polyethylene by a low pressure process. This product has been called linear low density polyethylene, or LLDPE. Even more recently, changes in catalyst polymerization technology have allowed manufacturers to carefully control the molecular weight and molecular weight distribution. This has led to development of newer grades of polyethylene having very well controlled molecular weight distribution and very low density. Low pressure polymerization techniques today can lead to polyethylenes with many short branches and compounds (such as 1-butene or 1-hexene) are used to facilitate the control of the branching and therefore the crystallinity.

By now, it should be clear that polyethylene is a very complex material. Its apparent simplicity; i.e., a composition consisting solely of repeating $-CH_2-$ functional groups, belies the fact that the actual polymer is comprised of segments imparting significantly different properties. The alignment of some of the chains imparts crystallinity. The non-aligned fractions can coil and are called the amorphous regions. The polymer itself is therefore a "mixture" of different physical segments. That is why it is referred to as "semicrystalline."

The amorphous regions, having relatively large distances between the polymer chains relative to the crystalline regions, are sites where foreign ingredients can reside. Such foreign contaminants can be not only dirt but ions. The crystalline regions, having aligned chains and being closer together than the amorphous regions, are the regions that resist residing of foreign ingredients and penetration of gases. The crystalline regions provide the toughness and resistance to environmental influences. However, without the amorphous regions mixed in, it would not be possible to extrude the polymer into a functional insulation.

What causes different polyethylenes to have different ratios of crystalline to amorphous regions? Any component present on the polymer chain (backbone) that induces chain separation will decrease the degree of crystallinity. Hence, a copolymer of ethylene with propylene, for instance, will decrease the number of consecutive methylene links in the chain and increase the tendency for the chains to be more amorphous, This suggests that EPR would be less crystalline than PE. This is exactly the case. The extent to which this occurs will be dependent upon the ethylene to propylene ratio present. One may wonder therefore, how the "lack" of crystallinity is compensated for in a completely or almost completely amorphous polymer. The answer is that inorganic fillers are incorporated to provide the needed "toughness" in amorphous insulations.

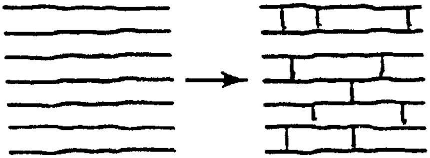
A second factor contributing to influencing the degree of crystallinity is, as noted earlier, the tendency for the chains to have branches. The conventional high pressure process of manufacturing polyethylene (from ethylene monomer) facilitates the formation of branches on the backbone. The branches can have different chain lengths themselves. This is depicted in Figure 5-4. It is the degree and nature of the branches in conventionally manufactured polyethylene that influences the degree of branching and therefore the tendency to align and, in turn, influences the density and crystallinity. It is for this reason that there are such a large variety of different densities available. Until the mid 1980s or thereabouts, high molecular weight, low density polyethylene was a material of choice for many users. This polymer has been replaced for new installations by crosslinked polyethylene and other materials such as EPR and tree resistant crosslinked polyethylene. Medium and high density polyethylenes have traditionally been used as components for cable jackets in medium voltage cables.

One of the properties of the crystalline regions that is of great significance to wire and cable applications is that they have a tendency to "separate" and "melt" as the temperature is raised. Such chain separation is referred to as melting. This melting process actually occurs over a wide temperature range due to the fact that different crystalline regions have different degrees of "perfection". Clearly, the ratio of crystalline to amorphous regions will change as a cable is thermally load cycled in service. The chain separation process leads to property changes such as: reduction in physical properties (tensile strength, elongation, modulus) and a reduction in dielectric strength. When a cable that has been subjected to thermal overload (heated to rather elevated temperatures that are defined in industry specifications) is later cooled down, the crystalline regions will reform. The physical and electrical properties will now improve. There are fine differences in the nature of the newly formed crystalline regions and the original structure, but the nature of these differences is beyond the scope of this book. The subject of thermal overload is relevant to crosslinked systems.

2.2 Crosslinked Polyethylene

Crosslinking means that the different polyethylene chains are linked together. This is shown in Figure 5-6. In a sense, XLPE can be considered to be a branched polyethylene where the branch is connected to a different PE chain instead of just "hanging loose." Crosslinking imparts certain quite desirable properties to the PE. From a cable perspective, it allows the polymer to maintain its form stability at elevated temperatures.

Figure 5-6
Simplified Description of Crosslinked Network



As we have seen from the previous discussion, conventional polyethylene is comprised of long chain polymers that, in turn, are comprised of ethylene groups. The individual molecules are very long. The backbone may contain 10,000 to 60,000 atoms, often more. Further, we have also seen that there are crystalline and amorphous regions and that any additives or impurities must be residing in the amorphous regions -- not the crystalline regions. Crosslinking adds yet another dimension to the complexity of the molecular arrangement.

Figure 5-7
What Crosslinking Does to Chain Length of Polyethylene

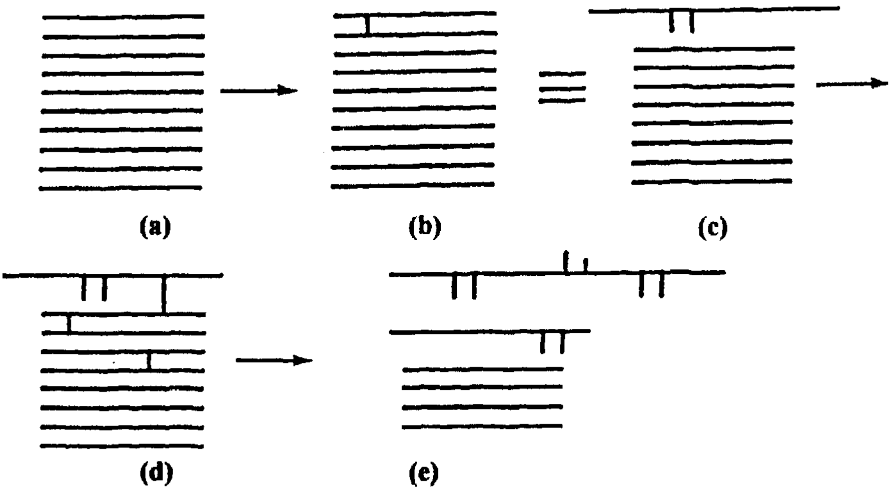


Figure 5-7 provides a description of how a conventional, non-crosslinked polyethylene "parent" is converted to the crosslinked "child". For simplicity, the chains (a) are all shown next to each other. The linear chains represent a simplified description to fit our purposes now. First, two adjacent chains link together (b). We immediately see that the molecular weight has increased. The first crosslink leads to two branches. In (c), we have simply redrawn the first two chains from (b) in a more familiar way. In (d), we have added three additional crosslinks, two to different chains. The third shows that the newer (previously crosslinked) higher molecular weight chain is again linked to another chain. In (e), we have redrawn (d) to show how the crosslinking process looks as the chains are again "stretched out." Note now that the original two chains have dramatically increased in molecular weight.

It should be clear from this description that the crosslinking process is a way of increasing the molecular weight. This is exactly what occurs. Note also that all the chains do not necessarily increase in molecular weight at the same rate. As the process continues (only the beginning of the process is depicted here), the molecular weight gets so great that the crosslinked polyethylene can be considered to have an "infinite" molecular weight.

One way of characterizing whether we have an extremely high molecular weight polymer or a crosslinked polymer is to check its solubility in an organic solvent such as toluene, xylene, or decalin. A conventional polyethylene, even one of very high molecular weight, will dissolve in a heated solvent of this type. Crosslinked polyethylene will not dissolve. The solubility results from the chains moving apart in the heated solvent. The chains also move apart in the crosslinked polymer, but not so far apart so that dissolution occurs. What happens instead is that the crosslinked polyethylene merely swells in the solvent and produces a gel. Indeed, this is called the gel fraction. Another way to determine whether the PE is crosslinked or not is to subject it to heat such as by placing the sample in contact with heated silicone oil or a hot surface. The conventional PE will flow while the XLPE will resist flowing and behave more "rubbery."

Commercial XLPE insulation also possess a "sol" fraction. This is the portion of the polymer chains that never get incorporated into the "infinite" network. In Figure 5-7, we see some chains in (e) not incorporated into the network. The gel fraction of a commercial XLPE is about 70 to 80%.

Another consideration is the number of crosslinks between individual PE chains. This is referred to as the molecular weight between crosslinks and has some theoretical significance. For commercial purposes, a 70 to 80% gel fraction is an adequate description. It is common to also refer to the "hot modulus." This is a somewhat easier measurement to make than is a sol fraction and does not involve the use of organic solvents. The hot modulus is directly related to the degree of crosslinking, or more correctly to the molecular weight between crosslinks. It is greater as the degree of crosslinking increases or as the molecular weight between crosslinks decreases.

The next issue to consider is, just how is crosslinking brought about?

Crosslinking of the PE chains can is induced by several different means:

- ☐ Use of organic peroxides
- ☐ Use of high energy radiation
- ☐ Modification of the backbone structure

2.2.1 Peroxide Induced Crosslinking. Polyethylene that is crosslinked by peroxides (the most common method for medium voltage cables) contains a small amount of a crosslinking agent that is dispersed throughout the polymer. This agent is an organic peroxide. Organic peroxides are chemicals that are stable at room temperatures, but decompose at elevated temperatures. There are many such peroxides available. One peroxide, called dicumyl peroxide, is used commercially for medium and high voltage cables. It is incorporated into PE pellets by the material suppliers. When the polyethylene is extruded (conversion of the pellets into cable insulation), it remains stable due to the fact that the decomposition temperature is higher than the extrusion temperature. After the extrusion process is complete and the PE is now surrounding the conductor and the conductor shield, the cable enters the long curing tube where the temperature is raised above the temperature employed in the extruder. At this high temperature and pressure, the peroxide now decomposes and induces the crosslinking process. Peroxide induced crosslinking uses a peroxide that is designed to intentionally decompose at a desired temperature after the conversion of the pellets into cable insulation. The tube is called a curing tube and the terms curing and crosslinking are often used synonymously. Note that this process takes place in the molten state of the insulation.

The peroxide acts by forming an active ingredient, called a free radical, that is unstable. The latter is so active that it interacts with any nearby molecule, which is virtually always the PE chain. This free radical forms when the peroxide "splits" into an active oxygen containing component that "pulls" hydrogen atoms off the polymer chains. The active "unstable" component is now the polymer chain and two such chains combine to stabilize the system once again. During this process, the peroxide decomposes and several by-products are ultimately formed. The major ones are dimethyl benzyl alcohol and acetophenone. Other ingredients may also be formed in smaller quantities such as alpha methyl styrene and methane as well as water vapor.

These by products form in the following manner. When the free radical (called cumyloxy radical) forms, it can undergo several different types of reaction in its quest to become stabilized. It can "grab" a hydrogen atom from the PE and form the relatively stable dimethyl benzyl alcohol molecule. However, the unstable radical may also undergo internal rearrangement and "kick out" a methyl radical and become acetophenone. The unstable methyl radical may also pick off a hydrogen atom from the polymer, hence forming methane gas. Water may be formed if the dicumyloxy radical kicks out a hydroxyl and hydrogen radical to form water. It is then converted to alpha methyl styrene in the process. The first three ingredients are always found in relatively large quantities in XLPE. The alpha methyl styrene is always present in smaller concentrations. It should be noted that, at times, cumene is also found as another by product. It is believed to develop from the further reaction of alpha methyl styrene.

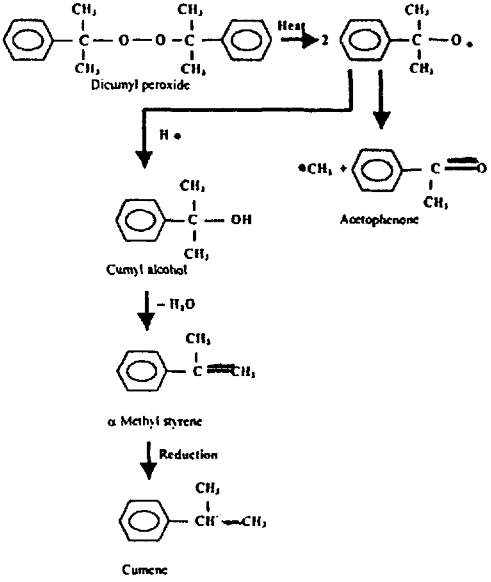
It should be apparent by now that the crosslinking process involves rather complex reactions. To achieve a good product, the peroxide must be uniformly dispersed within the PE. For appropriate uniformity of the crosslinking process to take place in the cable insulation, proper temperature and pressure must be maintained in a tube of long but finite length. The crosslinking process described here also applies to mineral filled EPR or TR-XLPE. The same by products are produced. It must not be forgotten that the carbon black containing shields are also being crosslinked concurrently.

Dicumyl peroxide has been commercially available in several forms:

- Free flowing powders that contain about 40% active materials, the inert ingredients being calcium carbonate or clay as a 94 to 97% active, light yellow, semicrystalline solid.
- Or a slightly more pure 98% active grade.

Acetophenone is a low melting solid (approximately 20 degrees C) with a somewhat sweet odor. It is not soluble in water and is partially soluble in polyolefins, the extent being dependent on the temperature. Its structure is shown below in Figure 5-8 along with that of dimethyl benzyl alcohol and alpha methyl styrene.

Figure 5-8.
Decomposition of Dicumyl Peroxide Leads to Formation of Volatile By-products.



Methane forms by reaction of methyl and hydrogen radicals. It is allowed to evolve from the XLPE insulated cable. Other by-prodcuts remain and may migrate out over time.

From what we have learned above, it is clear that this process must take place in the amorphous regions since the crystalline regions cannot hold the peroxide prior to the extrusion process. This is not a complication during the extrusion and crosslinking process since the crystalline regions melt in the heated tube. By the time the peroxide induced crosslinking takes place in the heated tube after extrusion, the entire polymer is amorphous. When the cable is cooled down after extrusion and crosslinking, recrystallization takes place. The newly formed by-products are now "forced" into the newly formed amorphous regions. It should be noted that the complex series of reactions described above do take place in polyethylene which, although melted, is still viscous.

Several points must be noted. When the PE (or EPR) is raised to an elevated temperature to manufacture the cable, it may be subjected to oxidative degradation. The polymer is subjected to temperatures significantly higher than it will experience in service. Oxidative degradation is potentially harmful as it introduces more polar materials that may influence changes in electrical properties and make the cable susceptible to failure mechanisms. To prevent this possible degradation from occurring, another material is incorporated into the polymer pellets called an antioxidant. Either an amine or phenolic-based compound is incorporated. It preferentially decomposes in the extruder and prevents/inhibits degradation of the polymer insulation. The antioxidant can be considered to be a sacrificial component that facilitates cable manufacturing. Also residing in the amorphous regions of the cable insulation will be antioxidant by-products. If not all of the peroxide and antioxidant are decomposed during the manufacturing process, small amounts of these ingredients may also be present -- again residing in the amorphous regions. It should be noted that the same events can occur with EPR insulated cables. While the entire polymer is amorphous, it is interspersed with clay and other additives.

Crosslinked polyethylene became the insulating material of choice for medium voltage cable in the late 1970s and early 1980s. It replaced conventional low density polyethylene due to its superior high temperature properties and better resistance to water treeing. Peroxide crosslinking has been the prime method of crosslinking for medium and high voltage cables as the process has been well developed and defined. For 69 kV transmission cables, peroxide crosslinked PE has also been the material of choice. At higher voltages, peroxide crosslinked PE has shared the market with conventional paper -- fluid filled cables. Other peroxides also have been used such as "vul-cup" which has a higher decomposition temperature. These higher temperature peroxides are of interest where it may be desired to extrude at higher than conventional temperatures. Such a material reduces the possibility of premature decomposition of the dicumyl peroxide that could cause processing problems. It should be noted that not all peroxides will decompose and induce crosslinking over the same temperature ranges.

For low voltage cables, peroxides may be used to induce crosslinking, but economic factors have allowed both silane and radiation crosslinking to share the market. In this voltage range, it is not uncommon to employ conventional polyethylene since the stresses experienced by these cables are generally lower.

Once crosslinking has been performed, the polyethylene (which was complex in nature to begin with), is now even more complex. Crosslinking typically takes place with about 70 to 80 % of the polymer chains. This means that 20 to 30 % of the insulation material is not crosslinked. Typically this represents the low molecular weight fractions of the initial material. The cable insulation of the cable that is installed consists of a mixture of LDPE and PE. The properties are clearly dominated by the XLPE fraction. At elevated temperatures, the XLPE cable insulation clearly maintains its form stability and functions as anticipated. For EPR, the low molecular weight sol fraction will be an ethylene copolymer.

As noted above, there are a number of by products evolved as a result of the decomposition of dicumyl peroxide. The acetophenone and dimethyl benzyl alcohol are liquids at ambient temperature. They will remain in the insulation wall. There is some evidence that they do indeed impart a measure of water tree resistance to the insulation. One by product, methane, is a gas. The methane must be allowed to migrate out of the insulation after crosslinking has been accomplished. This is easily induced by allowing the cable to "sit" for a defined time after manufacturer. Heating the finished cable shortens the time that is required.

2.2.2 High Energy Radiation. It is possible to crosslink polyethylene using high energy radiation. A beam of electrons emanating from special equipment can remove electrons from the polymer chain. this causes the reactive polymer chain to interact with another chain, hence inducing crosslinking. Radioactive isotopes can be used for the same purpose. High energy radiation causes some chemical changes that differ from those caused by peroxides. The main factor for use, or non-use, of radiation equipment is economics. This technology has been used in the low voltage area where high speeds can be attained.

2.2.3 Silane Induced Crosslinking. It is also possible to modify the polymer by introducing silane functionality. The silane interacts with moisture and leads to crosslinking of the different chains. Since moisture penetration is the key to inducing crosslinking, it is apparent that the process becomes more efficient as the wall thickness is reduced. Silane technology has had its major impact in application to secondary cables.

2.3 Tree Retardant Crosslinked Polyethylene

Over the years, many attempts have been made to improve the performance of conventional PE and, later, XLPE with regard to resistance to water treeing and in order to attain increased life. Additives had been incorporated into these insulations for this purpose. As noted earlier, one of the XLPE agent by products, acetophenone, has been reported to facilitate resistance to water treeing. Dodecyl alcohol was employed as an additive to HMWPE in the past. The most common TR-XLPE system was made available from Union Carbide in the early 1980s. The patent literature discloses that a mixture of additives is likely to be present. Historical information from field aging combined with laboratory data, some of which has been generated under EPRI sponsorship, suggests that TR-XLPE is justified as being considered in a separate category from conventional XLPE. It should be noted, however, that many approaches may be employed in seeking to achieve tree retardant insulation materials. In contrast to solely incorporating additives into PE, or PE that is to be later crosslinked, it is possible to graft additives onto the polymer backbone, or to use a combination of both techniques. It is to be expected that not all "tree retardant crosslinked polyethylenes" will respond the same upon service or laboratory aging. Physical and electrical property data are of interest, not only after cable manufacture, but also after aging. TR-XLPE must still possess peroxide crosslinking agent and antioxidant, as does conventional XLPE and EPR.

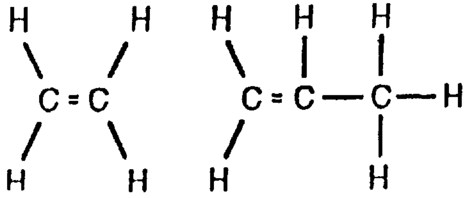
Table 5-1
Comparison of XLPE and TR-XLPE

Crosslinked Polyethylene	**Tree Retardant-XLPE**
XLPE	TR-XLPE
	Tree retardant additives
Residual amounts of dicumyl peroxide	Residual amounts of dicumyl peroxide
Crosslinking agent by-products	Crosslinking agent by-products same as XLPE
Acetophenone	Acetophenone
Cumyl alcohol	Cumyl alcohol
Alpha methyl styrene	Alpha methyl styrene
Antioxidant plus some antioxidant degradation by-products	Antioxidant plus some antioxidant degradation by-products

2.4 Ethylene Copolymer Insulations

When ethylene monomer is polymerized with propylene, a copolymer results that is called ethylene propylene copolymer, or EPR. The ratio of ethylene to propylene can vary over a wide range. This copolymer has significantly different properties than polyethylene. Perhaps the most significant is the fact that the propylene segments in the polymer chain interfere with the natural tendency of the polyethylene chains to align. The result is reduced crystallinity.

Figure 5-9
Copolymer of Ethylene and Propylene (about 50:50)



Single molecule structure

- Short chain branches
- Non crystalline-amorphous structure
- Needs reinforcing fillers (about 50%)
- Needs to be crosslinked

Sometimes, it is preferable to add a third monomer to the ethylene propylene system prior to polymerization. This is called a diene monomer, and is used to facilitate certain crosslinking processes. These materials are called EPDM. In the cable industry, it is common to call all ethylene co- or ter-polymers of this type as EPRs.

EPR materials are known as elastomers. All conventional elastomers have significantly different properties from semicrystalline polymers. Reduced crystallinity means that the property of "toughness" and high tensile strength are missing. It means than an insulation that is analogous to high molecular weight polyethylene cannot be produced with an uncrosslinked ethylene copolymer. To achieve improved physical properties, it is necessary to incorporate inorganic mineral fillers into the EPR compound. The EPR resin must also be crosslinked to render it useful as an insulation material. If it were not crosslinked, EPR would still be too soft and tacky to serve as an insulation. An EPR insulation material is generally referred to as a compound as there are several other additives that are present in EPR insulations. Once these additives are incorporated, the resin used as an insulation is referred to as a compound. The method of mixing the ingredients together is referred to as a compounding process. Tables 5-2 shows a typical EPR formulations supplied commercially. It should be noted that many EPR compounds that are used as insulations for cables are proprietary and the formulations are not published.

Table 5-2
Nordel Based EP Insulation Compounds in Parts per Hundred

Ingredient	Amorphous	Semicrystalline
Nordell 1040 (amorphous)	100.0	
Nordell 2722 (semicrystalline)		100.0
Low density PE		5.0
Zinc oxide	5.0	5.0
Red lead (90% dispersion)	5.0	5.0
Silane treated Kaolin	120.0	60.0
Vinyl silane A-172	1.0	1.0
Process oil	15.0	
Paraffin wax	5.0	5.0
Antioxidant	1.5	1.5
Dicumyl peroxide	3.5	2.6

The purpose of the various ingredients (published EPR formulations) are noted below:

☐ Ethylene Propylene Co- or Ter-polymer. This is the base material that forms a continuous phase in which all the ingredients noted below are uniformly dispersed. This controls the flexibility of the final formulation.

☐ Inorganic Mineral Filler. This is a coated clay that serves to improve the mechanical properties of the formulation. Since the rubber material has little or no crystallinity, the filler serves the purpose of providing mechanical strength. The clay is coated with a silane material to improve polymer-filler interaction at the interface. The filler particles are extremely large compared to the polymer chain.

☐ Zinc Oxide. A traditional component in EPR and EPDM compounds that was initially incorporated into cable insulation as it was used in automobile tire formulations.

☐ Ion Scavenger. This is known as "red lead" or lead oxide. It improves electrical properties under wet aging. Incorporated many years ago to meet low voltage cable test requirements.

☐ Crosslinking Agent. Generally dicumyl peroxide. It serves the same role as it does in XLPE.

☐ Processing Aids. Generally a wax or oil that is incorporated to improve the processing of the formulation during extrusion since the inorganic additives are "abrasive".

☐ Antioxidant. Serves the same roll as it does in PE or XLPE to prevent polymer decomposition during extrusion.

Additional silane may be added to assure adequate polymer/filler interaction. In additional to all these, individual manufacturers may have proprietary ingredients in the EPR formulations. These can serve various purposes such as to further enhance processing, enhance aging properties, or modify dielectric properties.

It is also possible to incorporate a third monomer into the ethylene/propylene mixture when polymerization takes place. This is sometimes referred to as "diene monomer," and the term EPDM is used to describe the resins. In the wire and cable industry, both of these types of elastomers are referred to as "EPRs." It should be noted that the difference is indeed commonly noted when accessories are studied. The diene ter-polymer is used in formulations where the unsaturation in the polymer chain is desired, such as for specialized methodology where the unsaturation of the third monomer is preferred or required.

All EPR compounds must be crosslinked to be useful as insulation, as noted above. The process for inducing crosslinking is exactly the same as for medium voltage XLPE cables. Peroxide induced crosslinking is also used for low voltage EPR insulated cables. It is not common to use silane processing for EPR although radiation crosslinking is not uncommon.

Processing of medium voltage EPR insulated cables is performed on the same equipment used for XLPE or TR-XLPE. Steam or dry curing may be employed, although steam curing is more common for EPR.

3. PAPER INSULATED CABLES

The oldest type of insulation still used for power cables is paper. Paper must be impregnated with a dielectric fluid -- initially oil obtained from cracking of petroleum, and now synthetic fluid. This section reviews the fundamentals of paper as an insulation.

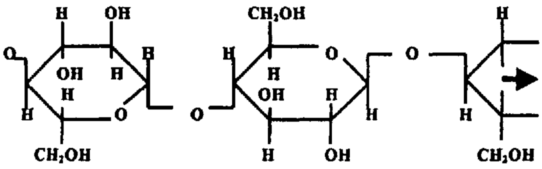
Paper is derived from wood for cable insulation. It consists of three major ingredients:

About 40%	Cellulose
About 30%	Hemicellulose
About 30%	Lignin

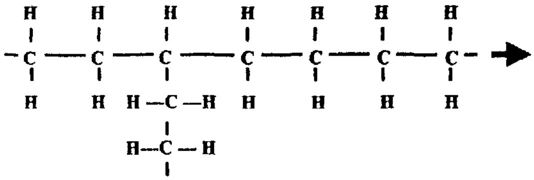
The cellulose is of interest as an insulating material and must be separated from the other ingredients by bleaching with sulfates or sulfites. The hemicellulose is a non-fibrous material, is more polar than cellulose and hence more lossy. A very low level of hemicellulose is preferred in the final material, but some quantity remains after the bleaching process. (It can be noted that cotton is pure cellulose. If cotton were used as a source for paper, no hemicellulose would be present.) The lignin is an amorphous material and serves as a binder for these components. It is removed in the manufacture of the tape. Details of the process of converting wood into a useful insulation material are beyond the scope of this book, but it should be noted that the process is well developed and has been used for scores of years.

The chemical structure of paper in shown in Figure 5-10. For comparison, polyethylene is also shown. The differences are apparent. Note that cellulose has a saturated cyclic structure (five carbons and one oxygen in a ring) and this is absent in polyethylene. In contrast to polyethylene, it is more common to refer to the molecular weight of cellulose in terms of degree of polymerization, or "DP." The DP represents the number of individual cellulose molecules in a chain. The DP of a typical cellulose molecule in wood is about 10,000. The cellulose consists of fibrils, and as noted above, it is converted into paper by the conventional processes used in the paper industry. When used as an insulation for cable, the paper is impregnated with dielectric fluids--low molecular weight hydrocarbons. As with polyethylene, these oils or fluids consist solely of carbon and hydrogen.

Figure 5-10
Chemical Structure of Cellulose



Chemical Structure of Polyethylene



4. SHIELDS

Polymers used for shields are ethylene copolymers. They may be copolymers with propylene or with other monomers such as vinyl acetate or ethyl acrylate. Each of these other co-monomers imparts different properties to the polymeric shields. As with insulation, one must consider molecular weight and molecular weight distribution issues, but crystallinity is not an issue. In addition, it is necessary to incorporate an adequate amount of a conducting carbon black into the copolymer to achieve the required semiconducting properties. One must assure appropriate particle to particle contact. It is possible to incorporate yet additional additives. For example, controlled strippability of insulation shields may be achieved with additional additives, but such additives would not be used for conductor shields where strippability is not desired.

5. JACKETS

Jackets are used over the cable to impart abrasion resistance and to protect the cable from local environment. Ideally, a jacket will aid in keeping water and foreign ions out of the insulation. Jacketing materials have varying properties that is controlled by their molecular structure and compound ingredients.

For medium voltage cables, several polyethylene types are used as jacketing materials:

Low density	(LDPE)
Medium density	(MDPE)
High density	(HDPE)
Linear low density polyethylene	(LLDPE)

It is clear by now that the differences between the first three are in the amount of "chain alignment" that takes place and that HDPE is more crystalline than is LDPE. As the name implies, MDPE is in-between the others in crystallinity.

HDPE is manufactured by a different process than are the low and medium polyethylenes. The higher the degree of crystallinity, the greater the toughness and abrasion resistance, but the more complex is the extrusion process. LLDPE is manufactured in such a manner that it approaches HDPE in properties, but by a less expensive method of manufacture.

The moisture resistance of the different PE types will vary with the degree of crystallinity. See Table 5-3.

Table 5-3
Moisture Vapor Transmission Rates

Material	**Density**	**Moisture Vapor Transmission Rate**
LDPE	0.92	1.16
MDPE	0.93	0.51
HDPE	0.94	0.58
HDPE	0.95	0.32
LLDPE	0.92	0.74
PVC	1.30	10.0
Semicons	1.15	5.00

PVC (polyvinyl chloride) is a material that was used as a jacket. Although PVC by itself is a very ridged material, it becomes quite flexible when plasticizers are added. A typical plasticizer could be dioctyl phthalate. Plasticized PVC, while providing some degree of protection against dig-ins and corrosion protection, has very poor abrasion resistance and very poor resistance to water migration. PVC is now rarely used as a cable jacket for underground distribution cables even though it is quite inexpensive relative to other materials. For low voltage cables, it is common to use other materials such as Neoprene (poly chloroprene) or Hypalon (chlorosulphanated poly-ethylene).

6. COMPARISON OF INSULATING MATERIALS

Since paper insulation was used first in the power industry, and was later replaced in low and medium voltage applications, any comparison of properties usually employs the paper-fluid system as the standard.

Table 5-4
Major Differences Between Paper and Polyolefinic Insulations

Paper / Cellulose	**Polyethylene**
Natural	Synthetic
Carbon / hydrogen/oxygen	Carbon / hydrogen/oxygen
More polar / medium losses	Less polar, low losses
Chains linear	Chains branched
Fibrils	Non-fibrils
Partially crystalline/ Relatively constant	Partially crystalline/ Varies with grade employed
No thermal expansion on heating	Significant thermal expansion
Not crosslinked	Not crosslinked
Thermal degradation via cleavage at weak link	Degrades at weak links

Crosslinked Polyethylene	**Ethylene Propylene Rubber**
Synthetic	Synthetic
Carbon / hydrogen	Carbon / hydrogen
Less polar, low losses	Losses due to additives
Chains branched, crosslinked	Chains branched, crosslinked
Non-fibril	Non-fibril
Slightly less crystalline vs PE	Least crystalline of all
Same thermal expansion as PE	Slight thermal expansion
Crosslinked	Crosslinked
Degrades at weak links	Same as XLPE

Table 5-4 provides a comparison of the properties of paper, polyethylene, crosslinked polyethylene, and ethylene propylene rubber insulations. Only the paper is a natural polymer and is therefore processed differently. Paper is obtained from a wood or cotton source. The synthetic polymers are produced by polymerization of monomers derived from petroleum. All consist of carbon and hydrogen, but paper also contains oxygen. The latter is present as functional hydroxyl or ether groups. The contribute a measure of polarity that is absent in the synthetic polymers. (Polarity means increased dielectric losses.) Of special note is the concept of thermal expansion during heating. While all of the synthetic polymers undergo thermal expansion during heating, this does not occur with cellulose—although the oil will do so. How these insulations respond on aging is a well studied subject since it is directly related to reliability of the cable after installation and energization. When cellulose degrades, it does so at a "weak link," the region of the oxygen linkage between the rings. When this happens, the DP is reduced. On the other hand, polyolefins degrade by a completely different mechanism—oxidative degradation at specific sites. Protection against degradation is imparted to polyolefins by adding an antioxidant to the pellets prior to extrusion. Note that adding antioxidants to oil to prevent it from degrading is rather common.

One further point should be noted on the chart: the different response of the insulation types to dc testing. DC testing of cables has traditionally been performed to ascertain the state of the cable at specific times during their use, such as before peak load season. This is a technique that was adopted for PILC cables many years ago. This was later carried over to extruded dielectric cables. Research and development in the past few years has shown that PE and XLPE may be harmed by the use of a dc test, but this does not occur with paper-oil systems. EPR cables have not been studied to the same extent and no conclusions can be drawn at this time about the effect of dc testing on the insulation.

Advantages of polyethylene:

- Low permittivity (low dielectric constant)
- Low tan delta (low dielectric loss)
- High initial dielectric strength

Advantages of crosslinked polyethylene (in addition to the ones above):

- Improved mechanical properties at elevated temperature
- No melting above 105 °C but thermal expansion occurs
- Reduced susceptibility to water treeing

Advantages of EPR:

- Reduced thermal expansion relative to XLPE
- Reduced sensitivity to water treeing
- Increased flexibility

Advantages of PILC:

- Lack of sensitivity to dc testing
- Known history of reliability

Particular advantages of synthetic polymer insulations over PILC:

- Reduced weight
- Accessories more easily applied
- Easier to repair faults
- No hydraulic pressure / pumping requirements
- Reduced risk of flame propagation
- Reduced initial cost

Some of these advantages are electrical and some are not.

Care must be taken in seeking to compare EPR to XLPE to TR-XLPE. There are many different EPR formulations. The nature of the non-polymeric additives, including fillers, plays a major role in influencing properties as well as the nature of the mixing process. What is clear is that any EPR formulation will have higher losses than a non-mineral filled PE or XLPE system. Some EPR systems may have very high losses. This may influence resistance to water treeing. However, EPR systems are generally "softer" due to their lack of crystallinity and therefore easier to handle in the field—especially at very low temperatures.

Disadvantages to PILC include the fact that lead is usually used as an outer sheath and the motivation not to use lead for new installations is very high. Paper is also highly susceptible to deterioration from moisture.

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CHAPTER 6

ELECTRICAL PROPERTIES OF INSULATING MATERIALS

Bruce S. Bernstein

1. INTRODUCTION

Electrical properties of interest for insulation materials can be classified into two major categories:

- Those of significance at low voltage operating stresses
- Those of importance at high voltage operating stresses

At low stresses, the properties of interest relate to dielectric constant, power factor, and conductivity (resistivity). Dielectric constant represents the ability of the insulation to "hold charge." Power factor represents a measure of the amount of energy lost as heat rather than transmitted as electrical energy. A good dielectric (insulation) material is one that holds little charge (low dielectric constant) and has very low losses (low power factor). Polyolefins represent examples of polymers that possess excellent combinations of these properties. This is discussed in depth in Chapter 5.

At high stresses -- greater than operating stress -- the characteristic of importance is dielectric strength. Here, the insulation must be resistant to partial discharges (decomposition of air in voids or microvoids within the insulation). Also of interest is the inherent ability of the polymeric insulation material to resist decomposition under voltage stress. Unfortunately, the measured dielectric strength is not a constant, but has a variable value depending upon how the measurement is performed. This will be discussed later in this chapter. In any event, the dielectric strength must be "high" for the insulation to be functional. This chapter will review factors that influence electrical properties at low and high voltage stresses.

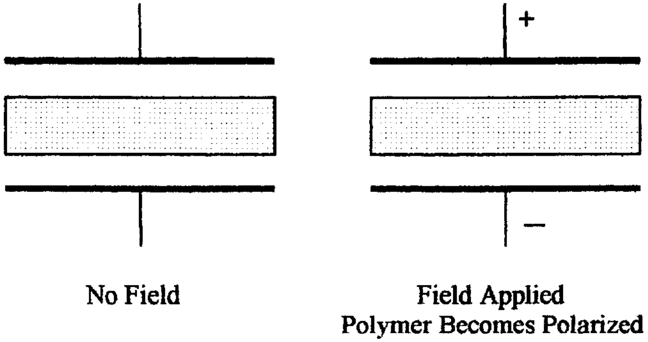
2. STRUCTURE-PROPERTY RELATIONSHIPS

The electrical properties of an insulation materials are controlled by their chemical structure. Chapter 5 reviewed the inherent chemical structure of polyolefins, and described how the structure influences physico-chemical properties. In this chapter, we shall review how these factors influence the electrical properties. The emphasis shall be on polyolefins.

Low stress electrical properties are determined by the polar nature of the polymer chains and their degree of polarity. Polyethylene, composed of carbon and hydrogen or methylene chains, is non-polar in nature, and has low conductivity. If a polar component, such as a carbonyl, is on the chain, the polymer chain now becomes more polar and the characteristics that lead to low conductivity are diminished. Ethylene copolymers with propylene retain their non-polar nature since the propylene moiety is as non-polar as is the ethylene moiety.

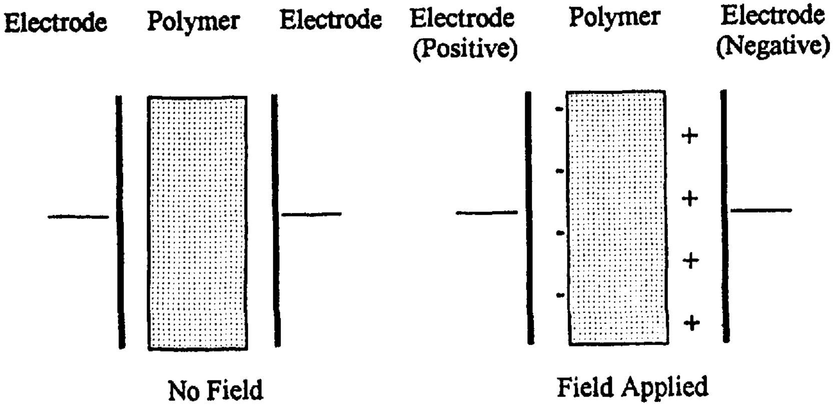
When a polyolefin is subjected to an electrical field, the polymer chains have a tendency to become polarized. Figure 6-1 shows what happens when a polymer is "stressed" between electrodes, with different polarities resulting. Figure 6-2 shows how the polymer insulation material responds. There is a tendency for the positive charges on the polymer to move toward the negative electrode, and for the negative charges on the polymer to move toward the positive electrode, hence pulling the polymer in two directions. This is a general description, and does not take into account the chemical structure, which is discussed later.

Figure 6-1
Polarization of a Polymer Subjected to an Electric Field



Schematic description of a polymer subjected to electric field; polymer becomes polarized.

Figure 6-2
Charge Migration on Polymer Chains Subjected to Electric Field

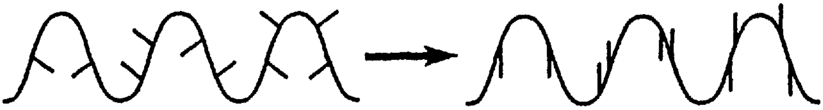


Insulation response to electric field application. Positive charges on polymer chain migrate toward the cathode and negative charges migrate toward the anode.

Where do these charges come from? After all, we have described the polyolefins as being comprised of carbon and hydrogen, and as not being polar compared to say the polyamides or ethylene copolymers possessing carbonyl or carboxylate groups. It can be noted that such description is "ideal" in nature. While being technically correct for a pure polyolefin, in the real world there are always small amounts of such polar materials present. This will be discussed later.

Figure 6-3 shows what may happen to a polymer insulation material that has polar groups on the side branches, rather than on the main polymer chain. Note that in this idealized description of the "folded" chain, the main chain does not undergo any movement under voltage stress. The side chains, which were once "random," are now aligned toward the electrodes. Figure 6-4 shows a "more realistic" coiled polymer chain with polar branches. Note how the alignment toward the positive and negative electrodes has taken place.

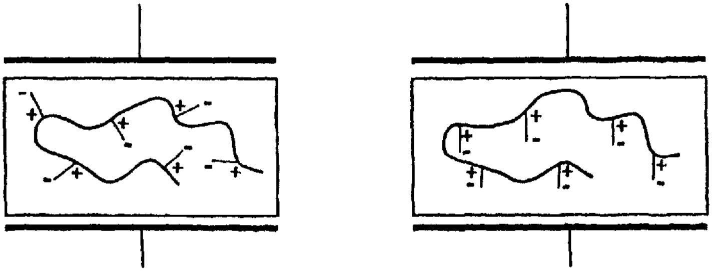
Figure 6-3
Schematic Description of Orientation of Polar Functionality on Polymer Side Chains Subjected to Electric Field



No Voltage Voltage Stress Applied

Under voltage stress, a polar chain orients toward the cathode or anode, depending upon the charge it possess. The non-polar chain does not migrate.

Figure 6-4
Polarization of Side Chains Depicted on a Coiled Polymer



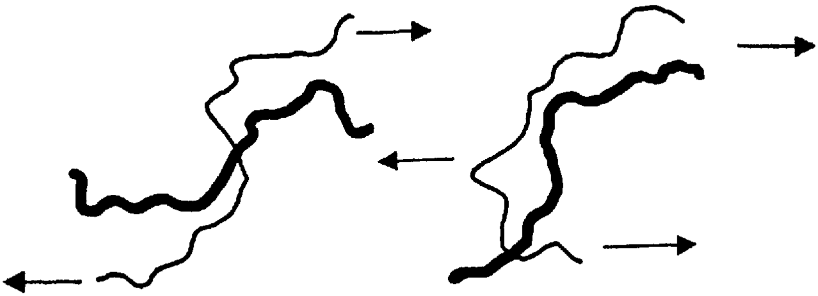
No Voltage Field

Field Applied
Polymer Becomes Polarized

A polymer is typically coiled, as shown here. The positive charges on a polymer are attracted to the cathode. The negative charges are attracted toward the anode. The movement of these charged regions causes motion of the entire side chain.

In Figure 6-5, we show what happens to the main chain. Prior to this, we had considered what happened to the relatively short branches. However, the entire main chain may undergo motion also, assuming it possesses functional groups that respond to the voltage stress. The figure shows that entire chain segments may move and rotate, in accordance with the field.

Figure 6-5
Main Chain Motion of Polymer Subjected to Electric Field



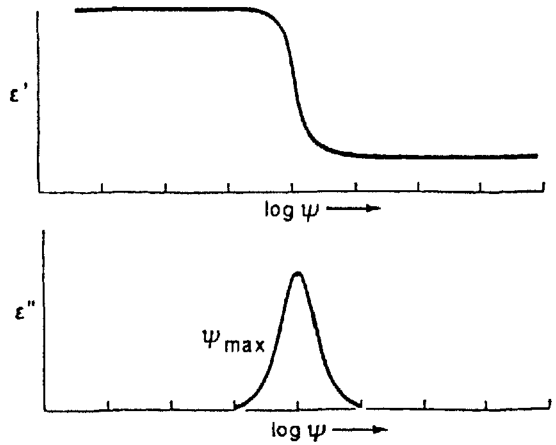
When the main chain length possesses charged regions, the entire main chain may exhibit motion under the electric field. Here, the center portion of the thin chain migrates to the left. The lower portion of the chain, depicted here as being thick, migrates toward the right. The depiction indicates that one chain is positively charged and the other is negatively charged.

It should be emphasized that this description is what would happen under dc. Consider now what would happen under ac; here the alignments will have to be shifting back and forth in accordance with the polarity change. Furthermore, this will take place at a rate controlled by the frequency. In considering these points, it becomes evident that the response of a polyolefin polymer, even a slightly polar one, is quite different under ac than dc. The next question to consider is what happens if the movement of the chains cannot "keep up" with the change in frequency? Of course, our interest is in the 50 to 60 hertz range, but to understand the polymer response, it is desirable to review what happens over a very broad frequency range. This is reviewed in the Section 3.0. Before entering that subject, it is necessary to recall that the polymer chains that we have been considering consist of many, many methylene groups linked together and these are non-polar in nature. However, after formation (polymerization), these very long chains are always subjected to small chemical changes. These small chemical changes, known as oxidation, may occur during conversion of the monomer to the polymer. This may also occur during conversion of the polymer to a fabricated part (in our case, the cable insulation). When extrusion is performed, the polymer is heated to very high temperatures in an extruder barrel, and is subjected to mixing and grinding due to screw motions. As noted earlier, an effort is made to prevent this elevated-temperature-induced degradation (but more realistically, the effect is kept to a minimum) by incorporating an antioxidant into the polymer. The antioxidant preferentially degrades and protects the polymer insulation. However a small degree of oxidative degradation cannot be prevented, and always occurs. Therefore there will always be some oxidized functional groups on the polymer chains. These are important points to keep in mind when reviewing the polymer insulation response to frequency.

3.0 DIELECTRIC CONSTANT AND POWER FACTOR

Different regions of the polymer chains will be sensitive and respond differently to voltage stress. This phenomena is intimately related to the frequency. Different functional groups will be sensitive to different frequencies. When the "proper" frequency-functional group combination occurs, the chain portion will respond by moving, e.g., rotating. Since this phenomenon is frequency dependent, one might expect that different responses will result from different functional group-frequency combinations. This is exactly what occurs. Referring to the top curve in Figure 6-6, we can see that at low frequencies, when stress is applied, the polar region-dipoles-can respond and "accept" the charge, and align as described above. The dielectric constant is relatively high under these conditions. As the frequency increases, no change occurs in this effect will occur as long as the dipoles can respond. At some point as the frequency continues to increase, the chains will have difficulty responding as fast as the field is changing. When the frequency change is occurring at so rapid a rate that no rotation can occur, the charge cannot be held and the dielectric constant will be lowered.

Figure 6-6
Dielectric Constant and Power Factor as a Function of Frequency



Upper portion of Figure 6-6 depicts the change in dielectric constant with frequency. The lower portion of the figure depicts the change in power factor with frequency.

For a polymer like polyethylene, with very small amounts of polar functionality, the dielectric constant is always low (compared to a more polar polymer such as a polyamide [Nylon for example]). However, oxidized regions will respond more readily due to their more polar nature. The reason for the change in dielectric constant with frequency is clear. It should also be noted that other parameters affect this property; e.g., temperature. In essence, any change that affects motion of the polymer chain will affect the dielectric constant.

The point where the polymer chain segments undergo change in rate of rotation is of special interest. The lower curve of Figure 6-6, focusing on losses (e.g., power factor), shows a peak at this point. In considering power factor, the same explanation applies; changes are affected by frequency and specific polymer nature. At low frequencies, the dipoles on the polymer chains follow variations in the ac field, and the current and voltage are out of phase; hence the losses are low. At very high frequencies as noted above, the dipoles cannot move rapidly enough to respond, and hence the losses are low here also. But where the change is taking place, the losses are greatest. This can be visualized by thinking in terms of motion causing the energy to be mechanical rather than electrical in nature. It is common to refer to the dielectric constant and power factor at 50 or 60 Hertz, and at 1,000 hertz.

In relating the information shown in Figure 6-6 to the earlier figures, it is to be noted that the polar functionality can be due to motion of main chains or branches. Where the oxidized groups are the same, as in carbonyl, one could expect that the chains (ideally) to respond the same way at the same frequency. But what happens if there are different functional groups present such as a carbonyl, carboxyl, or even amide or imide functionality? Also, how does the main chain nature affect all this? The answer is that these factors are quite significant. Different functional groups will respond differently at the same frequency, and the main chain can hinder motion due to its visco-elastic nature. If the dipole is rigidly attached on the polymer backbone, then main chain motion is going to be involved. If the dipole is on a branch, it can be considered to be flexibly attached, and the rate of motion of the branch will be expected to differ from the main chain, even if the functional group is the same. The end result of all of this is a phenomenon called dispersion. Here the chains move at different rates at any single frequency and temperature. They may exhibit a change over a broad region rather than a sharp, localized region as the frequency and temperature is changed slightly.

For purposes of understanding power cable insulation response, the main interest is, of course, at 50 or 60 hertz. Also, our interest is in what is intended to be relatively non-polar systems. It is necessary to remember that no system is perfect and there will be variations in degrees of polarity not only from one insulation material to another, and not only from one grade of the same material to another, but perhaps also form one batch of supposedly identical material to another. Much depends upon the processing control parameters during extrusion.

The literature reports dielectric losses of many different types of polyolefins as a function of temperature, at controlled frequencies. Hence, it is known that conventional low density polyethylene undergoes losses at various different temperatures. In addition, antioxidants, and antioxidant degradation by products, low molecular weight molecules, will also respond, and this complicates interpretation. With conventional crosslinked polyethylene, the situation is even more complex as there are peroxide residues and crosslinking agent by-products. These low molecular weight organic molecules, acetophenone, dimethyl benzyl alcohol, alpha methyl styrene, and smaller quantities of other compounds, will gradually migrate out of the insulation over time. Hence interpretation of data requires not only knowledge of the system, but some degree of caution is prudent. In addition to all of this, if there are foreign contaminants present, it is possible that they also can influence the measured dielectric constant and power factor.

The dielectric constant of polyethylene is dependent upon the temperature and frequency of testing. At constant temperature, it is reduced slightly as the frequency increases; at constant frequency, it increases with temperature.

4. DIELECTRIC STRENGTH

The dielectric strength of an insulation material can be defined as the limiting voltage stress beyond which the dielectric can no longer maintain its integrity. The applied stress causes the insulation to fail; a discharge occurs which causes the insulation to rupture. Once that happens, it can no longer serve its intended role. Unfortunately, the dielectric strength is not an absolute number; the value obtained when dielectric strength is measured depends on many factors, not the least of which is how the test is performed. Therefore, it is necessary to review the issues involved, so that the value and the limitations of the term "dielectric strength" are well understood.

The dielectric strength is usually expressed in stress per unit thickness--volts per mil, or kV per mm. For full size cable, it is common to merely report the kV at which the cable has failed. Hence if a 175 mil wall cable fails at 52.5 kV (or 52,500 volts), the dielectric strength can also be expressed as 300 V/mil.

The most obvious value of dielectric strength is called the intrinsic strength. This is defined by the characteristics of the material itself in its pure and defect-free state, measured under test conditions that produce breakdown at the highest possible voltage stress. In practice, this is never achieved experimentally. One reason, as noted above, is the difficulty in attaining a defect-free pure insulation specimen. The closest one can come is on measurement of very thin, carefully prepared films with appropriate electrodes. (The thinner the film, the less the chance for a defect to exist.) Under these ideal conditions, the insulation itself would fail due to its inherent properties (bond strength rupture).

It is more likely is that failure will occur under discharge conditions; here, gas (e.g., air) present in small voids in the insulation, present due to processing characteristics, will undergo decomposition. Air is the most likely gas present for polyethylene and crosslinked polyethylene (in contrast to vapors of crosslinking by products). Its intrinsic dielectric strength is significantly less than that of polyethylene. Under these conditions, the discharges that take place in these small void(s) leads to "erosion" of the insulation surface in contact with the air. This in turn leads to gradual decomposition of the insulation and eventual failure. The decomposition of the air in the voids occurs at voltage stresses much lower than the inherent strength of the polyethylene itself. For example, the dielectric strength of a one mil thick film of polyethylene measured under identical conditions to a layer of air (atmospheric pressure), gives a dielectric strength value 200 times greater. Polyethylene give value of about 16,500 volts per mil, while that of air is about 79. The dielectric strength of air increases with pressure (that of polyethylene does not change), and this concept has commercial impact; however the degree of improvement is small. By increasing the pressure by a factor of 6, the dielectric strength increases by a factor of about 5 -- still well below that of the polymer film.

When focusing on extruded cable insulation, we are now concerned with relatively thick sections; 175 to 425 mil walls for distribution cables, and even thicker walls for transmission cables. Discharges that occur in these practical systems may not lead to immediate failure. It is possible that the discharge will cause rupture of a portion of the wall, and then cease. This could be related to the energy of the discharge, the size of the adjacent void, and, of course, the nature of the insulation material. When this occurs, we will develop a blackened needle-shaped series of defects, sometimes resembling a tree limb; these are called electrical trees. Discharges may occur repetitively, and hence the tree will appear to grow. In time the "tree" will bridge the entire insulation wall and cause failure. Discharges may also occur on the surface of the insulation, particularly if there is poor adhesion between the insulation and shield layers.

Another mechanism of failure is known as thermal breakdown. This occurs when the insulation temperature starts to increase as a result of aging phenomena under operating stress. Under voltage stress, some insulation systems will start to generate heat, due to losses. If the rate of heating exceeds the rate of cooling (that normally occurs by thermal transfer) then thermal runaway occurs, and the insulation fails by essentially, thermally induced degradation. Several points should be kept in mind here:

(1) The heat transfer capability of polyolefins is low, and heat dissipation is not normally rapid

(2) These events may occur in the presence or absence of discharges

(3) The presence of inorganic fillers contributes to increasing the dielectric losses, and may exacerbate the situation. Also, some organic additives in the insulation may also lead to increasing the dielectric losses/ Finally, it should be noted that thermal breakdown of poylolephins is a very well-studied area.

Although not a direct cause of failure, mention should be made of water treeing; water trees lead to a reduction in dielectric strength, but are not a direct cause of failure. These trees have a different shape for electrical trees, and also have different cause. The differences are outlined below.

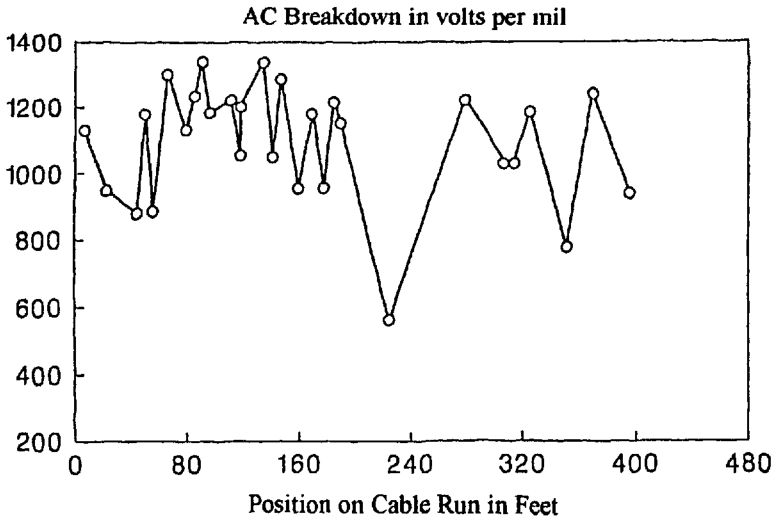
WATER TREES	**ELECTRICAL TREES**
Water required	Water not required
Fan or bush shaped	Needle or spindle shaped
Grow for years	Failure shortly after formation
Microvoids connected by tracks	Carbonized regions

Water trees grow under low (normal) operating stress, do not require the presence of "small voids," and lead to a reduction in dielectric strength. Laboratory studies have shown that such trees can penetrate virtually the entire insulation wall yet not lead immediately to failure. As the chart shows, the "channels" or "tracks" that comprise water and electrical trees differ.

AC breakdown strength is commonly performed on full size cables as an aid in characterization. For full size cables, it is common to perform many such tests of long lengths of cables (e.g., 25 to 30 feet) and plot the data on Weibull or Log normal curves. This is done as the data always has some variation. A good example is data developed on a project for the Electric Power Research Institute (EPRI).

Figure 6-7

AC Breakdown Strength of 15 kV XLPE Insulated Cable as a Function of Position on Reel that Contained 5,000 Feet of Cable and Total Extrusion Run was 50,000 Feet



In Figure 6-7, it is seen that the dielectric strength of full size cables varies from a low of about 600 V/mil to a maximum of about 1,300 V/mil. This demonstrates that although the cable was manufactured in presumably the same manner (this cable was tested from the same extrusion run, and the same reel), some variation is inevitable. This is apparent from the ac breakdown strength measurement, and is the reason that statistical evaluation of the data obtained is a necessity. From what has been noted above, it is likely that these variations are due to inevitable imperfections that result during processing. Figure 6-7 demonstrates the variation in measured ac breakdown strength of crosslinked polyethylene insulated cable. Sample lengths tested were from the same production run and from the same reel. Variations such as these are common and are the reason for employing statistical analysis of data, such as Weibull distribution.

The data shown from the EPRI project was obtained at a five minute step rise time. If the time interval between the steps is increased (e.g., from 5 to 10 minutes), the apparent ac breakdown strength decreases. If the time interval between steps is increased again, to say 30 minutes, the apparent dielectric strength is reduced even more. In other words, the apparent dielectric strength that one obtains in performing a test increases as the stress is applied more rapidly. [This is analogous to what happens during a tensile strength test for polyethylene; the apparent tensile strength increases as the stress is applied more rapidly]. Therefore, the meaning of an "ac breakdown strength" value is relevant only if the manner in which the test was performed is known. In comparing ac dielectric strength values for different insulation materials, the test should always be performed in the same manner. This holds true whether one is comparing different grades of the same material (different grades of polyethylene) or different insulation materials (polyethylene versus polypropylene), for example.

The testing of thin films or slabs of insulation materials is performed in the laboratory and the opportunity to control the local environment during testing is present. This should be done and should be reported. Since relatively small specimens are involved (compared to full size cables), a large number are usually tested to overcome the inherent variability in results, as noted above. When working with small samples, the opportunity to control the local environment during testing is greater, and reproducibility may be enhanced. Hence the following variables are to be controlled so that the information obtained represents a true representation of the statistical distribution in homogenieties for the material under study.

- specimen thickness
- temperature
- electrode shape and size

The reasons for controlling the thickness have been noted. This is especially of increasing importance as the thickness is reduced. Temperature control is vital, as the dielectric strength is related to the temperature of the specimen at the time breakdown occurs. Clearly, when working with small samples, the opportunity to generate experimental data at controlled uniform temperatures [such as by testing in a controlled environment room, or in an oven] is present.

The electrode shape and size represents a significant parameter for small sample testing. The most common electrodes are Rogowski types, where the electrode is curved and inserted into the polymer slab; this provides a uniform stress gradient and enhances the opportunity for obtaining meaningful information. If the electrode-polymer interface is sharp (instead of rounded) the voltage stress will be enhanced at this location. The failure of the test specimen will be induced at this location. Should that happen, the dielectric strength measured will be related more to the manner in which the test was performed (inducing a high localized stress) rather than related to the properties of the insulation itself.

Needle tests are also performed, where a sharp, but controlled radius of curvature exists at the needle tip, and the latter is inserted into the specimen part way to the ground plane. Voltage stress is applied and the dielectric strength is measured; this approach has been used to determine the influence of additives, designed to increase the breakdown strength, and aid in developing superior insulation materials. A detailed description of typical arrangements of electrodes that may be used for dielectric strength testing of thin films is provided by Mathes in the references.

The frequency of measurement may be readily varied in thin film studies, much more easily than for full size cables. While most testing is performed at 60 hertz, testing has also been performed at frequencies ranging to 1,000 hertz. Again, the rate of rise of the field is vitally important, and can readily be controlled.

The reasons for controlling the thickness have been noted above. This is especially critical when working with thin samples. Temperature control is also vital, as the dielectric strength is related to the temperature of the specimen at the time breakdown occurs. Clearly, when working with small samples, the opportunity to generate experimental data at controlled, uniform temperatures is present. For instance, do the testing in a controlled environment room or oven.

The electrode shape and size represents a significant parameter for small sample testing. The most common electrodes are Rogowski types where the electrode is curved and inserted into the polymer slab. This provides a uniform stress gradient and enhances the opportunity for obtaining meaningful information.

If the electrode-polymer interface is sharp (instead of rounded), the voltage stress will be enhanced at this location. Failure of the test specimen will be induced at this location. Should that happen, the dielectric strength measured will be related more to the manner in which the test was performed (inducing a high localized stress) rather than related to the properties of the insulation itself. Needle tests are also performed where a sharp, generally controlled radius of curvature exists at the needle tip. This needle is then inserted into the specimen part way to the ground plane. Voltage stress is applied and the dielectric strength is measured. This approach has been used to determine the influence of additives, designed to increase the breakdown strength, and an aid in developing superior materials. A detailed description of typical arrangements of electrodes is provided by Mathes in the references. The frequency of measurement may be readily varied in film studies much more easily than for full size cables. While most testing is performed at 60 hertz, testing has also been performed at frequencies ranging to 1,000 hertz. Again, the rate of rise of the field is vitally important and can readily be controlled.

5. SUMMARY

The chemical structure of the polymeric insulation determines the magnitude of the dielectric constant and power factor. These two properties are significant at operating stress and generally considered to be "low." Polyolefins such as polyethylene or crosslinked polyethylene have low dielectric constants and low power factors. Low levels of oxidation, generally resulting from processing the polymer, lead to slight increases in these properties. Higher than normal operating stresses are used to determine the dielectric strength of an insulating material. The manner in which the test is designed and performed can influence the results. Statistical evaluation of the dielectric strength data is required. Failure mechanisms are briefly reviewed and the differences between water and electrical trees are noted.

6. REFERENCES

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[6-2] Ken Mathes, "Electrical Insulating Materials."

[6-3] M. L. Miller, "The Structure of Polymers," Reinhold Book Corporation, SPE Polymer Science and Engineering Series, Chapters 1, 2, 3, 10, & 13, 1966.

CHAPTER 7

SHIELDING OF POWER CABLES

Lawrence J. Kelly and Carl C. Landinger

1. GENERAL

Shielding of an electric power cable is accomplished by surrounding the assembly or insulation with a grounded, conducting medium. This confines the dielectric field to the inside of this shield. Two distinct types of shields are used: metallic and nonmetallic.

The purposes of the insulation shield are to:

1. Obtain symmetrical radial stress distribution within the insulation.
2. Eliminate tangential and longitudinal stresses on the surface of the insulation.
3. Exclude from the dielectric field those materials such as braids, tapes, and fillers that are not intended as insulation.
4. Protect the cables from induced or direct over-voltages. Shields do this by making the surge impedance uniform along the length of the cable and by helping to attenuate surge potentials.

2. CONDUCTOR SHIELDING

In cables rated over 2,000 volts, a conductor shield is required by industry standards. The purpose of the semiconducting, also called screening, material over the conductor is to provide a smooth cylinder rather than the relatively rough surface of a stranded conductor in order to reduce the stress concentration at the interface with the insulation.

Conductor shielding has been used for cables with both laminar and extruded insulations. The materials used are either semiconducting materials or ones that have a high dielectric constant and are known as stress control materials. Both serve the same function of stress reduction.

Conductor shields for paper insulated cables are either carbon black tapes or metallized paper tapes.

The conductor shielding materials were originally made of semiconducting tapes that were helically wrapped over the conductor. Present standards still permit such a tape over the conductor. This is done, especially on large conductors, in order to hold the strands together firmly during the application of the extruded semiconducting material that is now required for medium voltage cables. Experience with cables that only had a semiconducting tape was not satisfactory, so the industry changed their requirements to call for an extruded layer over the conductor.

In extruded cables, this layer is now extruded directly over the conductor and is bonded to the insulation layer that is applied over this stress relief layer. It is extremely important that there be no voids or extraneous material between those two layers.

Present-day extruded layers are not only clean (free from undesirable impurities) but are very smooth and round. This has greatly reduced the formation of water tress that could originate from irregular surfaces. By extruding the two layers at the same time, the conductor shield and the insulation are cured at the same time. This provides the inseparable bond that minimizes the chances of the formation of a void at the critical interface.

For compatibility reasons, the extruded shielding layer is usually made from the same or a similar polymer as the insulation. Special carbon black is used to make the layer over the conductor semiconducting to provide the necessary conductivity. Industry standards require that the conductor semiconducting material have a maximum resistivity of 1,000 meter-ohms. Those standards also require that this material pass a long-time stability test for resistivity at the emergency operating temperature level to insure that the layer remains conductive and hence provides a long cable life. This procedure is described in reference [7-1].

A water-impervious material can be incorporated as part of the conductor shield to prevent radial moisture transmission. This layer consists of a thin layer of aluminum or lead sandwiched between semiconducting material. A similar laminate may be used for an insulation shield for the same reason.

There is no definitive standard that describes the class of extrudable shielding materials known as "super smooth, super clean". As will be described in Chapter 9, Standards and Specifications, it is not usually practical to use a manufacturer's trade name or product number to describe any material. The term "super smooth, super clean" is the only way at this writing to describe a class of material that provides a higher quality cable than an earlier version. This is only an academic issue since the older type of materials are no longer used for medium voltage cable construction by known suppliers. The point is that these newer materials have tremendously improved cable performance in laboratory evaluations.

3. INSULATION SHIELDING FOR MEDIUM-VOLTAGE CABLES

The insulation shield for a medium voltage cable is made up of two components: (1) a semiconducting or stress relief layer and (2) a metallic layer of tape or tapes, drain wires, concentric neutral wires, or a metal tube. They must function as a unit for a cable to achieve a long service life.

3.1 Stress Relief Layer

The polymer layer used with extruded cables has replaced the tapes shields that were used many years ago. This extruded layer is called the extruded insulation shield or screen. Its properties and compatibility requirements are similar to the conductor shield previously described except that standards require that the volume resistivity of this external layer be limited to 500 meter-ohms.

The nonmetallic layer is directly over the insulation and the voltage stress at that interface is lower than at the conductor shield interface. This outer layer is not required to be bonded for cables rated up to 35 kV. At voltages above that, it is strongly recommended that this layer be bonded to the insulation.

Since most users want this layer to be easily removable, the Association of Edison Illuminating Companies (AEIC) has established strip tension limits. Presently these limits are that a 1/2 inch wide strip cut parallel to the conductor peel off with a minimum of 6 pounds and a minimum of 24 pounds of force that is at a 90° angle to the insulation surface.

3.2 Metallic Shield

The metallic portion of the insulation shield or screen is necessary to provide a low resistance path for charging current to flow to ground. It is important to realize that the extruded shield materials will not survive a sustained current flow of more than a few milliamperes. These materials are capable of handing the small amounts of charging current, but cannot tolerate unbalanced or fault currents.

The metallic component of the insulation shield system must be able to accommodate these higher currents. On the other hand, an excessive amount of metal in the shield of a single-conductor cable is costly in two ways. First, additional metal over the amount that is actually required increases the initial cost of the cable. Secondly, the greater the metal component of the insulation shield, the higher the shield losses that result from the flow of current in the central conductor. This subject is treated more completely in Chapter 13, Ampacity.

A sufficient amount of metal must be provided in the cable design to ensure that the cable will activate the back-up protection in the event of any cable fault over the life of that cable. There is also the concern for shield losses. It therefore becomes essential that:

☐ The type of circuit interrupting equipment to be analyzed. What is the design and operational setting of the fuse, recloser, or circuit breaker?

☐ What fault current will the cable encounter over its life?

☐ What shield losses can be tolerated? How many times is the shield to be grounded? Will there be shield breaks to prevent circulating currents?

Although there are constructions such as full and one-third neutral listed in ICEA standards for single-conductor, URD, and UD cables, these may not be the designs that are the most economical for a particular installation. Studies have been published on the optimum amount of metal to use in the neutral [7-2, 7-3]. Documents such as these should be reviewed prior to the development of a cable design. In Chapter 13, Ampacity, there is an in-depth discussion of shield losses.

3.3 Concentric Neutral Cables

When concentric neutral cables are specified, the concentric neutrals must be manufactured in accordance with ICEA standards. These wires must meet ASTM B3 for uncoated wires or B33 for coated wires. These wires are applied directly over the nonmetallic insulation shield with a lay of not less than six or more than ten times the diameter over the concentric wires.

4. SHIELDING OF LOW VOLTAGE CABLES

Shielding of low voltage cables is generally required where inductive interference can be a problem.

In numerous communication, instrumentation, and control cable applications, small electrical signals may be transmitted on the cable conductor and amplified at the receiving end. Unwanted signals (noise) due to inductive interference can be as large as the desired signal. This can result in false signals or audible noise that can effect voice communications.

Across the entire frequency spectrum, it is necessary to separate disturbances into electric field effects and magnetic field effects.

4.1 Electric Fields

Electric field effects are those which are a function of the capacitive coupling or mutual capacitance between the circuits. Shielding can be effected by a continuous metal shield to isolate the disturbed circuit from the disturbing circuit. Even semiconducting extrusions or tapes supplemented by a grounded drain wire can serve some shielding function for electric field effects.

4.2 Magnetic Fields

Magnetic field effects are the result of a magnetic field coupling between circuits. This is a bit more complex than for electrical effects.

At relatively low frequencies, the energy emitted from the source is treated as radiation. This increases with the square of the frequency. This electromagnetic radiation can cause disturbances at considerable distance and will penetrate any "openings" in the shielding. This can occur with braid shields or tapes that are not overlapped. The type of metal used in the shield also can effect the amount of disturbance. Any metallic shield material, as opposed to magnetic metals, will provide some shield due to the eddy currents that are set up in the metallic shield by the impinging field. These eddy currents tend to neutralize the disturbing field. Non-metallic, semiconducting shielding is not effective for magnetic effects.

In general, the most effective shielding is a complete steel conduit, but this is not always practical.

The effectiveness of a shield is called the "shielding factor" and is given as:

$$SF = \frac{\text{Induced voltage in shield circuit}}{\text{Inducted voltage in unshielded circuit}} \tag{7.1}$$

Test circuits to measure the effectiveness of various shielding designs against electrical field effects and magnetic field effects have been reported by Gooding and Slade.

5. REFERENCES

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CHAPTER 8

SHEATHS, JACKETS, AND ARMORS

Lawrence J. Kelly and Carl C. Landinger

1. SHEATHS

The terms "sheaths" and "jackets" are frequently used as though they mean the same portion of a cable. Sheath is properly the term that applies to a metallic component over the insulation of a cable. An example is the lead sheath of a paper insulated, lead-covered cable. See the definition of jacket in 2.0 below.

Various metals may be used as the sheath of a cable such as lead, copper, aluminum, bronze, steel, etc. A sheath provides a barrier to moisture vapor or water ingress into the cable insulation. It is necessary to use such a sheath over paper insulation, but it also has a value over extruded materials because of water ingress.

The thickness of the metal sheath is covered by ICEA and AEIC standards and specifications, but there are some constructions that are not covered. The thickness is dependent on the forces that can be anticipated during the installation and operation of the cable. Designs range from a standard tube to ones that are longitudinally corrugated. The bending radius of the finished cable is dependent on such configurations.

To fully utilize the metal chosen, one should consider first cost, ampacity requirements -- especially during fault conditions, and corrosion [8-1].

2. THERMOPLASTIC JACKETS

The term jacket should be used for nonmetallic coverings on the outer portions of a cable. They serve as electrical and mechanical protection for the underlying cable materials.

There are many materials that may be used for cable jackets. The two broad categories are thermoplastic and thermosetting. For each application, the operating temperature and environment are important factors that must be considered.

2.1. Polyvinyl Chloride (PVC)

PVC is the most widely used nonmetallic jacketing material in the wire and cable industry. Starting in 1935, when it first became available, the use of PVC grew rapidly because of its low cost, its easy processing, and its excellent combination of overall properties including fire and chemical resistance.

PVC belongs to a group of polymers referred to as vinyls. The unmodified polymer contains approximately 55 % chlorine. It is fairly linear in structure (few side chains) with approximately 5 to 10 % crystallinity. The material must be compounded with additives such as fillers, plasticizers, and stabilizers to attain flexibility, heat resistance, and low temperature properties. General purpose jacketing materials normally posses good physical strength, moisture resistance, adequate oil resistance, good flame resistance and excellent resistance to weathering and to soil environments. Flame resistance and low temperature flexibility can both be improved within limits by the use of additives.

General purpose PVC compounds are recommended for installation at temperatures above -10 °C, but specially formulated compounds may be used as low as -40 °C.

One of the limitations of PVC jacketed cable is its tendency to creep under continuous pressure. For this reason, cables which are to be supported vertically with grips should not have PVC jackets. Hypalon or neoprene are recommended for such use.

In the low voltage field, PVC is widely used as a single layer of material where it functions both as insulation and jacket. Since PVC is a thermoplastic material, it cannot take high temperatures. Under high current fault conditions the insulation can be permanently damaged by melting or can emit plasticizers and become stiff and brittle. For this reason, it is not used as utility secondary network cable. Similarly, in industries that handle large amounts of heated material, or where there is the possibility of excessive heat, the use of PVC is avoided because of its tendency to melt or deform when heated to a high temperature. Under continuous dc voltage in wet locations, as in battery operated control circuits, single-conductor PVC-insulated cables have frequently failed due to electro-endosmosis (water vapor ingress created by voltage stress).

The large percentage of chlorine can be released during a fire. When combined with moisture, hydrochloric acid may be produced. This situation highlights one of the major problems that can result from the use of PVC.

2.2 Polyethylene

Polyethylene (PE) has been widely used as a jacket for underground cables since it became commercially available in large quantities in about 1950. For use as a jacket, polyethylene may be compounded with carbon black or coloring material, and with stabilizers. Carbon black gives the material the necessary sunlight protection for outdoor use.

Polyethylene for jacketing is categorized under three different densities:

Low density	0.910 to 0.925 grams per cm^3
Medium density	0.926 to 0.940 grams per cm^3
High density	0.941 to 0.965 grams per cm^3

Density generally affects the crystallinity, hardness, melting point, and general physical strength of the jacketing material. In addition to density, molecular weight distribution is important since it influences the processing and properties of the polymer.

Polyethylene jackets are an excellent choice where moisture resistance is a prime design criteria since it has the best moisture resistance of any non-metallic jacket material. When polyethylene is used as a jacket material, it should be compounded with enough carbon black to prevent ultra-violet degradation. Linear, low density, high molecular weight (LLDPE) is the most popular jacket material since it has better stress-crack resistance that the high density materials. High density provides the best mechanical properties, but may be very difficult to remove from the cable.

In evaluating fillers, both black and non-black, it has been found that although many of these materials improve the aging characteristics, carbon black is by far the best. It has also been found that the aging resistance increases with carbon black loading from 2 to 5 percent. Normally, a 2.5 to 3.0 percent loading is used.

Although PE has good moisture resistance and good aging properties in its temperature limits, it has poor flame resistance. This discourages using it as a jacket in many circumstances. Polyethylene jackets have good cold bend properties since they will pass a cold bend test at about -55 °C. They are extremely difficult to bend at low temperature because of their stiffness. Like PVC, PE is a thermoplastic material and will melt at elevated temperatures. This temperature will vary slightly with molecular weight and density, but melt occurs at about 105 °C.

High density polyethylene (HDPE) has been used extensively as the second (outer) layer for "ruggedized" thermoplastic in secondary and low voltage street light cables because of its toughness.

While black polyethylene for jacketing is frequently an insulating material, with higher loadings of carbon-black it can be a semiconducting material. This material has been used for over 30 years in direct-buried applications to improve the grounding of the concentric neutral.

2.3 Chlorinated Polyethylene (CPE)

CPE can be made either as a thermoplastic or as a thermosetting jacket material. As a thermoplastic material, it has properties very similar to PVC, but with better higher temperature properties and better deformation resistance at high temperatures than PVC. CPE jackets also have better low temperature properties than PVC unless the PVC is specifically compounded for this property.

2.4 Thermoplastic Elastomer (TPE)

TPE is a thermoplastic material with a rubber-like appearance. It is a form of crystalline polyethylene and it comes in various types. It can be compounded for use as either an insulation or a jacketing material. By use of compounding techniques, a good electrical insulation can be developed with good moisture resistance properties.

Also, a jacketing material can be compounded to provide flame resistance, low temperature performance, good abrasion resistance, and good physical properties. This material is relatively new as compared to the thermoplastics previously mentioned, but appears to be a very versatile material.

2.5 Nylon

Nylon is a thermoplastic with many properties which make it desirable for jacketing of wire and cable. Nylon has relatively high strength, tough, but rather stiff especially in cold weather. Nylon also has good impact fatigue and, within limitations, good abrasion resistance. A very important feature is the low coefficient of friction in contact with conduit materials. This is an aid in pulling cables into conduits. Nylon has excellent resistance to hydrocarbon fuels and lubricants as well as organic solvents. However, strong acids and oxidizing agents will attack nylon. The most common use of nylon in cable jacketing is the jacket on THHN and THWN building wire.

3., THERMOSETTING JACKETING MATERIALS

Thermosetting jackets are not widely used for underground distribution cables except for the special case of medium- or high-density crosslinked polyethylene that is used as the outer layer on two layer, "ruggedized", secondary cables. Thermosetting jackets are more commonly utilized in industrial and power plant applications.

3.1 Crosslinked Polyethylene

Crosslinked polyethylene, with the addition of carbon black to provide sunlight resistance, provides a tough, moisture, chemical, and weather resistant jacket material. The medium and high density materials are especially tough and are widely used as the outer layer on two layer "ruggedized" secondary cables. Only limited use is found for other purposes.

3.2 Neoprene

Neoprene has been used as a jacketing material since 1950 for large power cables such as paper insulated, lead-covered cables and portable cables. Compounds of neoprene usually contain from 40 to 60% by weight of neoprene that is compounded with other ingredients to provide the desired properties such as good heat resistance, good flame resistance, resistance to oil and grease, and resistance to sunlight and weathering. Moisture resistance can be compounded into the material when required.

Properties that can be varied by compounding techniques are: improved low temperature characteristics, improved physical strength, and better moisture resistance. Most Neoprene compounds have good low temperature characteristics at -30 °C to -40 °C. Special compounding can lower this to -60 °C, but other properties, such as physical strength, have to be sacrificed.

Because of its ruggedness, tear resistance, abrasion resistance, flame resistance, and heat resistance, neoprene is the most widely used jacketing material for the mining industry. This is probably the most severe application for cables from a physical standpoint. The thermosetting characteristics of neoprene are desirable in this application since these cables must withstand high temperature while installed on cable reels. Thermoplastic jacketing materials would soften and deform under such environments.

3.3 Chlorosulphanated Polyethylene (CSPE)

CSPE is a thermosetting jacket compound with properties very similar to neoprene. CSPE is unique in that colored compounds of this material, protected by sunlight stable pigments, have weather resistant properties similar to black CSPE compounds. Hypalon is the trade name of the most commonly used material.

CSPE compounds are superior to neoprene compounds in the areas of resistance to heat, oxidizing chemicals, ozone, and moisture. They also have better dielectric properties than neoprene. The flame resistance of both materials is excellent. The superior heat resistance of CSPE as compared with neoprene, makes it the better choice for cables rated at conductor temperatures of 90 °C.

3.4 Nitrile Rubber

Nitrile rubber compounds are copolymers of butadiene and acrylonitrile. They provide outstanding resistance to oil at higher temperatures. Since this is their only outstanding feature, they are generally limited to oil well applications where temperatures up to 250 °C can be encountered. Their poor oxidation resistance in air limits their use for other applications.

3.5 Nitrile-Butadiene/Polyvinyl Chloride

These jacket compounds are blends of nitrile rubber mixed with PVC to provide a thermosetting jacket similar to neoprene. The advantage of this material over neoprene is that colored jackets of NBR/PVC have properties comparable to black jackets and can be compounded for physical properties and tear resistance similar to that of neoprene.

3.6 Ethylene Propylene Rubber

EPR is frequently used as an insulating material because of its balance of outstanding electrical properties. They can also be used for jackets, especially in low temperature applications where flexibility is required. These materials can be compounded for -60 °C applications with reasonably good physical properties and tear resistance.

EPR is not generally used for a jacketing material in other applications. They are used as jackets in low voltage applications when flame resistance has been compounded into the material.

4. ARMOR

4.1 Interlocked Armor

This armor consists of a single metal tape whose turns are shaped to interlock during the manufacturing process. Mechanical protection is therefore provided along the entire cable length.

Galvanized steel is the most common metal provided. Aluminum and bronze are used where magnetic effects or weight must be considered. Other metals, such as stainless steel or copper, are used for special applications.

Interlocked-armor cables are frequently specified for use in cable trays and for aerial applications so that conduit and duct systems can be eliminated. The rounded surface of the armor withstands impact somewhat better than flat steel tapes. The interlocked construction produces a relatively flexible cable that can be moved and repositioned to avoid obstacles during and after installation.

An overall jacket is often specified in industrial and power plants for corrosion protection and circuit identification. Neither flat-taped armor or interlocked armor is designed to withstand longitudinal stress, so long vertical runs should be avoided.

4.2 Round-Wire Armor

This construction consists of one or two layers of round wires applied over a cable core. For submarine cable applications, the wires are usually applied over a bedding of impregnated polypropylene or jute.

Round-wire armor is used where high tensile strength and resistance to abrasion and mechanical damage are desired. Vertical riser cables and borehole cables are made with round-wire armor when end-suspension from the wires is necessary for support for the longitudinal stresses. Round wires have less resistance to piercing than flat-tape armor or interlocked armor, but has superior tensile strength and abrasion resistance.

For single-conductor cables, copper or aluminum wires have been used to minimized losses due to circulating currents. Such constructions sacrifice mechanical strength in order to achieve the lower losses.

Armor wires can be made with the individual wires coated with polyethylene or other corrosion resistant coverings. Since there is a portion of the circumference without metal protection, cables with such covered wires are usually made with two layers of armor wires with the second layer in the opposite lay to the first.

For installations in severe rock environments, two layers of steel wires, with no individual coverings, are applied in reverse lay. The outer layer frequently is applied with a very short lay to achieve optimum mechanical protection.

The number of armor wires for a wire-armored cable may be calculated from the following equation:

$$N = \left[\frac{\pi (D + d)}{Fd} \right] -2 \qquad (8.1)$$

where
N = Number or armor wires, nearest whole number
D = Core diameter of cable under armor in inches
d = Diameter of armor wire in inches
F = Lay factor. See Table 6.2.
$D + d$ = Pitch diameter or armor wire in inches

Armor resistance may be calculated from the following equation:

$$Ra = \frac{r_a \text{ x } F}{1{,}000\, N} \qquad (8.2)$$

where
r_a = dc resistance of one armor wire or tape per 1,000 feet at temperature t in ohms
F = Lay factor. See Table 8.2.
N = Number or armor wires

Note: For steel wire armor, increase Ra by 50% to obtain approximate ac resistance.

Table 8-1
Approximate dc Resistance of Armor Wire

Wire Size	**Wire Diameter**	**Galvanized Steel**	**Hard Drawn Copper**	**Commercial Bronze**
BWG	inches	ohms per 1,000 feet	ohms per 1,000 feet	ohms per 1,000 feet
12	0.109	7.33	0.895	2.49
10	0.134	4.92	0.592	1.65
8	0.165	3.16	0.391	1.09
6	0.203	2.12	0.258	0.72
4	0.238	1.53	0.188	0.52
Basis: Conductivity,	% IACS	12.0	97.5	40.0
Temperature Coefficient of Resistivity	(α)	0.0035	0.00383	0.00190

Table 8-2
Lay Factor for Round Wire Armor

Ratio of Length of Lay to Pitch Diameter of Armor Wire	Lay Factor
7	1.095
8	1.072
9	1.057
10	1.048
11	1.040
12	1.034

Note: Use 7 as a typical value if the ratio is unknown.

5. REFERENCE

[8-1] Carl C. Landinger, Adapted from class notes of the *Power Cable Engineering Clinic,* University of Wisconsin–Madison, October, 1997.

CHAPTER 9

STANDARDS AND SPECIFICATIONS

Lawrence J. Kelly and Carl C. Landinger

1. INTRODUCTION

Standards and specifications for power and control cables have been prepared in the United States by various industry organizations since the early part of the twentieth century. Electrical cables are manufactured to these requirements depending on the application of the particular installation.

The power cables that are covered by these standards and specifications can be classified under three major categories:

☐	Low Voltage Cables	Rated up to 2,000 volts
☐	Medium Voltage Cables	Rated 2,001 through 46,000 volts
☐	High Voltage Cables	Rated 69,000 volts to 500,000 volts

The most widely used documents in the North America are those issued by the Insulated Cable Engineers Association (ICEA) in conjunction with the National Electrical Manufacturers Association (NEMA), the Association of Edison Illuminating Companies (AEIC), the Rural Electrification Administration (RUS), and Underwriter's Laboratories (UL).

2. MANUFACTURERS (ICEA / NEMA)

2.1 ICEA

This group was formerly known as IPCEA. They removed the "Power" from their name to more accurately describe a broader scope of activities. Sections in ICEA include:

Extruded Dielectric Power	EDP
Portable, Communication	COM
Control and Instrumentation	C&I

Membership is made up of technical employees of cable manufacturers in North America. They develop standards, guides, and committee reports on all aspects of insulated cable design, materials, and applications. They work with other organizations toward the development of joint standards. Many of their standards are subject to the approval of NEMA and these are published as a joint ICEA / NEMA standard.

These standards encompass the entire cable: conductor, shields, insulation, jackets, testing, etc. The only possible omission is packaging. This is considered to be an area that is not allowed by United States' law.

2.2 NEMA

NEMA's members are from cable manufacturing organizations and generally they are from the commercial side of those companies.

3. ASTM

The American Society of Testing and Materials prepare and publish standards for many of the materials in wire and cable. A notable example is for conductors. ICEA references these documents in their Standards, so the details of conductors are covered by ASTM.

4. AEIC

Cable specifications have been written by the Cable Engineering Section of the Association of Edison Illuminating Companies, a group of investor owned and municipal utility company engineers, since 1920. They also prepare Guides that pertain to power cables.

Their first specifications were written for paper insulated cables for medium voltage applications. Presently their specifications cover all forms of laminated cables from 5 to 345 kV such as paper-insulated, lead-covered, low-pressure oil-filled, and pipe-type. These specifications include conductors, insulations, sheaths, shields, jackets, and testing requirements.

AEIC also prepares specifications for extruded dielectric cables from 5 to 138 kV that build upon the ICEA documents (hence also on the applicable ASTM requirements). AEIC hence uses the ICEA standards for such items as conductors, shields, jackets, and testing requirements. A unique feature of AEIC's extruded cable specifications is that they require a qualification test be performed on a sample of cable that represents the cable to be manufactured.

Another feature of AEIC's specifications for extruded cables is a checklist of the available options is presented. This can be useful for those users that are in the process of developing a user specification for themselves.

5. RURAL ELECTRIFICATION ADMINISTRATION (now RUS)

This is also a user group of the U.S. Department of Agriculture that develops standards for the Rural Electric Cooperatives of the United States.

6. UNDERWRITER'S LABORATORIES (UL)

Underwriter's Laboratories has published several standards for low voltage cables and one for medium voltage cables.

7. FEATURES OF STANDARDS AND SPECIFICATIONS

7.1 Conductors

7.1.1 Resistance. Both copper and aluminum conductors are covered by ASTM and ICEA standards. Since resistance is the governing factor for establishing conductor size in most instances, they both establish a maximum resistance for each AWG and kcmil size. Conductor diameters and individual strand diameters are no longer required to meet a minimum dimension.

One of the possibilities with aluminum is that the conductivity may be better than the required 61.2%. The result can be that aluminum with 62% conductivity does not have the cross-sectional area of say a 1,000 kcmil conductor. This can be an important difference for such large conductors when they are connected using crimp connectors. Attention to the design of the connector and the compression tool and dies will keep this slight reduction in metal area from being a problem even during emergency overload conditions.

7.1.2 Compressed Strand. ASTM standards for stranded conductors give the manufacturer the option of "compressing" Class B and C conductors. This means that they can decrease the overall diameter of the conductor by a maximum of 3% from that of a concentric conductor. The need and advantages for such compression was presented in Chapter 3. Another way of saying this is that even if "concentric" stranding is requested, the manufacturer has the option of providing "compressed" strand.

7.1.3 Temper. An important decision that must be made involves the temper of the metal. This option should be based on such factors as the pulling forces, flexibility, and also on the cost.

The harder the temper, the greater force can be applied to the conductor during installation. A half-hard aluminum conductor will withstand less force than a 3/4 or full hard conductor. On the other hand, that increase in temper produces a conductor that requires more force to bend -- it is less flexible. This additional force may be negligible when compared with the bending forces of the finished cable, however. When conductors are drawn during the manufacturing process, the metal is work hardened and the temper increases. Annealing during the drawing process or after the conductor is formed will decrease the temper, but this takes energy so there is an increase in the cost of an annealed conductor. All of these points need to be weighed before a decision is reached.

7.1.4 Identification. Cable manufacturers have the capability of indent printing on the center strand of a seven strand, or greater, Class B or C conductor. If requested at the time of the inquiry, they can print the year of manufacturer and their name at one-foot intervals on this center strand. This provides a lasting identification of the manufacturer and the year.

7.1.5 Blocked Strand. Another consideration is to block, or fill, the strands of a Class B conductor with a compound that eliminates almost all the air from the interstices. This prevents the accumulation of moisture in the air space as well as prevents any moisture from longitudinal movement along the cable. The elimination of water in the strand reduces the treeing concerns and increases the life of cables in accelerated treeing tests. ICEA Standards contain a test for the effectiveness of this "water blocking" [9-1].

Another method of keeping water from entering (or leaving) the strand is to install a metal barrier in the semiconducting strand shielding. The layer is a "sandwich" of the semiconducting material with a lead or aluminum overlapped tape in the center.

7.2 Conductor Shielding

Conductor shielding (either a semiconducting or a stress control layer) is required for cables rated 2,000 volts and higher by these standards. Conductor shielding normally consists of a semiconducting layer applied between the conductor and the insulation. For this layer to function properly, it should be inseparably bonded to the insulation to ensure there are no air voids between the conducting layer and the insulation.

For compatibility reasons, this extruded semiconducting material is usually made from the same polymer as the insulation that it will be adjacent to ensure compatibility of the two materials. Its conducting properties are obtained by adding particles of special carbon black. The present requirement for the maximum resistivity of this layer is 1,000 meter-ohms. Industry standards require this material to pass a long-time stability test for resistivity at rated emergency overload temperature of the cable. Accelerated tests have shown that the cleanliness of the material can significantly effect the life of the cable when it is in a wet environment. A "super clean" semiconducting material can improve the life of a cable in an accelerated water treeing test by three to five times.

The stress control layer that may be used rather than semiconducting has properties that are best describe it as having a high dielectric constant (high K) material. This means that it acts like a rather poor conductor and produces a very low voltage drop between the conductor and the insulation. It does provide the stress control that is needed for smoothing out the conductor surface.

It is permissible to apply a conducting tape over the conductor and under the semiconducting layer. This functions as a binder and is sometimes used for larger conductors.

If a semiconducting conductor stress control layer is used, the resistivity shall be measured using the following procedure. A sample approximately 6 to 8 inches long shall be taken and the metallic shielding removed. The sample shall be cut in half by making two longitudinal cuts 180^0 apart. The conductor shall be removed. One of the 180^0 sections shall be painted with silver electrodes placed at least two inches apart on the conductor stress control layer to act as potential electrodes. If greater accuracy is desired, current electrodes may be placed one inch beyond each potential electrode.

The resistance shall be measured between the two potential electrodes. The power of the test circuit shall not exceed 100 milliwatts.

The volume resistivity shall be calculated from the following equation:

$$P = \frac{R\,(D^2 - d^2)}{100\,L} \tag{9.1}$$

where P = Volume resistivity in ohm-meters
R = Measured resistance in ohms
D = Diameter over conductor stress control layer in inches
d = Diameter over conductor in inches
L = Distance between electrodes in inches

7.3 Insulations

Crosslinked polyethylene (including tree retardant XLPE) and ethylene propylene rubber are the dominant materials presently being used as the insulation for medium voltage cables.

7.3.1 Crosslinked Polyethylene. AEIC has a specification for 5 to 46 kV medium voltage cable [9-5] that covers crosslinked (thermosetting) polyethylene cables. At this time, there is not any medium voltage thermoplastic polyethylene power cable being manufactured in North America.

AEIC CS5 and ICEA S-94-649 require that numerous tests be performed on the material that will be used in the manufacturing process. Applicable tests and their requirements include:

<u>Physical Requirements -- Unaged</u>

Tensile strength, psi, minimum, room temperature	1,800
Elongation, percent, minimum, room temperature	250

<u>Physical and Electrical Requirements -- Aged</u>

After Air Oven Test for 168 hours at 121 ^{0}C	
Tensile strength, % of unaged, minimum	75
Elongation, % of unaged, minimum	75

Electrical Characteristics at Room Temperature	
SIC at 80 V/mil, maximum	3.5
Dissipation Factor at 80 V/mil, maximum, XLPE	0.1
Dissipation Factor for filled or TR-XLPE	0.5
Insulation Resistance Constant	20,000

7.3.2 Ethylene Propylene Rubber. ICEA S-94-649 requires that tests be performed on the material to be used for these cables and that they have the following values:

<u>Physical Requirements -- Unaged</u>

Tensile strength, psi, minimum at room temperature,	EPR 1	700
	EPR 2	1,200
	EPR 3	700
Elongation, percent, minimum at room temperature, all three		250

<u>Physical and Electrical Requirements -- Aged</u>

After Air Oven Test for 168 hours at 121 ^{0}C		
Tensile Strength, percent of unaged, minimum,	EPR 1	75
	EPR 2	80
	EPR 3	75

Elongation, percent of unaged, minimum,	EPR 1	75
	EPR 2	80
	EPR 3	75
Electrical Characteristics at Room Temperature		
SIC at 80 V/mil, maximum, all three		4.0
Dissipation Factor at 80 V/mil, maximum, all three		1.5
Insulation Resistance Constant (K), minimum, all		20,000

7.3.3 Insulation Thickness And Test Voltages. Both crosslinked polyethylene and ethylene propylene rubber insulated cables have the same wall thickness requirements and test voltages in accordance with ICEA standards. The ac test voltage in ICEA is approximately 150 volts per mil of specified wall thickness.

AEIC specifies wall thickness for cables with both of these insulations for 5 to 46 kV service. Two important differences in the two philosophies is that AEIC no longer requires a dc test for these cables. The other is that they provide two wall thickness for each voltage rating -- Column A and B. See note 2 of Table 11-2 where they discuss the factors to be considered in making the choice.

RUS specifications require the use of Column B wall thickness for cables that are manufactured to their needs unless dispensation is given on the basis of selective designs.

7.4 Extruded Insulation Shields

In addition to the conductor stress control layer, medium voltage, shielded power cables require an insulation shield. The insulation shield consists of a nonmetallic covering directly over the insulation and a nonmagnetic metal component directly over or imbedded in the nonmetallic conducting covering. Since the nonmetallic insulation is over the insulation, the stresses are lower than at the conductor interface. This outer layer is not required to be bonded to the insulation for cables rated up to 35 kV. At higher ratings, bonding is both required and recommended. The insulation and the semiconducting material must be compatible since they are in intimate contact with one another.

7.4.1 Strip Tension. AEIC has established peel strength limits for the removal of the semiconducting layer for 5 to 35 kV cables. The lower limit is for cable performance and the upper limit is set to permit removal without damaging the surface of the insulation.

The AEIC test calls for a 1/2 inch wide strip be cut parallel to the center conductor. This cut may be completely through the layer (in contrast to field stripping practices). The 1/2 inch strip is removed by pulling at a 90^0 angle to the insulation surface at a set rate of speed. The limits are:

Table 9-1
AEIC Strip Tension Limits

Material	**Lower Limit in Pounds**	**Upper Limit in Pounds**
XLPE and TR-XLPE*	6	24
EPR	4	24

Note *: Recognition has been given to the availability of insulation shield with lower stripping tensions, but they are not covered by the 1994 version of AEIC CS5.

7.4.2 Resistivity. The volume resistivity of this extruded layer shall not be greater than 500 meter-ohms when tested in accordance with ICEA procedures. This layer can be used only as an auxiliary shield and requires a metal shield in contact with it to drain off charging currents and to provide electrostatic shielding.

The volume resistivity level is half that of the conductor shield because this layer is subject to chemical action from the environment. The function of the shielding properties would be acceptable with a higher value, but concerns over long-time stability have influenced this level.

The resistivity of the extruded layer shall be measured using the following procedure.

A sample approximately 6 to 8 inches long shall be taken and the outer coverings including the metallic shield shall be removed. Four silver-painted annular-ring electrodes shall be applied to the outer surface of the insulation shield. The inner two electrodes will be for the potential application and shall be at least two inches apart. If a high degree of accuracy is required, a pair of current electrodes shall be placed at least one inch beyond each potential electrode.

The resistance shall be measured between the two potential electrodes. The power of the test circuit shall not exceed 100 milliwatts.

The volume resistivity shall be calculated as follows:

$$P = \frac{2 \times R\,(D^2 - d^2)}{100\,L} \qquad (9.2)$$

where
P = Volume resistivity in ohm-meters
R = Measured resistance in ohms
D = Diameter over insulation shield in inches
d = Diameter under insulation shield in inches
L = Distance between potential electrodes in inches

7.4.3 Insulation Shield Thickness. AEIC has established a thickness for the extruded layer of insulation shield to provide guidance for the manufacturers of molded splices and terminations. In May of 1990, they issued an addendum that allowed for thinner layers for cables having an overall jacket or sheath.

7.5 Metallic Insulation Shields

In addition to the extruded insulation shield previously described, shielded cables must have a metallic member over and in contact with the nonmetallic layer. The following options are available for the metallic member.

Helically wrapped flat metal tape (usually copper)
Longitudinally corrugated metal tape (usually copper)
Wire shield (multiple #24 AWG or larger copper wires)
Concentric neutral wires (#14 AWG or larger to meet conductivity)
Flat straps (flat metal tapes applied with close coverage to meet conductivity)
Tape plus wires
Continuous welded corrugated metal sheath (copper, aluminum, etc.)

Wire shields and flat tapes are the most popular metallic shields and are almost always copper. A 5 mil copper tape with a minimum 10% overlap is generally used when tapes are specified. For wire shields, #24 to #18 AWG wires are used in proper multiples to provide 5,000 circular mils of area per inch of cable core conductivity. The first three types listed above, function as electrostatic shields only since they do not have a limited fault current capacity.

Concentric neutral wires and flat straps are normally specified on URD and UD cables where the metal functions both as a shield and a neutral. These constructions normally use copper wires with an overall jacket applied over the wires for corrosion protection.

In higher voltage cables such as 35 kV to 138 kV, fault currents often may be greater than the capabilities of wires. In those situations, the tape plus wire construction is frequently used.

Where shields must be sized for specific fault current requirements, there are several sources of data such as:

> ICEA T-45-482, "Short Circuit Performance of Metallic Shielding and Sheaths of Insulated Cable."
>
> EPRI RP 1286-2, (EL-5478),"Optimization of the Design of Metallic Shield / Concentric Neutral Conductors of Extruded Dielectric Cables Under Fault Conditions."

7.5.1 Concentric Neutral Cables. ICEA standards cover the number and size of concentric neutrals for this type of cable. The concentric neutral conductor shall be uncoated copper wire in accordance with ASTM B3 or tin coated wire in accordance with ASTM B33. The wires of the concentric neutral shall be applied directly over the insulation shield with a lay of not less that six or more than ten times the diameter over the concentric wires.

Although AEIC does not provide information on concentric neutrals, it is important to understand that a full or one-third neutral is not mandated by any standard. Many utilities use smaller amounts of neutral wires based on the fact that too much metal leads to increased losses. RUS standards do not require even a full neutral for URD cables.

7.6 Cable Jackets

Jackets are required over certain types of shields for mechanical protection and during the installation and operation. These shields are the flat tapes, corrugated tapes, wire shields having smaller wires than #14 AWG, and embedded corrugated wires.

There are many possible jacketing materials such as:

Polyethylene
Polyvinyl chloride (PVC)
Polychloroprene (Neoprene, Trade Mark)
Chlorosulphanated polyethylene
Chlorinated polyethylene

Their attributes are discussed in Chapter 8.

ICEA standards cover the thickness of these jackets. See Chapter 21 for tables.

8. REFERENCES

[9-1] ICEA S-19-81 (NEMA WC-3), "Rubber Insulated Wire and Cable, 0 to 28 kV".

[9-2] ICEA S-61-402 (NEMA WC-5), "Thermoplastic Insulated Wire and Cable, 0 to 35 kV."

[9-3] ICEA S-66-516 (NEMA WC-8), "Ethylene Propylene Rubber Wire and Cable, 0 to 35 kV."

[9-4] ICEA S-66-524 (NEMA WC-7), "Crosslinked Polyethylene Wire and Cable, 0 to 35 kV."

These ICEA-NEMA documents are available from:

National Electrical Manufacturers Association
1300 North 17 Street, Suite 1847
Rosslyn, VA 22209

[9-5] AEIC CS5-94, "Specifications for Crosslinked Polyethylene Insulated, Shielded Power Cables Rated 5 through 46 kV, 10th Edition."

[9-6] AEIC CS6-87, "Specifications for Ethylene Propylene Rubber Insulated, Shielded Power Cables Rated 5 through 69 kV, 5th Edition."

[9-7] AEIC CS7-93, "Specifications for Crosslinked Polyethylene Insulated, Shielded Power Cables Rated 69 through 138 kV, 3rd Edition."

These AEIC documents are available from:

Association of Edison Illuminating Companies
600 North 18 Street
P. O. Box 2641
Birmingham, AL 35291-0992

[9-8] UL Standard 1072, "MV Cables Rated 2,001 to 35,000 Volts."

[9-9] ICEA T-24-380, "Guide for Partial Discharge Test Procedures."

[9-10] ICEA P-45-482, "Short Circuit Performance of Metallic Shielding and Sheaths of Insulated Cable," 1979.

[9-11] ICEA T-25-425, "Guide for Establishing Stability of Volume Resistivity for Conductivity of Polymeric Compounds of Power Cables," 1981.

[9-12] ICEA T-28-562, "Test Method for Measurement of Hot Creep of Polymeric Insulations," 1983.

[9-13] ICEA T-22-294, "Test Method for Extended-Time Testing of Wire and Cable Insulations for Service in Wet Locations," revised 1983.

These ICEA documents are available from:

Mr. E. E. McIlveen, Secretary-Treasurer
ICEA
P. O. Box P
South Yarmouth, MA 02664

CHAPTER 10

CABLE MANUFACTURING [10-1, -2]

Lawrence J. Kelly and Carl C. Landinger

1. INTRODUCTION

Insulated electric power cable manufacturing involves a broad range of complexity depending on the cable design to be produced. Different cable plants may be capable of a limited or broad range of designs. Then, those capable of a broad range may limit operations to only a few steps in the manufacturing process.

Despite this large variability in plants, the steps in the manufacture remain basically the same, whether done in one facility or a number of facilities. Conductor manufacturing, in Chapter 3, is common to all cables with metallic conductors. The manufacture of extruded dielectric power cables and laminar dielectric power cables follow.

2. CONDUCTOR MANUFACTURING

In Chapter 3, Conductors, it was pointed out that for efficient distribution of electric power, the conductors must be produced from a high-conductivity material. It was also shown that copper and aluminum offer the best available combinations of conductivity, workability, strength, and cost to become the most popular power cable conductor materials. From the conductor manufacturing standpoint (we will not attempt to include mining, refining, and fabricating stages), we will begin at the point where copper and aluminum are received as large coils of round rod. The diameter of aluminum rod for conductors is commonly 3/8 inch (0.375 inches). For larger solid conductors—i.e., 1/0 AWG or larger—it is common and necessary to begin with a larger-diameter rod.

2.1 Wire Drawing

In wire drawing, the copper or aluminum rod is drawn through a series of successively smaller dies to reduce the rod to a wire of the desired diameter. The quality of the wire surface depends on sufficient drawing and reduction to eliminate surface defects. Thus, there is the need to utilize a rod having a diameter significantly larger than the solid wire to be produced. If fine wire is desired, it is common to utilize a coarse wire drawing machine followed by a fine wire drawing machine. The wires are taken up on spools for later stranding operations or on reels for use as a solid conductor.

2.2 Annealing

Drawing copper or aluminum wires increases the temper of the metal. That is, a rod of a "softer" temper is "hardened" as the wire is drawn down to the required diameter.

Except for the use of full hard temper aluminum stranded conductors for electric utility outside plant secondary and primary cables, it is generally desirable to use a softer temper.

To produce a softer temper, the wire is exposed to elevated temperatures well in excess of emergency operating temperatures of the cable. For many years, this has been accomplished in a large oven. Exposure time using this method is a matter of hours.

It is possible to partially anneal wires "on the fly". This is generally done on a wire before it is used in a stranding operation. The method is not generally suitable for full annealing to a soft temper nor to conductors after they have been stranded.

3. EXTRUDED CABLE MANUFACTURING

3.1 Insulating and Jacketing Compounds

There are literally thousands of insulating and jacketing compounds used in the cable industry. Many of these compounds are commercially available from compound suppliers. They may also be custom compounded by companies that sell them as finished, "ready-to-extrude" compounds. The cost of "ready-to-extrude" compounds is high enough so there is considerable incentive for the manufacturer to mix many compounds in-house. Low voltage compounds provide special opportunities ranging from the simple addition of one or more ingredients at the extruder to the complete mixing of all the ingredients and production of strips or pellets suitable for extrusion. The complex subject of compounding is beyond the scope of this text. For our purposes, we will assume compounds are complete, "ready-to-extrude". However, it is necessary to recognize that this all important compounding step is increasingly becoming a part of the manufacturing process.

3.2 Extrusion

The method of extrusion currently in use to produce polymeric layers comprising the cable are similar regardless of the polymer or layer being extruded.

Compound, in the form of pellets or strips, is fed into the back of a screw which rotates in a barrel. The material advances down the screw and is melted during the advance. In general, the barrel is divided into zones which are individually temperature controlled. There are some extrusions where the barrel is heated at the start of the extrusion, but as the extrusion continues, the mechanical shear and friction results in sufficient heat generation that barrel heating is no longer required. In fact, depending on compound and extrusion parameters, barrel cooling and even screw cooling may be required. Properly executed, the compound is all melted and forced through a die-head arrangement that deposits the melt on the core being passed through the head. This core may be a bare wire or cable in some stage of completion.

In many cases, the compound is introduced in its finished state. However, variations such as the addition of curing peroxides, color concentrates, or other ingredients at the extruder are quite commonly used.

3.3 Curing

This term is somewhat of a carryover from the rubber materials which required curing. The crosslinking process for modern thermosetting compounds, such as crosslinked polyethylene and ethylene propylene rubber, is often referred to as a curing stage. While materials such as polyethylene can be crosslinked by a radiation induced reaction, the majority of crosslinking continues to be by the chemical means.

Taking a simple case of polyethylene, the addition of a peroxide agent such as di-cumyl peroxide to the polyethylene and supplying heat energy results in a chemical reaction which crosslinks the polyethylene. Peroxides are also used for crosslinking EPR compounds.

The heating period to effect crosslinking is commonly called curing. It is also referred to as vulcanization, hence reference to the CV tube is the "continuous vulcanization" tube.

Curing tubes have three distinct configurations. The most commonly used is a curved tube that is in the shape of a catenary. The first portion is the curing section and the lower portion is the cooling section. The shape is designed to prevent touch-down of the cable until the cable has cured. The weight of the cable, line speed, and length of the total tube must be considered in this design.

Other forms of curing tubes may be horizontal or vertical. Horizontal tubes are used for very small cables or in special extruders that employ very long dies. A vertical extruder has the advantage of being able to make very large cables, especially transmission cables. They run relatively slowly, but gravity does not work to deform the shape of the cable.

The heat source most commonly used in the past was steam in a tube through which the extruded cable was passed. This continues to be the most popular means for curing secondary cables. When curing relatively heavy walls such as primary cables, the upper limit on temperature that steam can practically impose makes it desirable to use other heat sources. The most popular heat source today in radiant heating in a nitrogen filled tube. This is one of a number of dry curing methods. This method allows for much higher curing temperatures and therefore faster line speeds and curing. These curing tubes are divided into a number of zones each of which has its individual temperature controls. This allows for optimum temperature profiling to effect cure.

Because of the high temperature involved, care must be taken to avoid thermal damage of the polymer. More common in Europe and gaining in popularity in North America for cables up to 600 volts is silane curing. The system is based on the technology of silicones and "sioplas" as originally developed is a two part system of crosslinkable graft polymer and a master batch catalyst.

A further development, "monosil" introduces ingredients at the extruder and thus eliminates the grafting process. Water is the crosslinking agent in these silane systems and cure rates become very thickness dependent.

3.4 Cooling

Thermoplastic materials, such as polyethylene or polyvinyl chloride, do not require curing. Single layers that are relatively thin -- such as 600 volt building wire -- may be cooled in a water trough following extrusion. In the case of polyethylene, care must be taken to avoid too rapid a quench. This rapid cooling can result in locked-in mechanical stresses which will result in shrink-back of the material on the wire.

Heavier thermoplastic layers, such as encountered on primary cables, require gradient cooling to avoid these stress in the polyethylene.

Following curing, thermosetting materials must also be cooled. Then steam is the curing medium, water cooling is universally employed. Crosslinked polyethylene must not be rapidly quenched to avoid "shrink back" that is caused by locked-in stresses. Cooling zones are used to control the cooling process for water cooled cables.

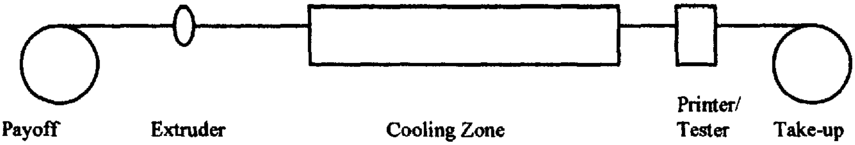
With the dry cure process, there is the possibility of using nitrogen as the cooling method. This is not frequently used for cables at this time. Cooling is sufficiently gradual that stresses are not locked-in.

4. EXTRUSION LINE CONFIGURATIONS

4.1 Straight Line

The simplest configuration for an extrusion line is one that can be used for low voltage thermoplastic cables having a single plastic layer over a conductor. A few examples of cables that are produced this way are: linewire, building wire, or a jacket over other cores.

Figure 10-1
Single Extrusion

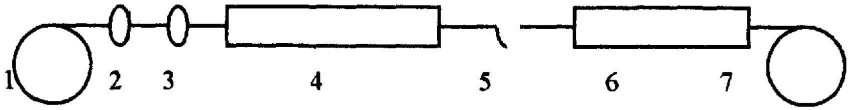


A curing zone may be added just before the cooling zone if curing is needed.

4.2 "Two Pass" Extrusion

Thermoplastic primary cables have been produced in a similar straight line configuration, but two separate extruders were used to apply the conductor shield and the insulation. Another "pass" through the third extruder after the first two layers were applied and cooled became knows as "two pass". The figures that are shown here do not imply that the curing and cooling tubes are straight. The figures are representing all possible configurations.

Figure 10-2
Dual Extrusion



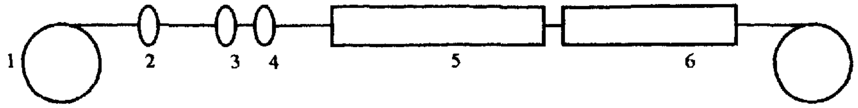
Where 1 is payoff, 2 is conductor shield extruder, 3 is insulation extruder, 4 is first cooling zone, 5 is insulation shield extruder, 6 is second cooling zone (for the insulation shield, and 7 is the takeup reel.

If the product was to be cured, a curing zone had to be included. Note that the third extruder, (#5 in Figure 10-2), was placed after the first cooling zone. That made it difficult to impossible to maintain the desired strippability of thermosetting insulation shields over thermosetting insulations. Thus, it was common to utilize a thermoplastic insulation shield over thermosetting insulation.

4.3 "Single Pass" Extrusion

The development of semiconducting thermosetting shield materials that would be readily strippable from thermosetting insulation even though all three layers were cured at the same time led to the development of lines where all three layers of a primary cable could be extruded over the core prior to any curing or cooling.

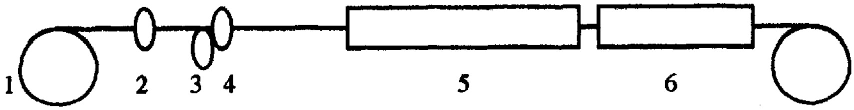
Figure 10-3
Single Pass withThree Extruders



Where 1 is the payoff reel, 2 is the conductor shield extruder, 3 is the insulation extruder, 4 is the insulation shield extruder, 5 is the curing zone, 6 is the cooling zone, and 7 is the take-up reel.

This was the first time the "triple extrusion" term was applied. While this arrangement was preferable to all previous methods because of minimal exposure of the insulation to possible contamination or abuse, further developments were desired. Dual extrusion of the two layers at positions 3 and 4 above would make for a smoother interface. Thus, the next improvement was single extrusion of the conductor shield and then, a few feet away, the dual extrusion of the insulation and the insulation shield. This was also called "triple extrusion"! About this time, dry curing lines were growing in popularity and many lines of this type were installed.

Figure 10-4
Single Pass with One Dual Extruder



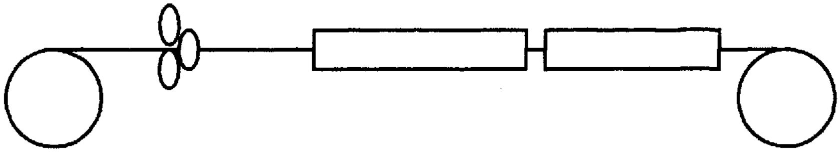
Where the equipment is the same as in Figure 10-3 except that extruders 3 and 4 are now in one "crosshead".

Unfortunately this method continued to allow the conductor shield to be vulnerable to scraping in the next extrusion head, continued to allow build-up on the extruder die face (die drool), and exposed the conductor shield to the environment.

4.4 "True Triple" Extrusion

The method now used for the majority of medium voltage cables utilizes a single crosshead where all three layers are applied simultaneously. This is referred to as "true triple" extrusion.

Figure 10-5
True Triple Extrusion



All three extruders feed into a single head for "true triple" extrusion. There are numerous lines now in service in North America, and the world in general, that make use of these triple heads.

4.5 Assembly

In cases of covered overhead service cables and similar constructions, a number of single cables may be assembled as a group. This is done on cablers or twisters. The equipment has some similarity to the equipment discussed under stranding. For assemblies to later be jacketed and serve as multi-conductor cables, it is common to add fillers to "round out" the assembly as well as using taping heads to apply binder and jacketing tapes in the same operation.

5. PAPER INSULATED CABLES

5.1 Paper Insulation

It has been found that up to a certain point, the mechanical strength of paper increases with its moisture content. Accordingly, prior to their use in the taping machine, pads (rolls) of paper are conditioned for a definite period in a room in which the temperature and humidity are controlled. This procedure assures that all the paper is in the same condition as it is being applied over the conductor and results in more uniformity in the taped insulation. When the paper is dried prior to impregnation, the paper shrinks uniformly. This allows for cables with sector conductors to be cabled without wrinkling.

5.2 Paper Taping

The importance of controlled tension in the taping process is realized when one is reminded that to have an optimum of electrical strength, paper insulation must be tightly applied, free from wrinkles, and other mechanical defects that non uniformly applied layers of tapes would have. Close, automatic control must be accomplished.

In one method, the tape from the pad passes around a pulley that is geared to a small motor armature whose direction or rotation is opposite to the direction of tape feed. As the tapes feeds along, the armature is revolved opposite to the direction it would take if turning freely and against the motor field torque. The pulley, therefore, exerts a back pull on the tape at all times and with a constant value. Torque must be regulated to the tension that is required.

5.3 Cabling

A large cabling machine is used for assembling individually insulated conductors into two, three, or four-conductor cables. The cradles may be operated rigidly or in a planetary motion to accommodate the large diameter cabling bobbins. This reduces the bending stresses to which the paper is subjected. Facilities are provided for mounting smaller bobbins between cradles which may be used for fillers, smaller cables such as fiber optic, or tubes. Small packages of fillers may also be carried on the spindles. Guides and bushings are used for placing sector-shaped conductors in their proper position without undue strain on the insulation. Behind the assembly bushings, heads are mounted for applying paper tapes on non-shielded type cables, or in the case of shielded cables, intercalated binder tapes.

Metal binder tapes are spot-welded when a new pad of tape is inserted in a taping head. The cable is drawn through the machine by a large capstan to a take-up reel. The large diameters of the capstan and impregnating reels reduce the bending stresses in the insulation.

5.4 Impregnating Compounds

Paper cables have been impregnated with numerous compounds over the years. A few of these that have been used include:

Type A. Unblended naphthenic-base mineral oil.
Type B. Naphthenic-base mineral oil blended with purified rosin.
Type C. Naphthenic-base mineral oil blended with a high-molecular-weight polymer.
Type D. Petrolatum blended with purified rosin.
Type E. Polybutene

When paper-insulated cable is impregnated with a dielectric fluid, the combination is better than either part and results in valuable characteristics:

1. High initial electrical resistivity.
2. Low rate of deterioration from high temperatures.
3. Extremely low power factor.
4. Very flat power factor vs. temperature curve.
5. Low ionization factor.

Careful investigation has shown that the unblended mineral oil is the most stable oil from a chemical and electrical standpoint. Natural inhibitors in the petroleum afford high oxidation stability.

These inhibitors are complex resins occurring naturally in crude petroleum. For the most part, they are eliminated in the refining process and necessarily so because they represent impurities. If the petroleum is over-refined, all these inhibitors are removed, resulting in a clear oil of high electrical characteristics but having unstable qualities. These resins act as anti-oxidants by taking up oxygen themselves from the oil and thus inhibiting oxidation deterioration. In the refining process used for this oil, a good balance is obtained between electrical characteristics and high thermal stability. Most of the oil impregnated, medium voltage cables were made with Type A compound. Types B, C, and D were more viscous than Type A and were suitable for long vertical runs or slopes with Type C being the most frequently used compound.

The predominant compound used since 1980 has been the synthetic material polybutene. Since this is not an oil, it is proper to refer to these as fluid-filled cables.

5.5 Drying and Impregnating

Assuming that the proper materials have been selected and good mechanical construction employed, the electrical characteristics of the completed cable depend primarily upon the drying and impregnating process.

It has been established by many laboratory investigations that oil, under heat and exposure to air, rapidly loses it desirable insulating properties. Also, the presence of residual air and moisture are harmful to impregnated paper insulation. Thus, paper insulated cables are dried and impregnated in a closed system.

The functional principles of this closed system are:

1. Transfer of hot impregnating fluid from a vacuum tank to another tank under vacuum without exposure to air.
2. Use of relatively high fluid pressure (85 to 200 pounds per square inch) during impregnation.
3. Complete degassing and dehydration of the fluid.
4. Use of extremely high vacuum (1 mm or less).

If there is more than one impregnating compound used in a plant, it is desirable to have separately assigned tanks for each material.

Prior to transfer to the impregnating tank, the fluid to be used is heated in its steam-jacketed storage tank where it is kept under vacuum. During this heating period, the fluid is agitated in order to maintain a uniform temperature.

In the center of each of the steam-jacketed vacuum and pressure impregnating tanks is a steam-jacketed cylinder of slightly smaller diameter than the hollow drum of the impregnating tanks. This reduces the amount of fluid subjected to heat during each impregnating cycle. Over the top of this cylinder, a large, circular baffle plate is mounted. When the fluid is admitted into the tank, it strikes this baffle where it forms a thin film. This affords an opportunity to subject the fluid to a second degassing treatment.

The impregnating of the paper can be considered to take place in two steps. First the fluid travels back and forth between the tapes from the outside of the insulation towards the conductor. This is best accomplished by applying vacuum. Second, the fluid penetrates into the fibers of the individual paper tapes. This is accomplished by using pressure.

5.6 Conditioning the Impregnating Fluid

When the fluid is subjected repeatedly to the temperatures used in impregnating, it gradually loses many of its desirable properties. A plant to condition the fluid is frequently installed at the factory to ensure uniform quality fluid. Each of the vacuum operations is performed under a vacuum of one millimeter of absolute pressure. The proper temperatures for each operation are maintained by automatically controlled electric heaters. By the use of this equipment, the fluid is maintained at all times at a quality equal to that of the new fluid. This, together with the impregnating control, results in cables of uniform quality.

5.7 Control of Impregnation

In the manufacturing of solid-type paper insulated cables, the general practice is to regulate the drying and impregnating process by setting up standard periods of time for each operation. Slight modifications are made for the particular size and type of cable to be treated.

Due to the inherent variations in materials and manufacturing, dielectric measurements are made on the cable undergoing drying and impregnation. This control consists of periodic readings, giving an accurate measure of temperature and degree of impregnation. This established definite control throughout every step of the impregnating process.

Flexible electrical connections are made between the ends of the cable and the permanent terminals on the tank as the cable is placed in the tank.

The conductor resistance is converted to conductor temperature. Knowing the viscosity-temperature characteristics of the fluid, these combined data effect a control of the impregnating ability of the fluid. Dryness is determined by the constancy of the ac capacitance values. Thorough saturation is determined by the change in ac capacitance. Complete cooling is determined from the conductor temperature measurements.

5.8 Control of the Cooling Cycle

Uniform cooling at a defined rate produces high quality paper insulated cable. To accomplish this, a large refrigeration plant can be installed as part of the impregnating system. This enables the mill to cool the impregnated cables at a prescribed rate independent of the water supply temperature.

The cooling is brought into use after the impregnation cycle is completed. The temperature of the entire tank is reduced under this controlled cycle to room temperature. This is a gradual reduction that is made while the cable is still in the sealed tank. The seal is then broken and the cables, coated with a thick layer of fluid, are transferred to the lead press, or other sheathing process.

The lead presses that were used for most medium voltage cables in the past, could extrude lead under pressures of 3,000 tons. A lead charge of up to 2,000 pounds was placed in a melting kettle located adjacent to each press. The advantage of a large charge was that fewer stops had to be made. This stop could last for several minutes and for all of that time the cable in the die-block was subjected to high temperatures. Continuous extrusion techniques were also developed.

The melting kettle had automatic temperature control to keep the lead at the proper, molten state. An agitator was used to keep the metal stirred so there was no separation in the mix. Means were provided to removing dross (oxidized lead) from the top of the molten mass. Over the lead, an atmosphere of in inert gas, such as carbon dioxide or nitrogen, could be used to reduce the formation of oxides.

The lead sheathing process takes the impregnated cables through a steel die-block attached to the cylinder of the press. The die-block has a core tube having a diameter just large enough to receive the cable core and a die having an outer diameter of the sheath diameter. Pressure is exerted on the lead in its plastic state by a hydraulic ram or piston. The lead is extruded at temperatures of about 375 to 400 ^{0}F from the cylinder into the die-block and around the outer portion of the core tube. The lead is squeezed down over the cable to form a thick, continuous, homogeneous sheath. Pressure behind the lead tube forces the cable through the die-block.

When the cylinder is charged, it is overflowed and the exposed lead is allowed to congeal. The exposed lead is then skimmed off level with the cylinder by means of a mechanical guillotine or cropping device that removes all traces of oxide. The hydraulic ram, having a rounded nose, is then immediately brought down onto the surface of the skimmed surface of the lead.

The press is started and a quantity of lead pipe is extruded and checked to make sure the crystalline structure, welds, and ductility are satisfactory. After the cable is started through the press, a sample of lead sheathed cable is cut off and concentricity checked. As the cable leaves the die-block, it is water cooled and either given a jacket or a coating of grease, as required.

The discontinuous type of extrusion presses with vertical rams and containers that had to be filled with liquid lead were largely replaced by continuous extrusion machines. The screw of these machines is vertical and lead is fed from the bottom end from a reservoir of lead. The extrusion temperature is about 300°C.

6. FACTORY TESTING

6.1 Electrical Tests for 100% Inspection

The Insulated Cable Engineers Association (ICEA) recognizes three alternative test methods for electrical testing of secondary cables (up to 1,000 volts phase-to-phase).

6.1.1 ac Spark Test. The cable conductor is grounded. The covered / insulated cable surface is passed through a close network of metallic bead chains or similar contact electrode. The electrodes are at an ac voltage potential selected on the basis of the type and thickness of the covering. In the event of a pinhole, skip, or other sufficiently weak spot (electrically speaking), a fault to the grounded conductor occurs. The fault triggers an alarm such that the operator can mark the fault for removal or repair.

6.1.2 dc Spark Test. This is similar to the ac spark test except direct current, higher potential values, and continuous circular electrodes are used.

6.1.3. Alternating Current Water Tank Test. The entire reel of finished cable is immersed in a water tank with only the cable ends protruding above the water. After a soak period to insure that water has permeated the entire reel of cable, the cable conductors are energized at an ac voltage level that is dependent on material type and thickness. The test voltage is applied for five minutes. The water acts as a ground and during the soak period it is hoped that water infiltrates in to any damage, pinhole, or electrically weak areas.

6.1.4. Insulation Resistance Test. For most modern insulations, this test is meaningless, but persists in industry standards. In connection with the water tank test above and while still immersed, a bridge is used to read the insulation resistance. For modern insulations, the readings are so high that "apparent" differences, even though possibly huge, are meaningless and dependent on numerous factors unrelated to the insulation resistance.

6.2 Testing Medium Voltage Cables.

The tests described under Section 6.1 are also applicable to medium voltage cables. These tests are generally conducted in a dry environment on finished cables.

Unique to medium and higher voltage cables is the partial discharge test. AEIC requires that such cables be subjected to a partial discharge while on the shipping reel.

The cable must be allowed to "rest" after manufacturing to allow any pressures that were developed during manufacturing to escape. It must be performed prior to the ac voltage test. Alternating current voltage is raised to an established level that is approximately four times operating voltage. The voltage is lowered while the partial discharge level in picocolombs is recorded.

Corona testing is extremely sensitive to defects in the cable as well as external electrical interference. Shielded rooms are provided to minimize this external noise.

7. · REFERENCES

[10-1] Carl Landinger, Adapted from class notes for "Power Cable Engineering Clinic," University of Wisconsin -- Madison, 1997.

[10-2] L. J. Kelly, Adapted from class notes for "Power Cable Engineering Clinic," University of Wisconsin -- Madison, 1995.

CHAPTER 11

CABLE INSTALLATION

James D. Medek and William A. Thue

1. INTRODUCTION

Thomas A. Edison installed his earliest cables in New York City in 1882. The cables were placed in iron pipes in the factory and then were spliced together in the field every 20 feet in an egg-shaped splice casing. Other systems, such as by Brooks, Callender, and Crompton, were installed by 1885 where they also used short sections of iron conduit. American Bell Telephone Company installed the first flexible communication cables in 1882 and 1883 where cables were pulled into the conduit in the field. "Pumplogs" were first used for water supply lines, but were used in 1883 in Washington, DC, for telegraph cables. Tree logs were hollowed out, the exterior was trimmed to make them square, and the entire log was treated with creosote. These became the conduits of choice! So began the duct and manhole systems with the need to pull cables.

The *Underground Systems Reference Book* [11-1] of 1931 stated that "It is necessary to inquire into the harmful effects of the pulling stress on the cable insulation. The conclusion that has been reached, based on tests and experience, is that satisfactory operation of the cable is assured, provided that it has suffered no mechanical injury." It was recommended that a coefficient of friction between 0.40 and 0.75 should be used and that the total tension should be limited to 10,000 pounds. Little other advice was offered.

Significant advances were made in the understanding of cable pulling calculations with the 1949 paper by Buller [11-2] and the 1953 work of Rifenberg [11-3]. These papers provide the basic data for making cable pulls in all situations encountered in the field. They provide excellent quantitative data when used to calculate pulling tensions.

Even in the 1957 version of the *Underground Systems Reference Book* [11-4], there was little additional guidance given for such an important consideration as sidewall bearing pressure for distribution type cables. It was generally felt that 100 pounds per foot was acceptable. Later this was increased to 300 pounds per foot with no test work to support that value. Experience was still relied upon and 300 pounds met that criteria. A 400 pound per foot value was given for pipe type cables.

Since the runs were relatively straight and short, this didn't pose a problem until the 1970s. Nuclear power plants had long pulls, many bends, and large cables. Many pulls exceeded that comfortable level established over the years.

Pipe-type cable systems pointed the way to the importance of accurate tension calculations. Here the avoidance of a splice could impact the cost of the system very significantly. Rifenburg's work [11-3] included all the necessary options, but the allowable sidewall bearing pressure needed to be evaluated since the somewhat arbitrary value of 400 pounds had not actually been tested in a laboratory environment. The understanding of the need for such information led to the project for "Increasing Pipe Cable Section Lengths," EPRI Final Report EL-2847, March 1983 [11-5].

A significant increase in understanding about cable pulls was reached with the completion of EPRI Final Report, EL-3333, "Maximum Safe Pulling Lengths for Solid Dielectric Insulated Cables," February 1984 [11-6]. A discussion of the results of these and other test work will be described below.

2.0 DISCUSSION OF CABLE PULLS

Cable manufacturers have handbooks in print that describe methods of making safe cable pulls and for making the necessary calculations of pulling tensions. Pull programs are available from suppliers of cable pulling compounds. Cable pull programs are available from EPRI [11-7]. There are many cable manufacturers, utilities, architect-engineering firms, and pulling equipment companies that also have programs.

An entirely new group of cable pulling compounds have become available since the EPRI project. They are able to achieve the very low coefficients of friction that their literature suggests -- generally these lower values are for the higher sidewall bearing pressures that are found in the field and in the newer test procedures.

2.1 Maximum Allowable Tension on Conductors

The maximum allowable tension on cable conductors that should be used during pulls must be based on experience as well as good engineering. Factors that have an impact on the value include type of metal, temper, and factors of safety. The limits have been set based on only the central conductor of the cable or cables. This quickly establishes one of the safety factors, because all of the components of a cable provide some mechanical strength.

One obvious limit is to consider the mechanical stress level at which the conductor will permanently deform/stretch. Upper limits have generally been set well below the elongation value of the conductor metal. The classic approach has been to use the values shown in Table 11-1, but the spread in values shown below represent present-day data from suppliers. Even higher values have been recommended and published by AEIC [11-7].

Table 11-1
Maximum Allowable Pulling Tension on Conductors

Metal	Temper	Pounds per cmil
Copper	Soft (annealed)	0.008
Aluminum	Hard	0.008
Aluminum	¾ Hard	0.006 to 0.008
Aluminum	½ Hard	0.003 to 0.004
Aluminum	Soft	0.002 to 0.004

2.2 Pulling Tension Calculations

The concept of the significant factors in a cable pull can be appreciated by looking at the equation for pulling a single cable in a straight, horizontal duct. The basic equation is:

$$T = W x L x f \tag{11.1}$$

where T = Tension in pounds
W = Weight of one foot of cable in pounds
L = Length of pull in feet
f = Coefficient of friction for the particular duct material and outer layer of the cable.

It is obvious that the weight of the cable and the length of the pull can be determined with great accuracy. The one thing that varies tremendously is the value of the coefficient of friction -- it can vary from 0.05 to 1.0. In test conditions, values as high as 1.2 have been recorded! Even when the materials used in the duct and jacket are known, the type and amount of lubricant can be an important factor in this variation.

The significance of this is that the accuracy of the calculation can't come out to six decimal places even if you have a calculator or computer with that many places! It is also not wise to argue whether one method of tension calculation can attain an accuracy of one percent better than another when one considers the probable inaccuracy of the coefficient of friction.

2.3 Coefficient of Friction

Since this is a significant variable in all calculations, let's look at this early in the discussion of cable pulling. What do we mean by "coefficient of friction?" Historically the test apparatus for friction determination consisted of a section of duct that was cut longitudinally in half. The open duct was mounted on an inclined plane. A short sample of cable was placed near the top end and the angle of incline was increased until the cable started to move as the result of gravity. Using the angle at which movement began, the static coefficient of friction was calculated. Generally the angle of incline could be decreased and the cable would maintain its slide. Using this second angle, the dynamic coefficient of friction was obtained.

As described above, many of the earlier publications suggested that the coefficient of friction that should be used varied from 0.40 to 1.0. This was, of course, very safe for most situations.

The EPRI project, [11-6], demonstrated that there were other important issues that needed to be established in making accurate determinations of the coefficient of friction such as the level of sidewall bearing pressure. This force is duplicated in present day test methods by applying a force that pushes the cable down on the conduit. The interesting fact is that this actually reduces the coefficient of friction in most instances! The quantity and type of lubricant are important. Too much lubricant can increase the friction. A more viscous lubricant should be used with heavier cables, etc.

2.4 Sidewall Bearing Pressure (SWBP)

When one or more cables are pulled around a bend or sheaves, the tension on the cable produces a force that tends to flatten the cable against the surface. This force is expressed in terms of the tension out of the bend in pounds divided by the bend radius in feet.

$$SWBP = T_O / R \tag{11.2}$$

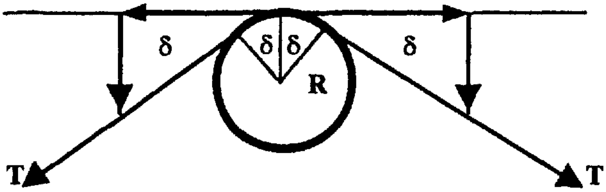
where $SWBP$ = Force in pounds per foot
T_O = Tension coming out of the bend in pounds
R = Radius of the inside of the bend in feet

SWBP is not truly a unit of pressure, but rather a unit of force for a unit of length. In the case of a smooth set of sheaves or bend, the unit is the entire length of contact. However, any irregularity, such as a bump on the surface, or a small radius sheave with limited bearing surface (even though it may be part of a multi-sheave arrangement), reduces the effective bearing surface length. This must be taken into account in the calculation to prevent damage to the cable.

For multiple cables in a duct, the matter is complicated because of the fact that the sidewall bearing pressure is not equally divided among the cables. This situation is taken into account by using the weight correction factor that will be discussed later in this chapter.

Figure 11-1 shows the mathematical derivation for a horizontal bend of one cable -- ignoring the weight of the cable. As the angle approaches zero, the force between the cable and the bend approaches unity.

Figure 11-1
Pulling Forces in Horizontal Bend



The force per unit length $= \dfrac{2T\sin\delta}{2R\delta}$ (11.3)

where $\sin\delta = \delta$ for small angles

and sidewall pressure, $T/R = \dfrac{2T\sin\delta}{2R\delta}$ (11.4)

The T / R ratio is independent of the angular change of direction produced by the bend. It depends entirely on the tension out of the bend and the bend radius with the effective bend radius taken as the inside of the bend. Increasing the radius of the bend obviously decreases the SWBP.

Sidewall bearing pressure limits that have been used historically are shown in Table 11-2. As with maximum pulling tension values, AEIC [11-7] has published limits that exceed the values shown in this table.

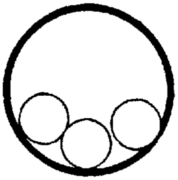
Table 11-2
Sidewall Bearing Pressure Limits

Cable Type	**SWBP in Pounds per Foot**
Instrumentation	100
600 V non-shielded control	300
600 V power	500
5 to 15 kV shielded power	500
25 to 46 kV power	300
Interlocked Armored	300
Pipe-type	1,000

2.5 Pulling Multiple Cables in a Duct or Conduit

2.5.1 Cradled Configuration. A frequent requirement is to pull three cables into one duct. This brings the relative diameters of the cables into play with the inner diameter of the duct. If the cables are relatively small as compared with the duct diameter, the cables are said to be "cradled."

Figure 11-2
Cradled Cables



The outer two cables push in on the center cable, making it seem to be heavier than it actually is.

The pulling calculation handles this by using a "weight correction factor" that increases the apparent weight of that center cable.

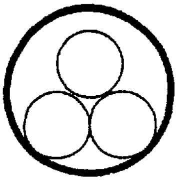
The sidewall bearing pressure (SWBP) on the center cable in Figure 11-2 is influenced by the other two cables. The effective SWBP for the cradled configuration may be calculated from:

$$SWBP = [(3\,W_C - 2)/3]\,T_O/R \qquad (11.5)$$

See equations 11.2 and 11.7 for definitions of terms.

2.5.2 Triangular Configuration. When the diameter of each of the three cables is closer to one-third that of the inner diameter of the duct, the situation is known as a "triangular" configuration.

Figure 11-3
Triangular Arrangement



In this situation, the top cable is riding on the two lower cables without touching the duct wall.

The effect of this is that the one cable effectively increases the weight of the two lower cables, but does not function as a longitudinal tension member. This means that one must use the cross-sectional area of only two of the cables in the maximum allowable tension determination in this example, not three cables.

The sidewall bearing pressure on the two lower cables in Figure 11-3 is influenced by the upper cable. The effective SWBP for the triangular configuration may be calculated from:

$$SWBP = W_C \, T_O / 2R \tag{11.6}$$

The units are defined in Equations 11.2 and 11.7.

2.5.3 Weight Correction Factor. When two or more cables are installed in a duct or conduit, the sum of the forces developed between the cables and the conduit is greater than the sum of the cable weights.

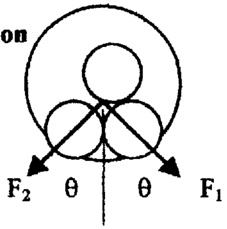
Weight correction factor is therefore defined as:

$$W_C = \Sigma F / \Sigma W \tag{11.7}$$

where W_C = Weight correction factor (also merely "c")
ΣF = Force between cable and conduit, usually in pounds
ΣW = Weight of the cable with same units as above

The mechanism for this relationship is shown in Figure 11-4 as:

Figure 11-4
Weight Correction



For the typical case of three cables of equal diameter and weights in a conduit of given size, the weight correction factor is higher for the cradled configuration than the triangular configuration.

Table 11-3
Weight Correction Factors

Configuration of Three Cables	Weight Correction Factor
Triangular	1.222
Cradled	1.441

It is always safer to anticipate the cradled configuration unless the cables are triplexed or if the clearance is near the 0.5 inch minimum.

The equations for calculating the weight correction factor are:

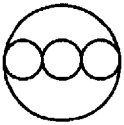
Cradled: $$W_C = 1 + 4/3\,(d/D-d)^2 \qquad (11.8)$$

Triangular: $$W_C = \frac{1}{1 - [(d/D-d)^2]^{1/2}} \qquad (11.9)$$

where
D = Diameter of inside of conduit
d = Diameter of each cable

2.5.4 Jamming of Cables. When the diameter of each cable is about one-third the inner diameter of the duct, a situation may occur where the cables may jam against the inside of the conduit. This generally occurs when the cables go around a bend or a series of bends. The "center" cable may try to pass between the outer two cables. When the sum of the diameters of the three cables is just slightly larger than the inner diameter of the duct, jamming can occur. Jamming increases the pulling tension many fold and can result in damaging the cable or even pulling cables in two, breaking pull irons in manholes, etc.

Figure 11-5
Cable Jamming



The condition that causes jamming for three cables in a conduit.

The "jam ratio" of the cables in this duct needs to be evaluated. The equation for finding the jam ratio of three cables in a duct may be determined by:

$$\text{Jam Ratio} = 1.05 \text{ x } D_d / D_c \qquad (11.10)$$

where D_d = Inside diameter of the duct or conduit
D_c = Outer diameter of each of the three cables

The factor of 1.05 has been used to account for the probable ovality of the conduit in a bend and to account for the cable having a slightly different diameter at any point. If precise dimensions are known, this 5% factor can be eliminated.

Where the jam ratio falls between 2.6 and 3.2, jamming is probable if there are bends in the run and unless other precautions are taken. To avoid any problems with jamming, it is wise to avoid pulls where the ratio is between 2.6 and 3.2.

How can jamming be avoided even though the calculation shows that the ratio indicates a significant probability of jamming? There are several solutions, some of which are obviously possible during the planning stages and some that are possible during the installation stage.

- ☐ Use a different size of cable or conduit to change the ratio.
- ☐ Have the cable triplexed (twisted together) at the factory.
- ☐ Tie the cables together in the field with straps.
- ☐ Use precautions at the feed point to keep a triangular configuration and allow no crossovers.

The National Electric Code, ANSI C-1, requires that the total fill of a conduit be 40% or less for three cables in a conduit. This means that the cross-sectional area of all three of the cables cannot be more than 40% of the cross-sectional area of the conduit. Unfortunately, for 40% fill, the jam ratio is 2.74, which is in the lower danger ratio. An example of this situation is when three 1.095 inch diameter cables are installed in a conduit with an inside diameter of exactly 3.0 inches. (The actual inside diameter of a nominal 3 inch conduit is 3.068 inches!)

If the designer tries to reduce the fill to say 38% to stay safely within the 40% limit, the jam ratio gets worse – 2.81.

Utility practices generally are not governed by the NEC, hence clearance limits are not based on percent fill. Utility practice considers that 0.5 inches of clearance is satisfactory for general pulls. Clearances as small as 0.25 inches have been successfully made when good engineering practices and careful field supervision are employed [11-7].

To complete this discussion of jam ratio, it is important to know that jamming can occur when more than three cables are installed in a conduit. A modification of the equation is necessary as shown:

$$\frac{3D}{n_1 d_1 + n_2 d_2 + n_3 d_3 + n_4 d_4 + \ldots\ldots} \tag{11.11}$$

where D = Conduit inner diameter (ID)
$n_1, n_2, n_3,$ = number of cables of diameter 1, 2, 3, etc.
$d_1, {}_2d, d_3,$ = diameters of cables in groups 1, 2, 3, etc.

Theoretically any combination of cable diameters that fall in the critical zone can jam. Field experience has shown that the probability of jamming decreases as the number of cables increases.

2.5.5 Clearance. Another consideration before cables are placed in a conduit is the amount of clearance between the cable or cables and the inside of the conduit. This may be quickly seen in the example of the three cables in a triangular configuration in Figure 11-1. The distance from the top cable to the inside "top" of the conduit is defined as the clearance.

3. PULLING CALCULATIONS

The previous sections have presented some of the fundamentals of pulling cables. Now let's see how those factors, plus a few more, come together when we actually calculate the tension on a cable or cables that are to be installed.

3.1 Tension Out of a Horizontal Bend

Bends in cable runs are a fact of life. The important point is that the friction and sidewall bearing pressure around that bend increase the tension coming out of the bend in respect to the tension on the cable coming into the bend.

$$T_O = T_{IN}\ e^{cfa} \tag{11.12}$$

where T_O = Tension going out of the bend
T_{IN} = Tension coming into the bend
c = Weight correction factor
f = Coefficient of friction
a = Angular change of direction in radians

This is a simplified equation that ignores the weight of the cable. It is sufficiently accurate where the incoming tension at the bend is equal to or greater than ten times the product of the cable weight per foot times the bend radius expressed in feet. The practical situation where T_{IN} is less than ten times the product of the weight and radius is where the cable is being fed at low tension into a large radius bend [11-8]. In such a case, the equation becomes:

$$T_O = T_{IN}\left[\frac{e^{cfa} + e^{-cfa}}{2}\right] + \left[(T_{IN})^2 + (w\,r)^2\right]^{1/2}\left[\frac{e^{cfa} - e^{-cfa}}{2}\right] \tag{11.13}$$

In order to fully appreciate the effect of the impact of the exponent of e, cfa, Table 11-4 shows the multiplier of the tension for various values of the exponent.

Table 11-4
Multiplier of Tension in Values for Various Exponents

cfa	45 Degree Bend	90 Degree Bend
0.1	1.08	1.17
0.2	1.17	1.37
0.3	1.27	1.60
0.4	1.48	2.19
0.5	1.60	2.56

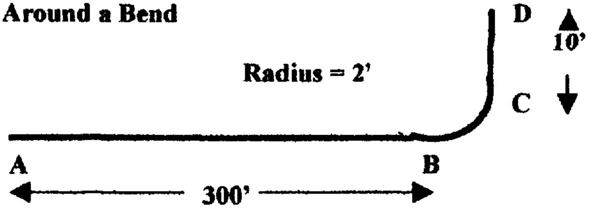
It is essential to remember that the exponent of e has three terms: weight correction factor, coefficient of friction, and angle of deflection. Sometimes this exponent is shown only as two factors because of limitations of older computer programs. In order to make that workable when multiple cables are installed, it is necessary to multiply the selected coefficient of friction by the weight correction factor. If you therefore have a situation where three cables will be cradled, for instance, the cfa value (from Table 11-4) is 1.442 times the coefficient of friction. Putting this another way, if you consider the proper coefficient of friction to be 0.2, and the cables will be in a cradled configuration, you must use a cfa value of 0.3. If there is only one cable, this means that you would use the 0.2 value of cfa for that same coefficient of friction since W_C for one cable is unity.

A large number of bends in a run can literally multiply the tension exponentially! This is one of the reasons that many installation practices keep the number of 90 ^{0} bends to a maximum of three or four.

3.2 Which Direction to Pull?

There are always two possible directions that a cable can be pulled for any run -- just as a cable always has two ends. Let us go through the calculations of an example that has one bend so that we can see how the pulling tension can vary.

Figure 11-6
Pulling Around a Bend



Given: 1 x 1,000 kcmil copper cable
Weight of cable = 6 pounds per foot
Coefficient of friction = 0.5

Pulling from A to D:

Tension at A = 0
Tension at B = 300 x 6 x 0.5 = 900 pounds
$e^{cfa} = e^{1 \times 0.5 \times 1.5708} = 2.713^{0.7854} = 2.19$
Tension at C = 900 x 2.19 = 1,971 pounds
Tension at D = -10 x 6 x 0.5 + 1,971 = 30 + 1,971 = 2,001

This exceeds the long established 1,000 pound limit for a pulling grip, so this must be pulled with a pulling eye on the conductor. The established limit for a 1,000 kcmil copper conductor is based on the conductor kcmils multiplied by 0.008, or 8,000 pounds.

The maximum allowable tension coming out of the bend at point C results in a sidewall bearing pressure of 1,971 / 2, or 985.5 pounds per foot which is above the value generally agreed to by the manufacturers.

Pulling from D to A:

Tension at D = 0
Tension at C = 10 x 6 x 0.5 = 30 pounds
e^{cfa} = $e^{1 \times 0.5 \times 1.5708}$ = $2.713^{0.7854}$ = 2.19
Tension at B = 2.19 x 30 = 65.7 pounds
Tension at A = 300 x 6 x 0.5 + 65.7 = 965.7 pounds

This is satisfactory in all respects. The total tension does not exceed 1,000 pounds and the tension coming out of the bend is well below accepted levels. A cable grip may be used to pull the cable from D to A.

From this example, it can be seen that it is always preferable to set up the reel as close to the bend as possible.

4. CABLE INSTALLATION RESEARCH

Pipe type cable pulling was addressed by EPRI in Final Report EL-2847, March 1983, entitled "Increasing Pipe Cable Section Lengths" [11-5]. Sidewall bearing pressures of up to 1,000 pounds per foot were recommneded.

The fact that the suggested values for pulling tension and related considerations of extruded distribution cables had developed only from an understanding of past successful pulls made it seem reasonable to look at extruded dielectric cables using laboratory and field generated data. EPRI undertook Research Project 1519 in the late 1970s. The work was published as Final Report EL 3333 [11-6] in March 1983. Additional insight into pulling considerations was accomplished through the publication of AEIC G5-90 [11-7], *Underground Extruded Power Cable Pulling Guide*, in May 1990.

The values of sidewall bearing pressure, allowable maximum tension on the conductors, and maximum allowable tension on a pulling basket, are much less conservative than the level generally accepted by cable manufacturers.

Since there are obvious advantages for a utility to make longer pulls based on this data, a good deal of caution and education is necessary.

4.1 Research Results

Before reviewing the results, a few words of caution are needed. Field conditions are seldom ideal. The actual installation may not go as smoothly as was planned. For instance, when one believes that the cable may be pulled in one continuous motion, the actual pull may be made in a series of starts and stops. This alters the coefficient of friction because of the unplanned start, with the cable probably already far into the duct. When one anticipates excellent lubrication, the amount of lubrication may be more or even less than that planned. Therefore,

- **Don't blindly use these values to their upper limits.**
- **Be conservative.**
- **Follow the cable manufacturer's recommendations.**

The most dramatic findings of this research project over previously accepted values were:

- ○ Pulling tension on both copper and aluminum conductors was about 50% greater than older limits.
- ○ Allowable sidewall bearing pressure was as much as 200% greater than previously recommended.
- ○ Coefficient of friction was about 50% lower -- with values as low as 0.05.
- ○ Basket grips could be used to pull 10 times (or more) the force previously recommended as long as tension limits on the conductor are not exceeded.

5. REFERENCES

[11-1] *Underground Systems Reference Book*, NELA, 1931.

[11-2] Buller, F. H., "Pulling Tension During Cable Installation in Ducts or Pipes," General Electric Review, Schenectady, NY; Volume 52, No. 8, August, 1949, pp. 21-33.

[11-3] Rifenberg, R. C., "Pipe-line Design for Pipe-type Feeders," AIEE Transactions on Power Apparatus and Systems, Vol. 72, Part III, December 1953.

[11-4] *Underground Systems Reference Book*, EEI, 1957.

[11-5] "Increasing Pipe Cable Section Lengths," EPRI Final Report EL-2847, March 1983.

[11-6] "Maximum Safe Pulling Lengths for Solid Dielectric Insulated Cables," EPRI Final Report EL-3333, February 1984.

[11-7] *Underground Extruded Power Cable Pulling Guide,* AEIC G5-90, May, 1990.

[11-8] Kommers, T. A., "Electric Cable Installation in Raceways," Pulp and Paper Industry Technical Conference, Portland, Oregon, June 1980.

CHAPTER 12

SPLICING, TERMINATING, AND ACCESSORIES

Theodore A. Balaska and James D. Medek

1. INTRODUCTION [12-1, 12-2, 12-3]

A fundamental concept that needs to be established early in this chapter is that when they are used here a "splice" and "joint" are one and the same! "Cable Splicers" have been around for about 100 years, but officially in IEEE Standards, when you join two cable ends together, you make a joint.

The basic dielectric theory that has been previously described for cable in Chapter 2 also applies to joints and terminations. Some repetition of those concepts may be presented so that this will be a stand alone treatment and some repetition is constructive.

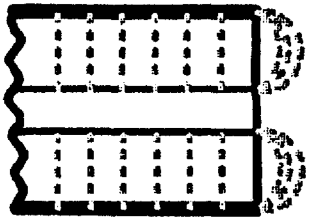
This chapter will address the design, application, and preparation of cables that are to be terminated or spliced together. The application of this material will cover medium voltage cable systems in particular with higher and lower voltage application being mentioned in particular designs and applications. The field theory described in Chapter 2 lays the foundation for the theory utilized in the design and construction of joints and terminations.

2. TERMINATION THEORY

A termination is a way of preparing the end of a cable to provide adequate electrical and mechanical properties. A discussion of the dielectric field at a cable termination serves as an excellent introduction to this subject.

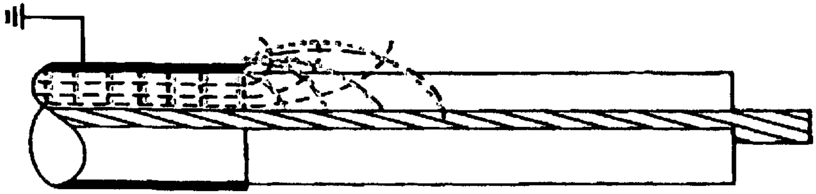
Whenever a medium or high voltage cable with an insulation shield is cut, the end of the cable must be terminated so as to withstand the electrical stress concentration that is developed when the geometry of the cable has changed. Previously the electrical stress was described as lines of equal length and spacing between the conductor shield and the insulation shield. As long as the cable maintains the same physical dimensions, the electrical stress will remain consistent. When the cable is cut, the shield ends abruptly and the insulation changes from that in the cable to air. The concentration of electric stress is now in the form of Figure 12-1 with the stress concentrating at the conductor and insulation shield.

Figure 12-1
Electrical Stress Field, Cut End



In order to reduce the electrical stress at the end of the cable, the insulation shield is removed for a sufficient distance to provide the adequate leakage distance between the conductor and the shield. The distance is dependent on the voltage involved as well as the anticipated environmental conditions. The removal of the shield disrupts the coaxial electrode structure of the cable. In most cases, the resulting stresses are high enough that they cause dielectric degradation of the materials at the edge of the shield unless steps are taken to reduce that stress.

Figure 12-2
Electrical Stress Field, Shield Removed



In this operation, the stress at the conductor is relieved by spreading it over a distance. The stress at the insulation shield remains great since the electrical stress lines converge at the end of the shield as seen in Figure 12-2. The equipotential lines are very closely spaced at the shield edge. If those stresses are not reduced, partial discharge may occur with even the possibility of visible corona. Obviously, some relief is required in most medium voltage applications.

2.1 Termination with Simple Stress Relief

To produce a termination of acceptable quality for long life, it is necessary to relieve voltage stresses at the edge of the cable insulation shield. The conventional method of doing this has been with a stress cone.

A stress cone increases the spacing from the conductor to the end of the shield. This spreads out the electrical lines of stress as well as providing additional insulation at this high stress area. The ground plane gradually moves away from the conductor and spreads out the dielectric field -- thus reducing the voltage stress per unit length. The stress relief cone is an extension of the cable insulation. Another way of saying this is the electrostatic flux lines are not concentrated at the shield edge as they are in Figure 12-2. It follows that the equi-potential lines are spaced farther apart.

Terminations that are taped achieve this increase in spacing by taping a conical configuration of tape followed by a conducting layer that is connected electrically to the insulation shield as in Figure 12-3. When stress cones are pre molded at a factory, they achieve the same result with the concept built into the unit.

Figure 12-3
Leakage Path

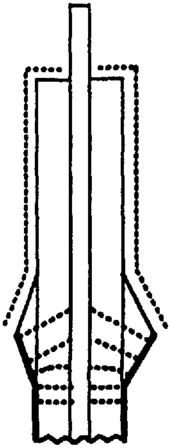
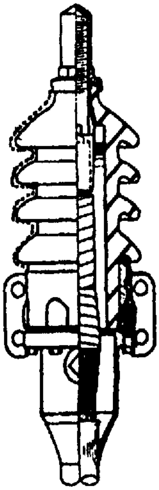


Figure 12-4
Leakage Path

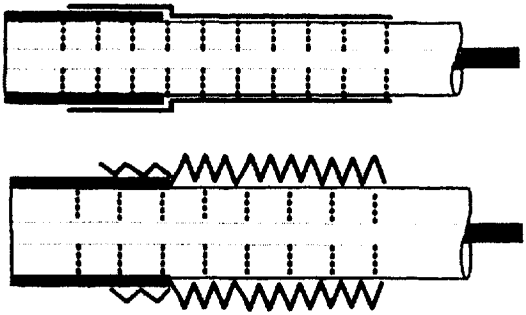


When additional leakage distance over the insulation is required, skirts can be placed between the conductor and insulation shield. These skirts can be built into the termination as shown in Figure 12-4 or added in a separate field assembly operation.

2.2 Voltage Gradient Terminations

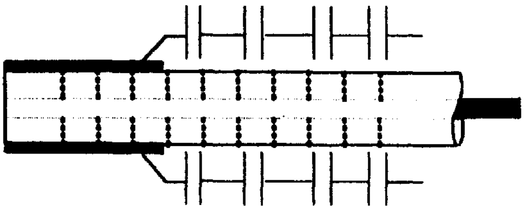
Electrical stress relief may come in different forms. A high permativity material may be applied over the cable end as shown in Figure 12-5. This material may be represented as a long resistor connected electrically to the insulation shield of the cable. By having this long resistor in cylindrical form extending past the shield system of the cable, the electrical stress is distributed along the length of the tube. Stress relief is thus accomplished by utilizing a material having a controlled resistance or capacitance. Other techniques may be employed, but the basic concept is to utilize a material with say a very high resistance or specific dielectric constant to extend the lines of stress away from the cable shield edge.

Figure 12-5
Stress Cones Using High Dielectric Constant and High Resistivity Materials



An application of a series of capacitors for stress control is frequently used on high and extra high voltage terminations. These specially formed capacitors are used to provide the stress relief. The capacitors are connected in series, as shown in Figure 12-6, and distribute the voltage in a manner that is similar to the high permativity material that was discussed previously.

Figure 12-6
Capacitive Graded Stress Cone



3.0 TERMINATION DESIGN

3.1 Stress Cone Design

The classic approach to the design of a stress relief cone is to have the initial angle of the cone to be nearly zero degrees and take a logarithmic curve throughout its length. This provides the ideal solution, but was not usually needed for the generous dimensions used in medium voltage cables. There is such a very little difference between a straight slope and a logarithmic curve for medium voltage cables that, for hand build-ups, a straight slope is completely adequate.

In actual practice, the departure angle is in the range of 3 to 7 degrees. The diameter of the cone at its greatest dimension has generally been calculated by adding twice the insulation thickness to the diameter of the insulated cable at the edge of the shield.

3.2 Voltage Gradient Design

Capacitive graded materials usually contain particles of silicon carbide, aluminum oxide, or iron oxide. Although they are not truly conductive, they become electronic semi-conductors when properly compounded. They do not have a linear E = IR relationship, but rather have the unique ability to produce a voltage gradient along their length when potential differences exist across their length. This voltage gradient does not depend on the IR drop, but on an exchange of electrons from particle to particle.

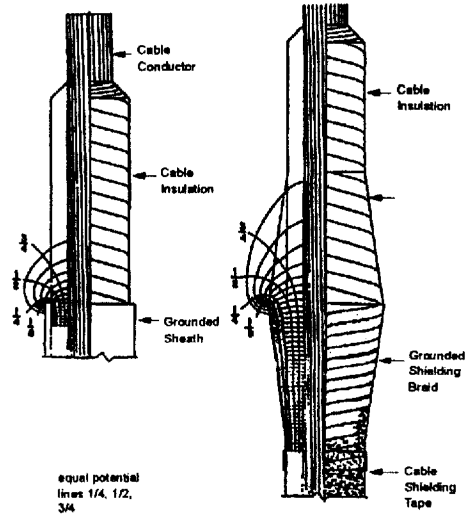
Resistive graded materials contain carbon black, but in proportions that are less than the semiconducting materials used for extruded shields for cable. They also provide a non linear voltage gradient along their length.

By proper selection of materials and proper compounding, these products can produce almost identical stress relief to that of a stress cone. One of their very useful features is that the diameter is not increased to that of a stress cone. This makes them a very valuable tool for use in confined spaces and inside devices such as porcelain housings.

3.3 Paper Insulated Cable Terminations

Cables that are insulated with fluid impregnated paper insulation exhibit the same stress conditions as those with extruded insulations. In the build up of the stress cone, insulating tapes are used to make the conical shape and a copper braid is used to extend the insulation shield over the cone, see Figure 12-7. Similar construction is required on each phase of a three conductor cable as it is terminated.

Figure 12-7
Equal Potential Lines



The field application of installing stress relief on individual phases can be seen in Figure 12-8 and 12-9. The type of termination is consistent on all types of PILC cables whether they are enclosed in a porcelain enclosure, a three conductor terminating device, or inside a switch or transformer compartment.

Figure 12-8
Gas Filled Termination

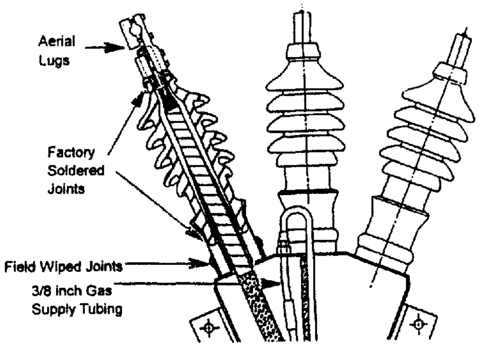
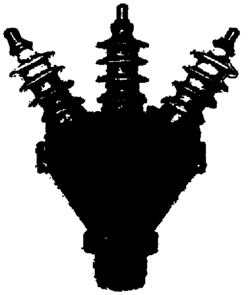


Figure 12-9
PILC Cable Termination



A critical part of the design is the material used to fill the space inside the porcelain or other material that surrounds the paper cable. Since the cable is insulated with a dielectric fluid, it is imperative that the filling compound inside the termination be compatible with the cable's dielectric fluid. In gas filled cable designs, the termination is usually filled with the same gas as the cable, but a dielectric fluid may be used in conjunction with a stop gland.

3.4 Lugs

The electrical connection that is used to connect the cable in a termination to be connected to another electrical device must be considered. Generally called a "lug", this connector must be able to carry the normal and emergency current of the cable, it must provide good mechanical connection in order to keep from coming loose and create a poor electrical connection, and it must seal out water from the cable. The water seal is accomplished by two forms of seals. Common to all terminations is the need to keep water out of the strands. Many early connectors were made of a flattened section of tubing that had no actual sealing mechanism and water could enter along the pressed seam of the tubing. Sealing can be accomplished by filling the space between the insulation cutoff and lug base with a compatible sealant or by purchasing a sealed lug.

The other point that requires sealing is shown in Figure 12-10 that is common to most PILC cable terminations. Here the termination has a seal between the end of the termination and the porcelain body. Another seal that is required is at the end of the termination where the sheath or shield ends. Moisture entering this end could progress along inside of porcelain and result in a failure.

Figure 12-10
Terminal Lug

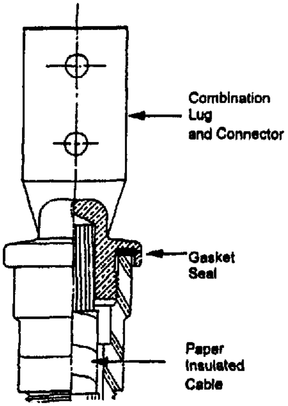
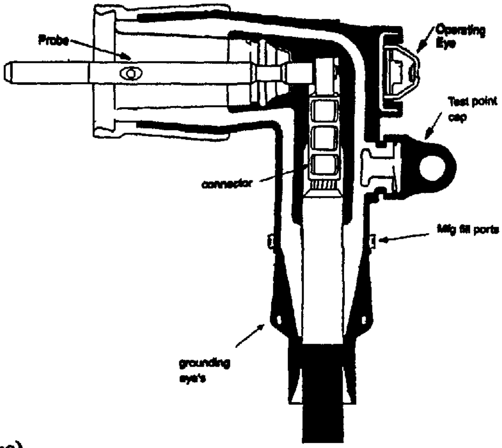


Figure 12-11
Load-break Elbow



3.5 Separable Connectors (Elbows)

One of the most widely used terminations for cables is the "elbow," as it was originally called, but is more properly called a separable connector. It is unique in that it has a grounded surface covering the electrical connection to the device on which it is used. Used as an equipment termination, it provides the connection between the cable and the electrical compartment of a transformer, switch, or other device. Since the outer surface is at ground potential, this type of termination allows personnel to work in close proximity to the termination. Another design feature is the ability to operate the termination as a switch. This may be done while the termination is energized and under electrical load. While elbows are available that cannot be operated electrically, this discussion will deal with the operable type shown in Figure 12-11. This figure shows a cut away of a separable connector followed by a brief description of the parts.

The insulating portion of the elbow is made of ethylene propylene diene monomer (EPDM) rubber with an outer covering of similar material that is loaded with carbon black to make it conductive. The inner semiconducting shields are the same material as the outer semiconducting layer.

Probe: The probe consists of a metallic rod with an arc quenching material at the end that enters the mating part, the bushing. The metallic rod makes the connection between the connector and the bushing receptor. Arc quenching material at the tip of the probe quenches the arc that may be encountered when operating the elbow under energized and loaded switching conditions. A hole in the metallic rod is used with a wire wrench to tighten the probe into the end of the cable connector.

Connector: The connector is attached to the conductor of the cable and provides the current path between the conductor and the metallic probe. It is compressed over the conductor to make a good electrical and mechanical connection. The other end has a threaded hole to accept the threaded end of the probe.

Operating Eye: This provides a place for an operating tool to be attached so that the elbow assembly can be placed or removed from the bushing. It is made of metal today and is molded into the conducting outer layer of the elbow.

Locking Ring: This maintains the body of the elbow in the proper position on the bushing. There is a groove at the end of the bushing into which the locking ring of rubber must fit.

Test Point: Elbows may be manufactured with a test point that allows an approved testing device to determine if the circuit is energized. The test point is in the form of a metallic button that is molded into the elbow body and is simply one plate of a capacitor. It is supplied with a conductive rubber cap that serves to shunt the button to ground during normal service. The molded cap can be removed when the energization test is performed. A second use of the test point is a place to attach a faulted circuit indicator -- a device made for test p[points that may be used to localize a faulted section of circuit for the purpose of reducing the time of circuit outage. When in use, the indicator can remain on the elbow during normal service.

Test Point Cap: Covers and grounds the test point when a test point is specified.

Grounding Eye: This is provided on all molded rubber devices for the purpose of ensuring the outer conductive material stays at ground potential.

Operating / Switching: Load-break elbows are designed to function as a switch on energized circuits. They can safely function on cables carrying up to 200 amperes and are capable of being closed into a possible fault of 10,000 amperes. Since this elbow can be operated while energized, devices are required to keep the internal surfaces free of contamination. Good operating practices call for cleaning the mating surfaces of the bushing and the elbow followed by the application of lubricant -- while both devices are de-energized! Lubricant is also applied when assembling the elbow on the cable. Some manufacturers supply a different lubricant for the two applications and consequently care should be taken that the correct lubricant is used in each application.

4. SPLICING / JOINTING

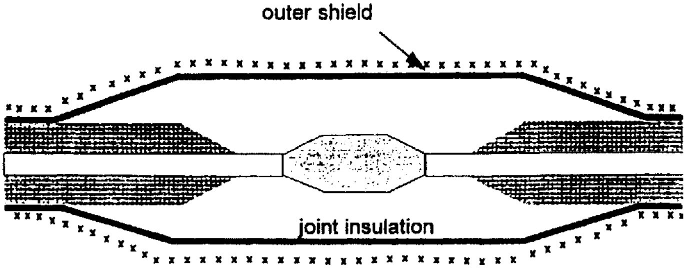
As was mentioned earlier in this chapter, a termination may be considered to be half of a joint. The same concerns for terminations are therefore doubled when it comes to designing and installing a splice.

4.1 Jointing Theory

The ideal joint achieves a balanced match with the electrical, chemical, thermal, and mechanical characteristics of its associated cable. In actual practice, it is not always economically feasible to obtain a perfect match. A close match is certainly one of the objectives.

The splicing or joining of two pieces of cable together can best be visualized as two terminations connected together. The most important deviation, from a theoretical view, between joints and terminations is that joints are more nearly extensions of the cable. The splice simply replaces all of the various components that were made in to a cable at the factory with field components. Both cable ends are prepared in the same manner unless it is a transition joint between say PILC and extruded cables. Instead of two lugs being attached at the center of the splice, a connector is used. At each end of the splice where the cable shielding component has been stopped, electrical stress relief is required just as it was when terminating. Figure 12-12 shows a taped splice and its components.

Figure 12-12
Taped Splice



Connector: Joins the two conductors together and must be mechanically strong and electrically equal to the cable conductor. In this application, the ends of the connector are tapered. This provides two functions: 1) it provides a sloping surface so that the tape can be properly applied and no voids are created, and 2) Sharp edges at the end of the connector are not present to cause electrical stress points.

Penciling: On each cable being joined, you will notice that the cable insulation is "penciled" back. This provides a smooth incline for the tape to be applied evenly and without voids.

Insulation: In this application, rubber tape is used. Tape is applied to form the stress relief cone at each end of the splice. The overlapped tape continues across the connector to the other side. The thickness at the center of the splice is dictated by the voltage rating.

Conducting Layer: Covering the insulation is a layer of conducting rubber tape that is connected to the insulation shield of the cable at both ends of the splice.

Metallic Shield: A flexible braid is applied over the conducting rubber tape and connects to the factory metallic portion of the cable on each end. This provides a ground path for any leakage current that may develop in the conducting tape.

While not shown in this figure, there must be a metallic neutral conductor across the splice. this may be in the form of lead, copper concentric strands, copper tapes, or similar materials. It provides the fault current function of the cable's metallic neutral system.

4.2 Jointing Design and Installation

4.2.1 Cable Preparation. This is the most important step in the entire operation and is the foundation upon which reliable joints and terminations are built. Improperly prepared cable ends provide inherent initiation of failures.

The acceptable tolerances of cable end preparation are dependent upon the methods and materials used to construct the device. Common requirements include a cable insulation surface that is free of contamination, imperfections, and damage caused by such things as shield removal. Smooth surface for extruded dielectric insulations minimizes contamination and moisture adhering to the surface. If the insulation shield can be removed cleanly, there is no reason to use an abrasive on the surface. If a rough surface remains, it must be made smooth.

One of the most critical areas is the edge where the insulation shield is removed. A cut into the insulation cannot be remedied and must be removed. For premolded devices. The edge of the shield must be "square" -- perpendicular to the cable axis. Metallic connections to the metal shield of the cable must not damage the underlying cable components. Cutting into the strands of wire, or even of greater importance, into a solid conductor, can not be tolerated.

The concern about length of the termination is somewhat modified for a joint since the environmental concerns of a termination (external creepage path) are really not a concern for joints. The internal creepage path in a joint is certainly of concern. If you study the literature of the 1950s [11-5], one finds that the internal creepage path for a paper insulated cable operating at 15 kV would be one inch for every 1 kV. When you look at the design of a premolded joint today, you find that the same class of cable has a joint with about one inch of creepage -- TOTAL. Both of those values are correct. Why is there such a difference? The paper cable was joined using hand applied tapes, either of paper or varnished cloth. There was an air path between the two insulating layers, so the one inch per kV was correct. Premolded joints fit very solidly over the cable insulation and uses its elastic pressure to maintain the seal. Experience has shown that the approximate 7 kV per inch is reliable for such joints.

4.2.2 Connecting the Conductors. Cable conductors are generally either copper or aluminum. Copper is a very forgiving metal in a splice and many methods of connecting two copper conductors together are possible: compression, welding, heat- fusion, soldering, (even twisting for overhead conductors 75 years ago), etc. Aluminum connections are not as tolerant. Great care must be taken to match the compression tool, die, and connector with each other for aluminum conductors. As conductor sizes approach 1,000 kcmil, these concerns must be addressed more completely. One of the facts involved in the larger size conductors is that, on utility systems especially, they are the feeder cables are more prone to extended periods of high temperature operation as well as emergency overloads. The operation of the connector must be stable throughout load cycling and be capable of carrying the maximum amount of current without causing thermal degradation of the joint.

The connector metal should be the same as the cable where this is possible. There are situations where this can not be done, such as the case where a copper conductor is to be connected to an aluminum conductor. It is acceptable to use an aluminum connector over a copper conductor, but a copper connector must not be used over an aluminum conductor because during load cycles the relative rates of expansion of the two metals causes the aluminum to extrude out and results in a poor connection.

The shape of the connection is always of importance if the connection is not in a shielded area such as exist in all premolded splices. In order to minimize voltage stress at the connection for all of those other conditions, special connectors are required for medium and higher voltage cables. Tapered shoulders and filled indents are hallmarks of these connectors. Semiconducting layers are generally specified over these connectors.

4.2.3 Insulation for Joints. The material used as the primary insulation in a joint must be completely compatible with the materials in the cable. The wall thickness and its interfaces with the cable insulation must safely withstand the intended electrical stresses. The old rule-of-thumb for paper insulated cables was that you "doubled" the insulation thickness of the cable. In other words, the designs called for putting a layer equal to twice the factory thickness over the cable insulation. In premolded devices today, the thickness is usually about 150% of the factory insulation. The joint insulation for hand taped joints (called self amalgamating tapes) are predominately made from ethylene propylene rubber but were originally made of a butyl or polyethylene base as long as the thermal properties matched the cable insulation. Premolded joints almost always made of ethylene rubber compounds. Heat shrink joints are made of polyolefin compounds that have the property of being expanded after being crosslinked using irradiation. The greater diameter remains until heat is applied to the product as it is in place over the connection.

It is not always a good idea to put on too much insulation. Besides being good electrical insulation, these materials are also good heat barriers. Too much insulation can reduce the ability of the joint to carry the same current as the cable without overheating the center of the joint.

4.2.4 Shield Materials. These materials must be compatible with the rest of the cable as well as having adequate conductance to drain off the electrostatically induced voltages, charging currents, and leakage currents. Electromagnetically induced currents and fault currents must also be safely handled across the joint area.

Joint shields, like cable shields, achieve their ability to perform the task of electrical shielding by having a considerable amount of carbon black (about 30%) compounded into the material. These particles do not actually have to touch each other in order to be conductive.

4.2.5 Jackets for Joints. They must provide physical strength, seal against moisture entry into the splice, and resist chemical and other environmental attacks. It is important to use a jacket over the splice when jacketed cables are spliced together since corrosion of metallic neutrals or shields may concentrate at this point.

4.2.6 Premolded Splices. The manufactured splice shown in Figure 12-13 has essentially the same components requirements of the taped splice. These devices are designed to cover the range of medium voltage cable sizes. It is essential that the specified cable diameters of the splice are within the specified size range of each of the cables. The body of the splice must be slid over one of the cable ends prior to the connector being installed. It is finally repositioned over the center of the joint.

Figure 12-13
Premolded Splice

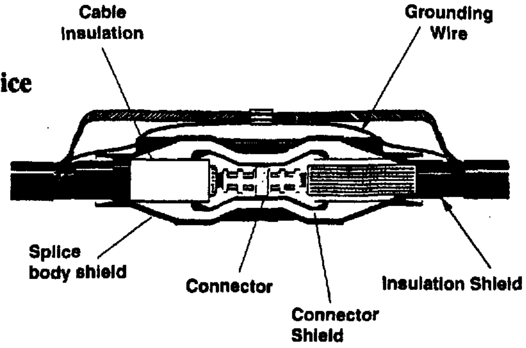
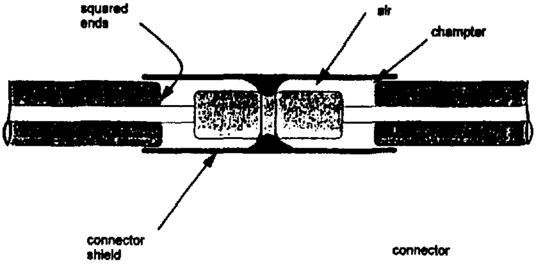


Figure 12-14
Detail of Connector Area of Premolded Splice



The components of this type of splice are listed as follows:

Connector: The connector shown indicates that it was mechanically pressed on the conductors. In addition, the shape of the ends are not tapered, nor is that a requirement when covered by a connector shield.

Cable End Preparation: The insulation of the cable at the connector is now cut at a right angle to the conductor. In the taped splice, a penciled end was required for proper application of tapes. However, in this design, there is no taping required and consequently a pencil is not required. A chamfer is required to remove any sharp edges of the cable to prevent scratching the inner surface of the splice housing and to make it easier to slide the splice body into position.

Connector Shield: This component is not found in this form in a taped splice, but is critical to the performance of a premolded splice. It is composed of conducting rubber material. In order to nullify the sharp edges of the connector and the air that is between the connector and the cable insulation, this connector shielding must make electrical contact with the cable conductor to eliminate any voltage difference to exist. When the connector shield makes contact with the connector and the cable is energized, both the connector and the shield material are at the same potential. With this design, no discharges can occur in the air or at the connector edges. Figure 12-14 gives an expanded view of the connector shield and its application over a connector.

Insulation: The EPDM insulation is injected between the connector shield and the outer conducting shield of the splice body.

Splice Body Shield: This is a thick layer of conducting rubber. It is designed to overlap the cable's conducting insulation shield on each end of the splice and to provide stress relief at both cable ends.

Grounding Eye: At each end of the splice, a grounding eye is required on all medium voltage premolded devices and they must be connected to the cable neutral. This provides a parallel path for the grounding of the splice body shield.

Neutral Across Splice: This generally consists of concentric strands from the cable that are twisted together and joined at the center of the splice. The wire used to make an electrical connection to the molded eye is shown connected into the neutral connector and to the concentric strands at each end of the splice.

In an actual field application, these strands should spiral around the splice and be in contact with the outer layer of the splice. This facilitates fault locating by providing a reliable metallic ground for the splice shield

Adapters: Some designs of premolded splices incorporate adapters. They extend the range of cables that can be accommodated in a specific housing. They also permit the jointing of two widely different cable sizes and they also may enable the user to minimize inventory of housings. Positioning of the adapter is important so that electrical stress points are not introduced. Adapters are applied before the connector is installed and as in the case of other premolded splices, the body must also be installed prior to the connection and the entire assembly is moved into place.

5. ALTERNATE DESIGNS

There are many ways of producing a joint or termination for medium voltage cables: hand application of tapes, combinations of premolded stress cones and hand applied tapes, premolded, and heat shrink -- just to mention some of them. The proper choice of which termination to select for a given application must consider factors such as cost of materials, time of installation, frequency of use, reliability, space requirements, and skill of the installer. Obviously, there is no universal solution to the wide variety of needs and conditions that are encountered in the field. The proper selection of a joint must consider all of these.

Field molded splices are constructed somewhat like a conventional taped splice. The insulating material is an uncured rubber material which may come in the form of tape or pre-formed sections. When the proper amount of material has been applied, the splice body in enclosed in a temperature controlled "oven" that confines the expanding material for the proper temperature and time required to cure the tapes. Stress relief is maintained by utilizing a conductive paint over the connector and the insulation after it is cured. The remainder of the shielding and neutral system are restored in the normal manner.

Heat shrink splices are available as a series of heat shrinkable tubes. Some may be pre-assembled by the manufacturer to reduce the number that must be handled in the field. The tubes must be slipped over the cable prior to connecting the conductors. After positioning each tube over the connected cables, heat is applied to shrink the tube snugly over the underlying surface and soften any mastic material used in the assembly. Stress relief is generally provided by stress control tubes that are also shrunk into place so that ends of the stress control tube overlap both cable insulation shields. The joint is finished in the normal manner.

Cold shrink splices are similar except that a removable liner is pulled out and the tube collapses over the underlying surface. As the name implies, no heat is required. Medium voltage joints contain all the necessary electrical components.

6. SELECTION OF JOINTS AND TERMINATIONS

When making a decision as to the best choice of devices to purchase, here are some of the questions and opportunities that should be considered:

- Are the components of the device compatible with the cable being spliced or terminated?
- Did the device pass all the tests that were specified so that it meets the requirements of the electrical system involved?
- Are codes applicable in the decision to use the chosen device?
- Review all safety requirements involved in the construction, application, and installation of the device.
- Will the device meet the mechanical requirements of the installation?
- Can the device be assembled with the tooling that is already available or are special tools required?
- Consider the positioning of the device. Splices are not recommended for installation at bends in the cable. Terminations are normally installed in an upright position. Other positions are possible but require special attention.
- Environmental conditions are of importance to attain expected life of any device. Heat may effect the ampacity of the device. Cold may have an effect on the assembly during installation. Contaminants are critical to the leakage path of a termination.
- Moisture is always the enemy of an underground system and must be controlled in construction and installation.
- Are there any existing work practices or procedures that will conflict with the application of this device?
- Investigate the economics of using different devices such as emergency reserve parts, training new personnel after original installation personnel have gone.
- The cost of the device and the cost of installation.
- Will the device do the job as well or better than what is presently used?

7. REFERENCES

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[12-3] T. A. Balaska, "Jointing of High Voltage, Extruded Dielectric Cables, Basics of Electrical Design and Installation," IEEE UT&D Conference Record, PP 318-26, 1974.

[12-4] L. G. Virsberg and P. H. Ware, "A New Termination for Underground Distribution," 1967 IEEE Transactions, Vol. PAS-86, PP 1129-35.

[12-5] *Underground Systems Reference Book*, EEI, 1956.

CHAPTER 13

AMPACITY OF CABLES

Lawrence J. Kelly and Carl C. Landinger

1. INTRODUCTION

Ampacity is the term that was conceived by William Del Mar in the early 1950s when he became weary of saying "current carrying capacity" too many times. AIEE/IPCEA published the term "ampacity" in 1962 in the "Black Books" of *Power Cable Ampacities* [13-1]. The term is defined as the maximum amount of current a cable can carry under the prevailing conditions of use without sustaining immediate or progressive deterioration. The prevailing conditions of use include environmental and time considerations.

Cables, whether only energized or carrying load current, are a source of heat. This heat energy causes a temperature rise in the cable that must be kept within limits that have been established through years of experience. The various components of a cable can endure some maximum temperature on a sustained basis with no undue level of deterioration.

There are several sources of heat in a cable, such as losses caused by current flow in the conductor, dielectric loss in the insulation, current in the shielding, sheaths, and armor. Sources external to the cable include induced current in a surrounding conduit, adjacent cables, steam mains, etc.

The heat sources result in a temperature rise in the cable that must flow outward through the various materials that have varying resistance to the flow of that heat. These resistances include the cable insulation, sheaths, jackets, air, conduits, concrete, surrounding soil, and finally to ambient earth.

In order to avoid damage, the temperature rise must not exceed those maximum temperatures that the cable components have demonstrated that they can endure. It is the careful balancing of temperature rise to the acceptable levels and the ability to dissipate that heat that determines the cable ampacity.

2. SOIL THERMAL RESISTIVITY

The thermal resistivity of the soil, rho, is the least known aspect of the thermal circuit. The distance for the heat to travel is much greater in the soil than the dimensions of the cable or duct bank, so thermal resistivity of the soil is a very significant factor in the calculation. Another aspect that must be considered is the stability of the soil during the long-term heating process. Heat tends to force moisture out of soils increasing their resistivity substantially over the soil in its native, undisturbed environment. This means that measuring the soil resistivity prior to the cable being loaded can result in an optimistically lower value of rho than the will be the situation in service.

The first practical calculation of the temperature rise in the earth portion of a cable circuit was presented by Dr. A. E. Kennelly in 1893 [13-2]. His work was not fully appreciated until Jack Neher and Frank Buller demonstrated the adaptability of Kennelly's method to the practical world.

As early as 1949, Jack Neher described the patterns of isotherms surrounding buried cables and showed that they were eccentric circles offset down from the axis of the cable [13-3]. This was later reported in detail by Balaska, McKean, and Merrell after they ran load tests on simulated pipe cables in a sandy area [13-4]. They reported very high resistivity sand next to the pipes. Schmill reported the same patterns [13-5].

Factors that effect the drying rate include type of soil, grain size and distribution, compaction, depth of burial, duration of heat flow, moisture availability, and the watts of heat that are being released. A lengthy debate has been in progress for over twenty years of the main concern for this drying: the temperature of the cable/earth interface or the watts of heat that is being driven across that soil. An excellent set of six papers was presented at the Insulated Conductors Committee Meeting of November 1984 [13-6].

In situ tests of the native soil can be measured with thermal needles. IEEE Guide 442 outlines this procedure [13-7]. Black and Martin have recorded many of the practical aspects of these measurements in reference [13-8].

3. AMPACITY CALCULATIONS

Dr. D. H. Simmons published a series of papers in 1925 with revisions in 1932, "Calculation of the Electrical Problems in Underground Cables," [13-9]. The National Electric Light Association in 1931 published the first ampacity tables in the United States that covered PILC cables in ducts or air. In 1933, EEI published tables that expanded the NELA work to include other load factor conditions.

The major contribution was made by Jack Neher and Martin McGrath in their June 1957 classic paper [9-10]. The AIEE-IPCEA "black books" [13-1] are tables of ampacities that were calculated using the methods that were described in their work. Those books have now been revised and were published in 1995 by IEEE [13-11]. IEEE also sells these tables in an electronic form [13-12].

The fundamental theory of heat transfer in the steady state situation is the same as Ohm's law where the heat flow varies directly as temperature and inversely as thermal resistance:

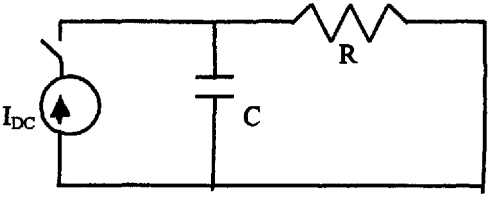
$$I = \sqrt{\frac{T_C - T_A}{R_{AC}\ (R_{TH})}} \tag{13.1}$$

where
I = Current in amperes that can be carried (ampacity)
T_C = Maximum allowable conductor temperature in $^{\circ}$C
T_A = Ambient temperature of ambient earth in $^{\circ}$C
R_{AC} = ac resistance of conductor in ohms/foot at T_C
R_{TH} = Thermal resistance from conductor to ambient in thermal ohm feet.

3.1 The Heat Transfer Model

Cable materials store as well as conduct heat. When operation begins, heat is generated that is both stored in the cable components and conducted from the region of higher temperature to that of a lower temperature. A simplified thermal circuit for this situation is equivalent to an R-C electrical circuit:

Figure 13-1



At time t = 0, the switch is closed and essentially all of the energy is absorbed by the capacitor. However, depending on the relative values of R and C, as time progresses, the capacitor is fully charged and essentially all of the current flows through the resistor. Thus, for cables subjected to large swings in loading for short periods of time, the thermal capacitance must be considered. See Section 4.0 of this chapter.

3.2 Load Factor

The ratio of average load to peak load is known as load factor. This is an important consideration since most loads on a utility system vary with time of day. The effect of this cyclic load on ampacity depends on the amount of thermal capacitance involved in the environment.

Cables in duct banks or directly buried in earth are surrounded by a substantial amount of thermal capacitance. The cable, surrounding ducts, concrete, and earth all take time to heat (and to cool). Thus, heat absorption takes place in those areas as load is increasing and permits a higher ampacity than if the load had been continuous. Of course, cooling takes place during the dropping load portions of the load cycle.

For small cables in air or conduit in air, the thermal lag is small. The cables heat up relatively quickly, i.e., one or two hours. For the usual load cycles, where the peak load exists for periods of two hours or more, load factor is not generally considered in determining ampacity.

3.3 Loss Factor

The loss factor may be calculated from the following formula when the daily load factor is known:

$$LF = 0.3(lf) + 0.7(lf)^2 \tag{13.2}$$

where:
LF = Loss factor
lf = Daily load factor per unit

Loss factor becomes significant a specified distance from the center of the cable. This fictitious distance, D_X, derived by Neher and McGrath, is 8.3 inches or 21.1 mm. As the heat flows through the surrounding medium beyond this diameter, the effective rho becomes lower and hence the explanation of the role of the loss factor in that area.

3.4 Conductor Loss

When electric current flows through a material, there is a resistance to that flow. This is an inherent property of every material and the measure of this property is known as resistivity. The reciprocal of this property is conductivity. When selecting materials for use in an electrical conductor, it is desirable to use materials with as low a resistivity as is consistent with cost and ease of use.

Copper and aluminum are the ideal choices for use in power cables and are the dominant metals used throughout the world.

Regardless of the metal chosen for a cable, some resistance is encountered. It therefore becomes necessary to determine the electrical resistance of the conductor in order to calculate the ampacity of the cable.

See Chapter 3 for details of the conductor loss calculation.

3.4.1 Direct-Current Conductor Resistance. This subject has been introduced in Chapter 3. Some additional insight is presented here that applies directly to the determination of ampacity. The volume resistivity of annealed copper at 20 $^{\circ}$C is:

$$\rho_{20} = 0.017241 \text{ ohm mm}^2/\text{meter} \tag{13.3}$$

In ohms - circular mil per foot units this becomes:

$$\rho_{20} = 10.371 \text{ ohm - circular mil / foot} \tag{13.4}$$

Table 13-1
Direct-Current Resistivity at 20 $^{\circ}$C

Metal	**Volume Conductivity**	**Volume**	**Resistivity**	**Weight Resistivity**
	in %, IACS	**Ohms-cmil/ft**	**Ohms-mm^2/m**	**Ohms-lb/ mile^2**
Soft copper	100.00	10.371	0.01724	875.2
Hard copper	96.16	10.785	0.01793	910.15
Copperweld	39.21	26.45	0.043971	2046.3
1350 - H19	61.2	16.946	0.02817	434.81
5005 - H19	53.5	19.385	0.03223	497.36
6201 T81	52.5	19.755	0.03284	506.85
Alumoweld	20.33	51.01	0.08401	3191.0
Steel	5.0	129.64	0.21551	9574.0

Conductivity of a conductor material is expressed as a relative quantity, i.e., as a percentage of a standard conductivity. The International Electro-technical Commission in 1913 adopted a resistivity value known as the International Annealed Copper Standard (IACS). The conductivity values for annealed copper were established as 100%.

An aluminum conductor is typically 61.2% as conductive as an annealed copper conductor. Thus a #1/0 AWG solid aluminum conductor of 61.2% conductivity has a volume resistivity of 16.946 ohms - circular mil per foot and a cross-sectional area of 105,600 circular mils. Thus, the dc resistance per 1,000 feet at

20 °C is:

$$R_{dc(20)} = 16{,}946 \times 1{,}000 / 105{,}600$$

$$R_{dc(20)} = 0.1605 \text{ ohms}$$

To adjust tabulated values of conductor resistance to other temperatures that are commonly encountered, the following formula applies:

$$R_{T2} = R_{T1}\ [1 + \alpha (T_2 - T_1)] \tag{13.5}$$

where:

R_{T2} = DC resistance of conductor at new temperature
R_{T1} = DC resistance of conductor at "base" temperature
α = Temperature coefficient of resistance

Temperature coefficients for various copper and aluminum conductors at several base temperatures are as follow:

Table 13-2
Temperature Coefficients for Conductor Metals

Metal at:	0 °C	20 °C	25 °C	30 °C
61.2 % Al.	0.00440	0.00404	0.00396	0.00389
100.0 % Cu.	0.00427	0.00393	0.00385	0.00378
98.0 % Cu.	0.00417	0.00385	0.00378	0.00371
96.0 % Cu.	0.00408	0.00377	0.00370	0.00364

3.4.2 Alternating-Current Conductor Resistance. This subject has been covered in Chapter 3, Section 7.2.

When the term "ac resistance of a conductor" is used, it means the dc resistance of that conductor plus an increment that reflects the increased apparent resistance in the conductor caused by the skin-effect inequality of current density. Skin effect results in a decrease of current density toward the center of a conductor. A longitudinal element of the conductor near the center is surrounded by more magnetic lines of force than is an element near the rim. Thus, the counter-emf is greater in the center of the element. The net driving emf at the center element is thus reduced with consequent reduction of current density.

Methods for calculating this increased resistance has been extensively treated in technical papers and bulletins [13-10, for instance].

3.4.3. Proximity Effect. The flux linking a conductor due to near-by current flow distorts the cross-sectional current distribution in the conductor in the same way as the flux from the current in the conductor itself. This is called proximity effect. Skin effect and proximity effect are seldom separable and the combined effects are not directly cumulative. If the distance apart of the conductors exceeds ten times the diameter of a conductor, the extra I^2R loss is negligible.

3.4.4. Hysteresis and Eddy Current Effects. Hysteresis and eddy current losses in conductors and adjacent metallic parts add to the effective ac resistance. To supply these losses, more power is required from the cable. They can be very significant in large ampacity conductors when magnetic material is closely adjacent to the conductors. Currents greater than 200 amperes should be considered to be large for these effects.

3.5 Calculation of Dielectric Loss

As has been seen in Chapter 4, dielectric losses may have an important effect on ampacity. For a single-conductor, shielded and for a multi-conductor cable having shields over the individual conductors, the following formula applies:

$$W_d = 2\pi f C n E^2 F_p \times 10^{-6} \tag{13.6}$$

and

$$C = 7.354\ \varepsilon / \text{Log}_{10}(D_O/D_I) \tag{13.7}$$

where

f = Operating frequency in hertz
n = Number of shielded conductors in cable
C = Capacitance of individual shielded conductors in µµF/ft
E = Operating voltage to ground in kV
F_p = Power factor of insulation
ε = Dielectric constant of the insulation
D_O = Diameter over the insulation
D_I = Diameter under the insulation

3.6 Metallic Shield Losses

When current flows in a conductor, there is a magnetic field associated with that current flow. If the current varies in magnitude with time, such as with 60 hertz alternating current, the field expands and contracts with the current magnitude. In the event that a second conductor is within the magnetic field of the current carrying conductor, a voltage, that varies with the field, will be introduced in that conductor.

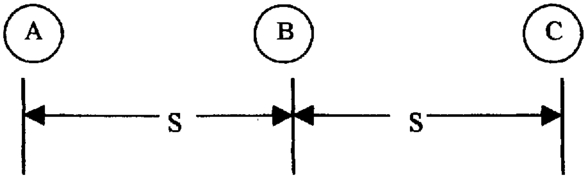
If that conductor is part of a circuit, the induced voltage will result in current flow. This situation occurs during operation of metallic shielded conductors. Current flow in the phase conductors induces a voltage in the metallic shields of all cables within the magnetic field. If the shields have two or more points that are grounded or otherwise complete a circuit, current will flow in the metallic shield conductor.

The current flowing in the metallic shields generates losses. The magnitude of the losses depends on the shield resistance and the current magnitude. This loss appears as heat. These losses not only represent an economic loss, but they have a negative effect on ampacity and voltage drop. The heat generated in the shields must be dissipated along with the phase conductor losses and any dielectric loss. Recognizing that the amount of heat which can be dissipated is fixed for a given set of thermal conditions, the heat generated by the shields reduces the amount of heat that can be assigned to the phase conductor. This has the effect of reducing the permissible phase conductor current. In other words, shield losses reduce the allowable phase conductor ampacity.

In multi-phase circuits, the voltage induced in any shield is the result of the vectoral addition and subtraction of all fluxes linking the shield. Since the net current in a balanced multi-phase circuit is equal to zero when the shield wires are equidistant from all three phases, the net voltage is zero. This is usually not the case, so in the practical world there is some "net" flux that will induce a shield voltage/current flow.

In a multi-phase of shielded, single-conductor cables, as the spacing between conductors increases, the cancellation of flux from the other phases is reduced. The shield on each cable approaches the total flux linkage created by the phase conductor of that cable.

Figure 13-2
Effect of Spacing Between Phases of a Single Circuit



As the spacing, S, increases, the effect of Phases B and C is reduced and the metallic shield losses in A phase are almost entirely dependent on the A phase magnetic flux.

There are two general ways that the amount of shield losses can be minimized:

☐ Single point grounding (open circuit shield)

☐ Reduce the quantity of metal in the shield

The open circuit shield presents other problems. The voltage continues to be induced and hence the voltage increases from zero at the point of grounding to a maximum at the open end that is remote from the ground. The magnitude of voltage is primarily dependent on the amount of current in the phase conductor. It follows that there are two current levels that must be considered: maximum normal current and maximum fault current in designing such a system. The amount of voltage that can be tolerated depends on safety concerns and jacket designs.

Another approach is to reduce the amount of metal in the shield. Since the circuit is basically a one-to-one transformer, an increase in resistance of the shield gives a reduction in the amount of current that will be generated in the shield. As an example, a 1,000 kcmil aluminum conductor, three 15 kV cables with multi-ground neutrals that are installed in a flat configuration with 7.5 inch spacing. A cable with one-third conductivity neutral will have four times as much current in the shields as a one-twelfth neutral cable. If the phases conductors are carrying a balanced 600 amperes, this means that the outside, lagging phase cable will have 400 amperes in the shield. A similar cable configuration with one-twelfth neutral will have only 100 amperes. The total current is reduced from 1,000 amperes to 700 amperes. This translates to an increase of ampacity of roughly 25 % for the reduced neutral cables.

In order to take shield losses into account when calculating ampacity, it is necessary to multiply all thermal resistances in the thermal circuit beyond the shield by 1 plus the ratio of the shield loss to the conductor loss. This incremental thermal resistance reflects the effect of the shield losses.

The shield loss calculations for cables in other configurations are rather complex, but very important. Halperin and Miller developed a method for closely approximating the losses and voltages for single conductor cables in several common configurations. This table is shown in reference [13-13, 14-6].

4. TYPICAL THERMAL CIRCUITS

4.1 The Internal Thermal Circuit for a Shielded Cable with Jacket

Thermal circuits will be shown in increasing complexity of the number of components. The symbols used throughout will be:

$\bar{R}$ = Thermal resistance (pronounced R bar) in ohm-feet
Q = Heat source in watts per foot

$\bar{C}$ = Thermal capacitance

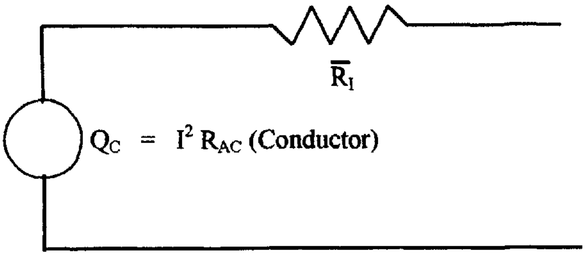
The subscripts throughout are:

C = Conductor
I = Insulation
S = Shield
J = Jacket
D = Duct
SD = Distance between cable and duct
E = Earth

4.2 Single Layer of Insulation, Continuous Load

The internal thermal circuit is shown in Figure 13-3 for a cable with continuous load. The conductor heat source passes through only one thermal resistance. This may be an insulation, covering, or a combination as long as they have similar thermal resistances. Note that these circuits stop at the surface of the cable. The remainder of the thermal circuit will be added in examples that follow.

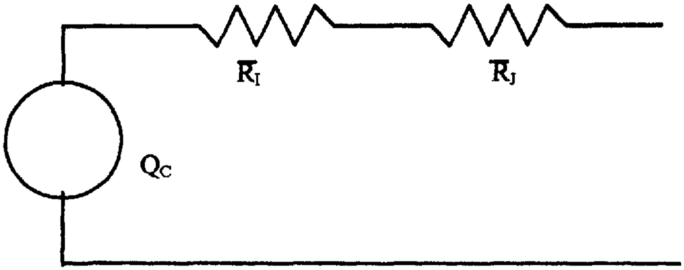
Figure 13-3



This diagram shows a continuous load flowing through one layer of insulation. The heat does not travel beyond the surface of the cable in this example.

4.3. Cable Internal Thermal Circuit Covered by Two Dissimilar Materials, Continuous Load

Figure 13-4

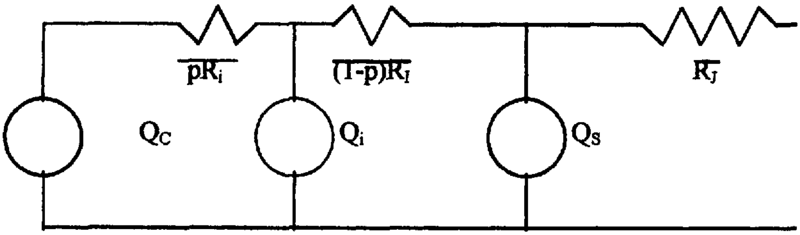


In this example, the continuous load flows through two dissimilar materials, but the heat still stays at the surface of the last layer of insulation.

4.4. Cable Thermal Circuit for Primary Cable with Metallic Shield and Jacket, Continuous Load

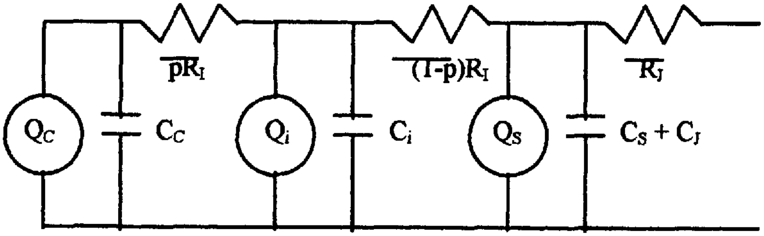
This thermal diagram shows a primary cable with its several heat sources and thermal resistances still with a constant load where p and (1-p) divide the thermal resistance to reflect Q_i.

Figure 13-5



4.5. Same Cable as Example 3, but with Cyclic Load

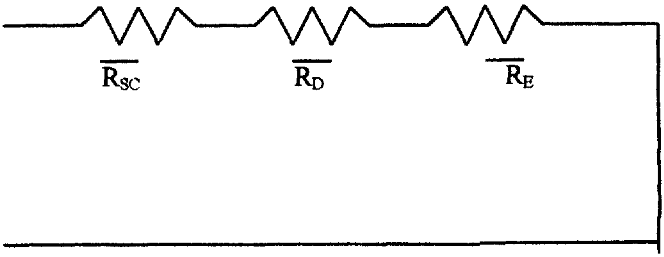
Figure 13-6



This diagram shows the same cable as in Figure 13-5, but the cyclic load is accounted for with the capacitors that are parallel to the three heat sources.

4.6. External Thermal Circuit, Cable in Duct, Continuous Load

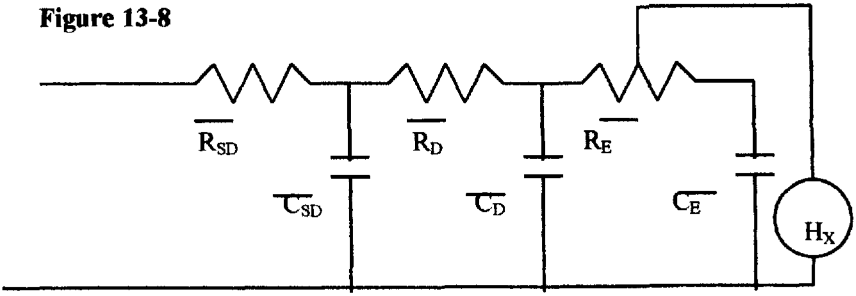
Figure 13-7



In this diagram, the resistances that are external to the cable are shown.

4.7. External Thermal Circuit, Cable in Duct, Time Varying Load, External Heat Source

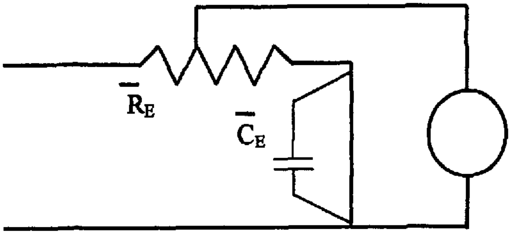
Figure 13-8



where H_X = External Heat Source

4.8. External Thermal Circuit, Cable Buried in Earth, Load May Be Cyclic, External Heat Source May Be Present

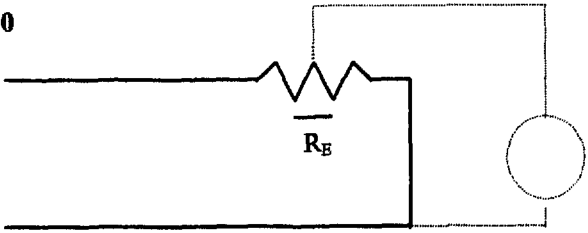
Figure 13-9



The depiction of possible cyclic load and external heat source are shown by dotted lines.

4.9. External Thermal Circuit, Cable in Air, Possible External Heat Source

Figure 13-10



The external thermal circuit is shown with the possible external heat source shown by dotted lines.

5. SAMPLE AMPACITY CALCULATION

5.1 General

Methods to calculate the ampacity of operating cables continues to be a popular subject for technical papers. Fortunately, the portion of the work that had been done by slide-rule and copious quantities of note paper have been replaced with computers. Manipulations were handled by assuming intermediate values of the various parameters prior to the advent of the computer. The hand calculations were laborious, but the user did achieve a feel for the concept. The availability of tables and computer programs could lead to quick, but possibly incorrect, answers. The Neher-McGrath paper [13-10] is the best reference to use before a hand calculation is attempted. As a matter of fact, you should read that paper even if you have decided to use available tables or programs!

The following simple example of a calculation is presented with the intent of giving insight into the process:

The general equation that has been previously given:

$$I = \sqrt{\frac{T_C - T_A}{R_{AC} \; (R_{TH})}} \qquad (13.1)$$

where

I = Current in amperes that can be carried (ampacity)
T_C = Maximum allowable conductor temperature in ^{O}C
T_A = Ambient temperature of ambient earth in ^{O}C
R_{AC} = AC resistance of conductor in ohms/foot at T_C
R_{TH} = Thermal resistance from conductor to ambient in thermal ohm feet, assuming no other heat sources.

Another form of this equation recognizes the other possible heat sources that have been indicated in the thermal circuit diagrams. Equation 13.1 expands to:

$$I = \sqrt{\frac{T_C - (T_A + T_D}{R_{AC} \; (R_i + R_{TH})}} \qquad (13.8)$$

where

T_D = Temperature rise due to dielectric loss in ^{0}C

$\overline{R_i}$ = To account for thermal resistance of insulation and/or coverings between the conductor and the first heat source beyond the insulation.
$\overline{R_{TH}}$ = Is the thermal resistance to ambient adjusted to account for additional heat sources such as shield loss, armor loss, steam lines, etc.

6. AMPACITY TABLES AND COMPUTER PROGRAMS

6.1 Tables

The *IEEE Standard Power Cable Ampacity Tables*, [13-11, 13-12], IEEE Std. 835-1994, is a book (or electronic version) that contains over 3,000 tables in 3,086 pages. Voltages range from 5 kV to 138 kV. Although there are situations that are not covered by these tables, this is an excellent beginning point for anyone interested in cable ampacities.

Manufacturers have also published catalogues that cover the more common situations [13-13, 13-14].

6.2 Computer Programs

Most of the large cable manufacturers and architect / engineering firms have their own computer programs for ampacity determination. This is an excellent source of information when you are engineering a new cable system. These programs generally are not for sale.

There are commercially available programs throughout North America. These are especially useful when you need to determine the precise ampacity of a cable, for instance, that is in a duct bank with other cables that are not fully loaded. The general cost of one of these programs is about $5,000 in US dollars.

7. REFERENCES

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[13-4] T. A. Balaska, A. L. McKean, and E. J. Merrell, "Long Time Heat Runs on Underground Cables in a Sand Hill," AIEE Paper No. 60-809, Summer General Meeting, June 19-24, 1960.

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[13-8] W. Z. Black, and M. A. Martin Jr., "Practical Aspects of Applying Thermal Stability Measurements to the Rating of Underground Power Cables," IEEE Paper No. 81 WM 050-4, Atlanta, GA, Feb. 1-8, 1981.

[13-9] D. M. Simmons, "Calculation of the Electrical Problems of Underground Cables," *The Electrical Journal,* East Pittsburgh, PA, May-Nov. 1932.

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[13-14] *Power Cable Manual,* Second Edition, The Southwire Company, 1997.

CHAPTER 14

SHEATH BONDING AND GROUNDING

William A. Thue

1. GENERAL

This discussion provides an overview of the reasons and methods for reducing sheath losses in large cables. While calculations are shown, all of the details are not covered as completely as are in the IEEE Guide 575 [14-1]. A very complete set of references is included in that standard. The reader is urged to obtain a copy of the latest revision of that document before designing a "single-point" grounding scheme.

The terms sheath and shield will be used interchangeably since they have the same function, problems, and solutions for the purpose of this chapter.

- ☐ Sheath refers to a water impervious, tubular metallic component of a cable that is applied over the insulation. Examples are a lead sheath and a corrugated copper or aluminum sheath. A semiconducting layer may be used under the metal to form a very smooth interface.

- ☐ Shield refers to the conducting component of a cable that must be grounded to confine the dielectric field to the inside of the cable. Shields are generally composed of a metallic portion and a conducting (or semiconducting) extruded layer. The metallic portion can be either tape, wires, or a tube.

The cable systems that should be considered for single-point grounding are systems with cables of 1,000 kcmils and larger and with anticipated loads of over 500 amperes. Fifty years ago, those cables were the paper insulated transmission circuits that always had lead sheaths. Technical papers of that era had titles such as "Reduction of Sheath Losses in Single-Conductor Cables" [14-2] and "Sheath Bonding Transformers" [14-3], hence the term "sheath" is the preferred word rather than "shield" for this discussion.

2. CABLE IS A TRANSFORMER

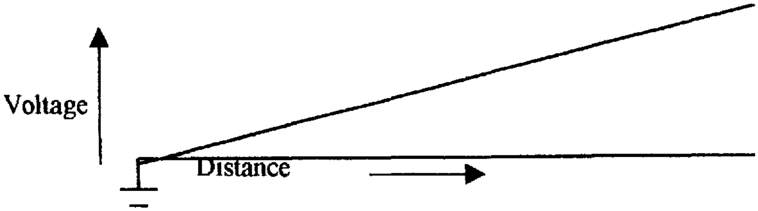
Chapter 2 described how a cable is a capacitor. That is true. Now you must think about the fact that a cable may also be a transformer.

When current flows in the "central" conductor of a cable, that current produces electromagnetic flux in the metallic shield, if present, or in any parallel conductor. This becomes a "one-turn" transformer when the shield is grounded two or more times since a circuit is formed and current flows.

We first will consider a single, shielded cable:

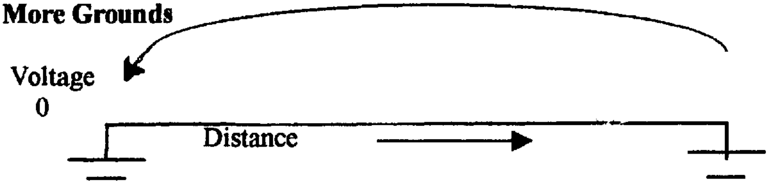
☐ If the shield is only grounded one time and a circuit is not completed, the magnetic flux produces a voltage in the shield. The amount of voltage is proportional to the current in the conductor and increases as the distance from the ground increases. See Figure 14-1.

Figure 14-1
Single Point Grounding



☐ If the shield is grounded two or more times or otherwise completes a circuit, the magnetic flux produces a current flow in the shield. The amount of current in the shield is inversely proportional to the resistance of the shield. (Another way of saying this is the current in the shield increases as the amount of metal in the shield increases.) The voltage stays at zero. See Figure 14-2.

Figure 14-2
Two or More Grounds



One other important concept regarding multiple grounds is that the distance between the grounds has no effect on the magnitude of the current. If the grounds are one foot apart or 1,000 feet apart, the current is the same -- depending on the current in the central conductor and the resistance of the shield. In the case of multiple cables, the spatial relationship of the cables is also a factor.

3. AMPACITY

3.1 Ampacity

In Chapter 13, there is a complete description of ampacity and the many sources of heat in a cable such as conductor, insulation, shields, etc. This heat must be carried through conduits, air, concrete, surrounding soil, and finally to ambient earth. If the heat generation in any segment is decreased, such as in the sheath, then the entire cable will have a greater ability to carry useful current.

The heat source from the shield system is the one that we will concentrate on in this discussion as we try to reduce or eliminate it.

3.2 Shield Losses

When an ac current flows in the conductor of a single-conductor cable, a magnetic field is produced. If a second conductor is within that magnetic field, a voltage that varies with the field will be introduced in that second conductor -- in our case, the sheath. See 13.3.6 for a more complete discussion of this condition.

If that second conductor is part of a circuit (connected to ground in two or more places), the induced voltage will cause a current to flow. That current generates losses that appear as heat. The heat must be dissipated the same as the other losses. Only so much heat can be dissipated for a given set of conditions, so these shield losses reduce the amount of heat that can be assigned to the phase conductor.

Let us assume that we are going to ground the shield at least two times in a run of cable. What is the effect of the amount of metal in the shield?

The following curves present an interesting picture of the shield losses for varying amounts of metal in the shield. These curves are taken from ICEA document P 53-426 [14-5]. As you can see, they were concerned about underground residential distribution (URD) cables where the ratio of conductivity of the shield was given as a ratio of the conductivity of the main conductor. Hence one-third neutral, etc.

In the situation where 2000 kcmil aluminum conductors are triangularly spaced 7.5 inches apart, the shield loss for a one-third neutral is 1.8 times the conductor loss!

For single-conductor transmission cables having robust shields, losses such as these are likely to be encountered in multi-point grounding situations and generally are not acceptable.

3.3 Shield Capacity

The shield, or sheath, of a cable must have sufficient conductivity in metal to carry the available fault current that may be imposed on the cable. Single conductor cables should have enough metal in its shield to clear a phase-to-ground fault and with the type of reclosing scheme that will be used. It is not wise to depend on the shield of the other two phases since they may be some inches away. You need to determine:

☐ What is the fault current that will flow along the shield?

☐ What is the time involved for the back-up device to operate?

☐ Will the circuit be reclosed and how many times?

Too much metal in the shield of a cable section with two or more grounds is not a good idea. It costs additional money to buy such a cable and the losses not only reduce the ampacity of the cable but cause undue economic losses from the heat produced.

One way that you can test your concept of a sufficient amount of shield is to look at the performance of the cables that you have in service. Even if the present cable has a lead sheath, you can translate that amount of lead to copper equivalent. You will also need to consider what the fault current may be in the future. EPRI has developed a program that does the laborious part of the calculations [14-6].

We can "convert" metals used in sheaths or shields to copper equivalent by measuring the area of the shield metal and then translate that area to copper equivalent using the ratio of their electrical resistivities.

Table 14-1
Electrical Resistivity of Metals

Metal	Electrical Resistivity in Ohm-mm^2/m x 10^{-8}, 20 °C
Copper, annealed	1.724
Aluminum	2.83
Bronze	4.66
Lead	22.0
Iron, hard steel	24.0

As an example, we have a 138 kV LPOF cable that has a diameter of 3.00 inches over the lead and the lead is 100 mils thick.

The area of a 3.00 inch circle is: = 7.0686 in^2.

The area of a circle that is under the lead is:

Diameter = 3.00-0.100-0.100 = 2.80 in.
Area = 1.4 x 1.4 x π = 6.1575 in^2.

Area of the lead is 7.0686 - 6.1575 = 0.9111 in^2.

The ratio of resistivities is 1.724 / 22.0 = 0.0784

The copper equivalent is 0.9111 in^2 x 0.0784 = 0.07139 in^2.

To convert to cmils, multiply in^2 by 4 / π x 10^6 = 90,884 cmils

This lead sheath is between a #1/0 AWG (105,600 cmils) and a #1 AWG (83,690 cmils).

If the sheath increases to 140 mils and the core stays the same, we have:

The area of the sheath is = 7.4506 in^2.

The area of lead is 7.4506 - 6.1575 = 1.2931 in^2.

Multiply by the same ratio of 0.0784 = 0.1014

To convert to cmils, multiply by $4/\pi \times 10^6$ = 129,106 cmils

This is almost a #2/0 AWG (133,100 cmil) copper conductor.

Using the same concept, one can change from aluminum to copper, etc.

The allowable short-circuit currents for insulated copper conductors may be determined by the following formula:

$$[I/A]^2\, t = 0.0297 \log_{10}[T_2 + 234 / T_1 + 234] \tag{14.1}$$

where
I = Short circuit current in amperes
A = Conductor area in circular mils
t = Time of short circuit in seconds
T_1 = Operating temperature, 90 °C
T_2 = Maximum short circuit temperature, 250 °C

A well-established plot of current versus time is included in [13-13]. It is important to be aware that these results are somewhat pessimistic since the heat sink of coverings is ignored and has not been addressed in equation (14.1). On the other hand, the answers given are very safe values.

3.4 Jumper Capacity

You must make a good connection between the bonding jumper and the cable sheath to have enough capacity to take the fault current to ground or to the adjacent section—no matter how well you designed the cable sheath. This is frequently a weak point in the total design.

The bonding jumper should always be larger than the equivalent sheath area and should be as short and straight as possible to reduce the impedance of that portion of the circuit. In all cases, the bonding jumper should be covered, such as with a 600 volt cable.

4. MULTIPLE POINT GROUNDING

4.1 Advantages

- No sheath isolation joints
- No voltage on the shield
- No periodic testing is needed
- No concerns when looking for faults

4.2 Disadvantages

- Lower ampacity
- Higher losses

4.3 Discussion

Although you may have already decided to drop this concept, you should be aware of the consequences of a second ground or connection appearing on a run of cable that had not been planned. Such a second ground can complete a circuit and result in very high sheath currents that could lead to a failure of all of the cable that has been subjected to those currents. The higher the calculated voltage on the sheath, the greater the current flow may be in the event of the second ground. Periodic maintenance of single-point grounded circuits should be considered. If this is will be done, a graphite layer over the jacket will enable the electrical testing of the integrity of the jacket.

5. SINGLE-POINT AND CROSS-BONDING

To be precise, single-point grounding means only one ground per phase, as will be explained later. Cross-bonding also limits sheath voltages and demonstrates the same advantages and disadvantages as single-point grounding.

5.1 Advantages

- Higher ampacity
- Lower losses

5.2 Disadvantages

- Sheath isolation joints are required
- Voltage on sheath / safety concerns

5.3 Background

The term used to describe single-point grounding from the 1920s to the 1950s was *open-circuit sheath.* The concern was to limit the *induced sheath voltage* on the cable shield. A 1950 handbook said that "The safe value of sheath voltage above ground is generally taken at 12 volts ac to eliminate or reduce electrolysis and corrosion troubles." The vast majority of the cables in those days did not have any jacket—just bare lead sheaths. Corrosion was obviously a valid concern. (Some cable manufacturers in the United States still recommend 25 volts as the maximum for most situations.) The vastly superior jacketing materials that are available today have helped change the presently accepted value of "standing voltage" to 100 to 400 volts for normal load conditions. Since the fault currents are much higher than the load currents, it is usually considered that the shield voltage during fault conditions be kept to a few thousand volts. This is controlled by using sheath voltage limiters -- a type of surge arrester.

5.4 Single Point Bonding Methods

There are numerous methods of managing the voltage on the shields of cables with single point grounding. All have one thing in common: the need for a sheath or shield isolation joint.

Five general methods will be explored:

- Single-Point Grounding
- Cross-Bonding
- Continuous Cross-Bonding
- Auxiliary Bonding
- Series Impedance or Transformer Bonding

Diagrams of each method of connection, with a profile of the voltages that would be encountered under normal operation, are shown below.

Figure 14-3
Single-Point Grounding

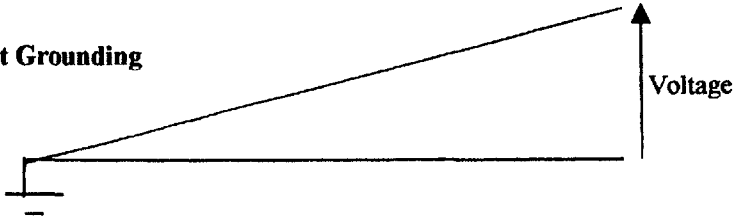
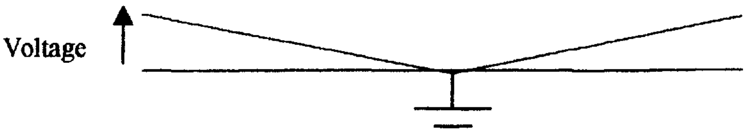


Figure 14-4
Single-Point Grounding near Center of Cable Run



In this situation, only half of the previous voltage appears on the sheath.

Figure 14-5
Cross-Bonding Connections

Legend: ● **Sheath Isolation**
○ **Continuous Sheath**

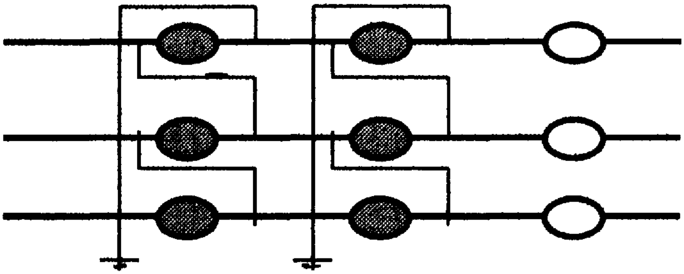


Figure 14-6
Continuous Cross-Bonding Connections

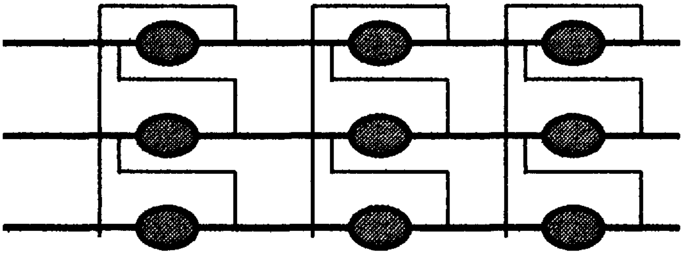
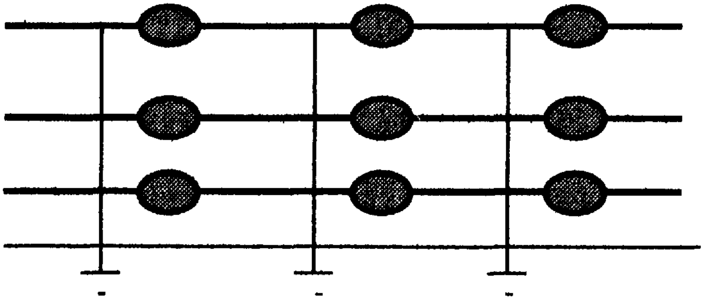


Figure 14-7
Auxiliary Cable Bonding



There are other types of grounding schemes that are possible and are in service. Generally they make use of special transformers or impedances in the ground leads that reduce the current because of the additional impedance in those leads. These were very necessary years ago when the jackets of the cables did not have the high electrical resistance and stability that are available today.

5.5 Induced Sheath Voltage Levels

Formulas for calculating shield voltages and current and losses for single conductor cables were originally developed by K. W. Miller in the 1920s [14-2]. The same general equations are also given in several handbooks. The table from reference [14-6] is included as Figure 14-7. The difference in these equations is the use of the "j" term -- to denote phase relationship -- so only the magnitude of the voltage (or current) is determined. Each case that follows will include the formulas from that reference [14-6].

The induced voltage in the sheath of one cable or for all cables in a circuit where the cables are installed as an equilateral triangle is given by:

$$V_{sh} = I \times X_m \tag{14.2}$$

where V_{sh} = sheath voltage in microvolts per foot of cable

I = current in a phase conductor in amperes

X_m = mutual inductance between conductor and sheath

The mutual inductance for a 60 hertz circuit may be determined from the formula:

$$X_m = 52.92 \log_{10} S / r_m \tag{14.3}$$

where X_m = mutual inductance in micro-ohms per foot

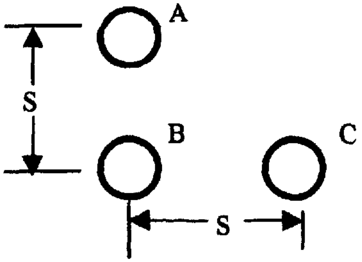
S = cable spacing in inches

r_m = mean radius of the shield in inches. This is the distance rom the center of the conductor to the mid-point of the sheath or shield.

For the more commonly encountered cable arrangements such as a three-phase circuit, other factors must be brought into the equations. Also, A and C phases have one voltage while B phase has a different voltage. This assumes equal current in all phases and a phase rotation of A, B, and C.

Right-angle or "rectangular" spacing is a probable configuration for large, single-conductor cables in a duct bank. One arrangement is:

Figure 14-8
Right Angle Arrangement



The induced shield voltages in A and C phases are:

$$V_{sh} = I/2\sqrt{3\,Y^2 + (X_m - \mathrm{A}/2)^2} \; \mathrm{x} \; 10^{-6} \qquad (14.4)$$

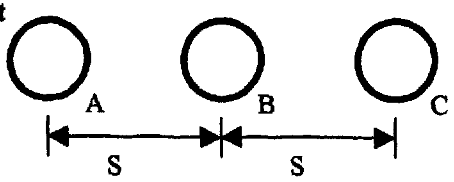
where
V_{sh} = sheath voltage on A and C phases in volts to neutral per foot
I = current in phases conductor in amperes
Y = $X_m + \mathrm{A}/2$
X_m = $52.92 \log_{10} \mathrm{S} / r_m$ for 60 hertz operation
S = spacing in inches
A = 15.93 micro-ohms per foot for 60 hertz operation

The induced shield voltage in B phase is:

$$V_{sh} = I \; \mathrm{x} \; X_m \; \mathrm{x} \; 10^{-6} \qquad (14.5)$$

A flat configuration is commonly used for cables in a trench, but this could be a duct bank arrangement as well.

Figure 14-11
Flat Arrangement



The induced shield voltages in A and C phases are:

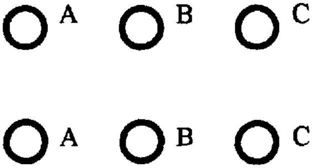
$$V_{sh} = I/2\sqrt{3\,Y^2 + (X_m - \mathrm{A})^2} \quad \text{x } 10^{-6} \qquad (14.6)$$

where V_{sh} = sheath voltage on A and C phases in volts to neutral per foot
I = current in phases conductor in amperes
Y = X_m + A {This factor has changed from 14.4)!!!}
X_m = 52.92 $\log_{10}$ S / r_m for 60 hertz operation
S = spacing in inches
A = 15.93 micro-ohms per foot for 60 hertz operation

The induced shield voltage in B phase is the same as equation 14.5:

$$V_{sh} = \mathrm{I} \text{ x } X_m \text{ x } 10^{-6} \qquad (14.7)$$

Figure 14-10
Two Circuits, Flat Configuration



The induced shield voltages in phases A and C are:

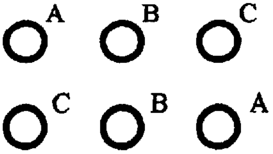
$$V_{sh} = \mathrm{I}/2\sqrt{3\,Y^2 + (X_m - \mathrm{B}/2)^2} \qquad \text{x } 10^{-6} \qquad (14.8)$$

where V_{sh} = sheath voltage on A and C phases in volts to neutral per foot
I = current in phase conductors in amperes
Y = X_m + A + B / 2 {This factor has changed again!!!}
X_m = 52.92 $\log_{10}$ S / r_m for 60 hertz operation
S = spacing in inches
A = 15.93 micro-ohms per foot for 60 hertz operation
B = 36.99 micro-ohms per foot for 60 hertz operation

The induced shield voltage for B phase is:

$$V_{sh} = I\,(X_m + A/2) \times 10^{-6} \qquad (14.9)$$

Figure 14-11
Two Circuits, Flat Configuration, Phases Opposite



The induced shield voltages in phases A and C are similar to equation (14.7), but Y changes:

$$V_{sh} = I/2\sqrt{3\,Y^2 + (X_m - B/2)^2} \times 10^{-6} \qquad (14.10)$$

where V_{sh} = sheath voltage on A and C phases in volts to neutral per foot
I = current in phases conductor in amperes
Y = $X_m + A - B/2$ {Now a minus, not +}
X_m = $52.92 \log_{10} S / r_m$ for 60 hertz operation
S = spacing in inches
A = 15.93 micro-ohms per foot for 60 hertz operation
B = 36.99 micro-ohms per foot for 60 hertz operation

The induced voltage on B phase uses the same equation as (14.9):

$$V_{sh} = I\,(X_m + A/2) \times 10^{-6} \qquad (14.11)$$

5.6 Discussion of Bonding Methods

5.6.1 Cross-Bonding. The goal of any shield isolation system is to reduce induced shield currents to the point that they will not seriously affect ampacity of the circuit and to limit the voltage to a safe value.

The most commonly used is cross bonding where the cable circuit is divided into three equal sections (or six, or nine, etc.). The shield is solidly grounded at the beginning of the first section and at the end of the third section. The second section is isolated by means of shield "breaks" from the first and third sections and has its sheath bonded to other phases. See Figure 14-5.

The induced shield voltage from A phase is "cross-bonded" to B phase, etc. This phase change reduces the resultant sheath voltage, and so on, for all sections of the circuit.

Bonding conductors must have sufficient capacity to carry the fault current that will be imposed and voltage resistance to keep the bonding jumper from being inadvertently grounded.

This method has the disadvantage of needing the joints evenly spaced through each triple section. When the joints are not evenly spaced, the voltage from one phase does not completely cancel out the other phase. This may not be critical, but it does mean that somewhat higher voltage levels will result.

5.6.2 Continuous Cross-Bonding. This is basically the same as the cross bonding of Figure 14-5 except that all of the joints have shield isolation provisions. Such a scheme is useful in situations where the triple sections are not practical from a field standpoint, such as for four sets of joints -- where the matched sets of three are not attainable.

The sheath voltages are approximately the same as for cross-bonded circuits. A disadvantage of this system is that there are no solid grounds except at the terminations.

5.6.3 Auxiliary Cable Bonding. This system is similar to the continuous cross-bonding method since all the joints must have shield isolation and all shields are bonded at each splice. The unique part of this arrangement is that the shields are connected to each other and to a separate neutral cable that runs the length of the circuit.

This permits the through fault current to be transmitted both on the shield as well as the parallel neutral cable. A reduction in the amount of shield materials is thus possible. A cable fault must still be cleared by having the fault current of that phase taken to ground at a remote point. This means that you must still put on a sufficient amount of shield metal to permit the breaker, or other back-up device, to “see” the fault.

5.6.4 Continuous Cross-Bonding, Star Ground. This system and other impedance type systems have been included in this discussion since they have been employed over the years. The basic need for these systems was to keep the sheath voltage down to that very low value of 12 volts. Now that 100+ volts is considered safe and reliable, the complications of these systems does not seem to be worthwhile. The equipment needed to accomplish these hookups are not very easy to find, have not been too reliable, and take up room in a manhole that is at a premium. Another concern is that these devices require additional maintenance time to be certain that they remain operational.

6. REFERENCES

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[14-2] Halperin, H. and Miller, K. W. "Reduction of Sheath Losses in Single-Conductor Cables", *Transactions AIEE,* April 1929, p 399.

[14-3] *Sheath Bonding Transformers,* Bulletin SBT 2, H. D. Electric Co., Chicago, IL.

[14-4] AIEE-IPCEA *Power Cable Ampacities,* AIEE Pub. No. S-135-1 and -2, IPCEA P-46-426, 1962.

[14-5] *IEEE Standard Power Cable Ampacities,* IEEE 835-1994.

[14-6] ICEA P-53-426.

[14-7] *Engineering Data for Copper and Aluminum Conductor Electrical Cables,* Bulletin EHB-90, The Okonite Company.

[14-8] IEEE Std. 532-1993 ISBN 1-55937-337-7, "IEEE Guide for Selection and Testing Jackets for Underground Cables."

[14-9] EPRI EL-3014, RP 1286-2, "Optimization of the Design of Metallic Shield / Concentric Neutral Conductors of Extruded Dielectric Cables Under Fault Conditions."

[14-10] EPRI EL-5478, "Shield Circulating Current Losses in Concentric Neutral Cables."

[14-11] "Sheath Over-voltages in High Voltage Cable Due to Special Sheath Bonding Connections," IEEE, Transactions on Power Apparatus and Systems, Vol. 84, 1965.

[14-12] "The Design of Specially Bonded Cable Systems," *Electra,* (28), CIGRE Study Committee 21, Working Group 07, May, 1973.

CHAPTER 15

POWER CABLE TESTING IN THE FIELD

James D. Medek

1. INTRODUCTION [15-1]

This chapter provides an overview of known methods for performing electrical tests in the field on shielded power cable systems. It is intended to help the reader select a test which is appropriate for a specific situation of interest. Field applied tests can be broadly divided into the following categories:

> (1) Type 1 field tests are intended to detect defects in the insulation of a cable system in order to improve the service reliability after the defective part is removed and appropriate repairs performed. These tests are usually achieved by application of relatively elevated voltages across the insulation for prescribed duration.
>
> (2) Type 2 field tests are intended to provide indications that the insulation system has deteriorated. Some of these tests will show the overall condition of a cable system and others will indicate the locations of discrete defects which may cause the sites of future service failures. Both varieties of such tests may be categorized as "pass/fail" or "go/no go" and are usually performed by means of moderately elevated voltages applied for relatively short duration, or by means of low voltages.

The following sections list various field test methods that are presently available for testing shielded, insulated power cable systems rated 5 kV through 500 kV. A complete tutorial or debate forum for one method versus another has not been attempted. A brief listing of "advantages" and "disadvantages" is included, but the users should avail themselves of the technical papers that are referenced, the material listed in the references, manufacturers' literature, and recent research results to make decisions on whether to perform a test and which test method to use. In making such decisions, consideration should be given to the performance of the entire cable system, including joints, terminations, and associated equipment.

1.1 OVERVIEW

1.1.1 Summary of Direct Voltage Testing. DC testing [15-2] has been accepted for many years as the standard field method for performing high voltage tests on cable insulation systems. Recent research has shown that dc testing tends to be blind to certain types of defects and that it can aggravate the deteriorated condition of some aged cables insulated with extruded dielectrics and affected with water trees. Whenever dc testing is performed, full consideration should be given to the fact that steady-state direct voltage creates within the insulation system an electrical field determined by the conductance of the insulation, whereas under service conditions, alternating voltage creates an electric field determined chiefly by the dielectric constant (or capacitance) of the insulation. Under ideal, homogeneously uniform insulation conditions, the mathematical formulas governing the steady-state stress distribution within the cable insulation are of the same form for dc and for ac, resulting in comparable relative values. However, should the insulation contain defects where either the conductivity or the dielectric constant assume values significantly different from those in the bulk of the insulation, the electric stress distribution obtained with direct voltage will no longer correspond to that obtained with alternating voltage. As conductivity is generally influenced by temperature to a greater extent than dielectric constant, the comparative electric stress distribution under dc and ac voltage application will be affected differently by changes in temperature or temperature distribution within the insulation. Furthermore, the failure mechanisms triggered by insulation defects vary from one type of defect to another. These failure mechanisms respond differently to the type of test voltage utilized, for instance, if the defect is a void where the mechanism of failure under service ac conditions is most likely to be triggered by partial discharge, application of direct voltage would not produce the high partial discharge repetition rate which exists with alternating voltage. Under these conditions, dc testing would not be useful. However, if the defect triggers failure by a thermal mechanism, dc testing may prove to be effective. For example, dc can detect presence of contaminants along a creepage interface.

Testing of extruded dielectric, service aged cables with dc at the presently recommended dc voltage levels can cause the cables to fail after they are returned to service [15-3]. The failures would not have occurred at that point in time if the cables had remained in service and not been tested with dc [15-4]. Furthermore, from the work of Bach [15-5], we know that even massive insulation defects in solid dielectric insulation cannot be detected with dc at the recommended voltage levels.

After engineering evaluation of the effectiveness of a test voltage and the risks to the cable system, high direct voltage may be considered appropriate for a particular application. If so, dc testing has the considerable advantage of being the simplest and most convenient to use. The value of the test for diagnostic purposes is limited when applied to extruded installations, but has been proven to yield excellent results on laminated insulation systems.

1.1.2 Summary of Alternative Test Methods. Alternating voltage tests at alternating voltages are highly acceptable since the insulation is stressed in a similar way to normal operation and the test is similar to that used in the factory on new reels of cable.

A serious disadvantage of power frequency ac tests at elevated voltage levels was the requirement for heavy, bulky and expensive test transformers which may not be readily transportable to a field site. This problem has been mitigated through use of resonant (both series and parallel) test sets and compensated (gapped core) test transformers. They are designed to resonate with a cable at power frequency, the range of resonance being adjustable to a range of cable lengths through a moderate change of the excitation voltage frequency, or a pulse resonant system. Power frequency ac tests are ideally suited for Type 1 field tests, such as partial discharge location, and dissipation factor (tan δ) evaluation.

Some of the practical disadvantages of power frequency tests are reduced while retaining the basic advantages by the use of very low frequency (VLF 0.1 Hz) voltage or by the use of other time-varying voltages. Examples of these latter are the oscillating wave (OSW, Section 10) and the alternating-polarity dc-biased ac voltage (APDAC). When such variations of power frequency test sets are used for conducting Type 1 tests, it is necessary to establish the equivalence of the results obtained at various voltage levels and test duration with corresponding results obtained by testing at power frequency.

A major objection to Type 1 field tests is the concern that application of elevated voltages without any other accompanying diagnostic measurements may trigger failure mechanisms which will not show during the test but which may cause subsequent failures in service. The test voltages enumerated previously can be used not only to force cable systems to fail at the sites of defects, but also to provide a useful evaluation of the condition of the insulation system.

As cable system insulations age, their dielectric properties undergo characteristic changes. These can be used to perform various Type 2 (diagnostic) field tests. A brief overview of the known methods follows:

> For a defective cable insulation, the dc leakage current versus voltage plot departs from linearity as the voltage is increased beyond some threshold value (tip-up curve), allowing a simple diagnostic test to be performed in the field.
>
> Another set of tests consists of applying a moderately elevated direct voltage across the cable insulation, removing the voltage source, shorting the cable while monitoring the short-circuit current as a function of time (depolarization current test), or measuring the voltage build up as a function of time after the removal of the short, (return voltage test) [1.1].

The rate of depolarization current decay or the rate of return voltage build up can be used as indicators of the degree of insulation aging. Measurement of polarization index (ratio of insulation resistance after 10 minutes to resistance after one minute of a voltage application) can also be utilized as an insulation diagnostic test.

As a cable deteriorates, its dissipation factor (tan δ) versus voltage plots can assume a gradually higher rate of increase (tip-up) beyond some threshold voltage. This test can be conducted either by means of a power frequency voltage or by means of a VLF voltage.

Water treeing in extruded cables causes a slight rectification of the ac voltage impressed across their insulation, producing a very small dc component in the ac leakage current. The magnitude of this component has been shown to increase with the severity of treeing.

Another developing diagnostic test, propagation characteristics spectroscopy (PCS), monitors the changes in the wave propagation characteristics (attenuation versus frequency spectrum) of a cable by means of a low voltage pulse which can be applied while the cable is energized and in service. Experiments have shown that the attenuation spectrum changes characteristically as the insulation ages.

The Type 2 field tests previously described are intended to monitor the overall condition of a cable insulation system throughout its length. At least two additional diagnostic methods are intended to identify the location of discrete defects which may be the site of future service failures. Service-aged cables with water trees have been shown to produce partial discharge (PD) signals from the tips of their longest trees, when subjected to time-varying voltage in the range of 1 to 3 times service level. The exact identification and of these discharge sites is now possible by means of equipment capable of functioning even in high ambient noise environments. The severity of defects is assessed by the closeness of the PD inception voltage to service voltage. Partial discharge location in installed cables is usually performed by means of power frequency excitation voltage sources, but also has been shown to be possible by means of APDAC, impulse voltage or oscillatory voltage. A guide covering the use of this method using very low frequency voltage under development. Another diagnostic test, known as the DIACS method, identifies the location of discrete impedance discontinuities or anomalies in the cable insulation through low voltage reflectometry. Water trees are reported to act as discontinuities after the cable has been pre-conditioned for some length of time by means of unipolar high dc and impulse voltages. The ability of this method to assess the severity of anomalies and to identify defective joints has yet to be demonstrated.

1.2 Need For Testing

While medium and high voltage power cables are carefully tested by the manufacturer before shipment with alternating or direct voltage, some defects may not be detected or, more likely, damage during shipment, storage, or installation may occur. Additional testing of completed installations prior to being placed in service, including joints and terminations, may be conducted. Additionally, many users find that, with time, these cable systems degrade and service failures become troublesome. The desire to reduce or eliminate those failures may led cable users to perform periodic tests after some time in service. As well, cable users need special diagnostic tests as an aid in determining the economic replacement interval for deteriorated cables.

AEIC G7-90 [15-6] states that "There are no field tests available that will provide an exact measurement of remaining service life in an operating cable system." Users may mix cable types on a system, so there is a need to base the test voltages and time on the circuit basic impulse level (BIL) rather than on the type and thickness of the insulation.

Research work has begun to show that certain types of field testing may lead to premature service failures of XLPE cables that exhibit water treeing when tested in a laboratory. This substantiates some field observations that led to the concern about field test methods and levels of voltage. Additional data is being compiled rapidly. The traditional method of factory testing the insulation of medium voltage cable has been to subject it to high alternating potential followed by direct potential. Because of the size and weight of conventional ac test equipment, many systems have been field tested with dc or no field testing has been performed. Experience with paper insulated, lead covered cable systems that have been tested in the field with dc for over 60 years has shown that testing with the recommended dc voltage does not seem to deteriorate sound insulation, or if it does, it is at a very slow rate of degradation.

The decision to employ maintenance testing must be evaluated by the individual user, taking into account the costs of a service failure, including intangibles, the costs of testing, and the possibility of damage to the system. As proven non-destructive diagnostic test methods become available, the users may want to consider replacing withstand type voltage tests with one or more of these methods.

CAUTION: Cables subjected to high voltage testing that are not grounded for sufficiently long periods of time following such tests can experience dangerous charge buildups as a consequence of the very long time constant associated with dielectric absorption currents. For this reason, the grounding procedures recommended in appropriate work rules should be followed.

2. DIRECT VOLTAGE TESTING

2.1 Introduction

The use of direct voltage has a historical precedent in the testing of laminated dielectric cable systems. Its application for testing extruded dielectric cable systems at high voltage is a matter of concern and debate. Reference [15-3] contains information relevant to these concerns.

This section presents the rationale for using dc testing, including the advantages and disadvantages and a brief description of the various dc field tests which can be conducted. These are generally divided into two broad categories, delineated by the test voltage level: low voltage dc testing (LVDC) covering voltages up to 5 kV and high voltage dc testing (HVDC) covering voltage levels above 5 kV.

Testing with a dc voltage source requires that only the dc conduction current be supplied rather than the capacitive charging current. This may greatly reduce the size and weight of the test equipment.

2.2 Performing LVDC Tests

Equipment for producing these voltages are typified by commercially available insulation resistance testers. Some have multi-voltage range capability.

Cable phases not under test should have their conductors grounded. Ends, both at test location and remote, should be protected from accidental contact by personnel, energized equipment and grounds.

Apply the prescribed test voltage for specified period of time. It may be advantageous to conduct the test with more than one voltage level and record readings of more than one time period.

Such test equipment provides measurements of the insulation resistance of the cable system as a function of time. Interpretation of the results, covered in greater detail in [15-2], IEEE 400.1, usually makes use of the change in resistance as testing progresses. A value of polarization index can be obtained by taking the ratio of the resistance after 10 minutes to the resistance after 1 minute.

ICEA provides minimum values of insulation resistance in its applicable publications.

2.3 Performing HVDC Tests

Equipment for producing these voltages are typified by rectification of an ac power supply. Output voltage is variable by adjusting the ac input voltage. Output current, i.e., current into the cable system under test, may be measured on the HVDC side or ratio transformation of the ac input. For the latter case, the test equipment leakage may mask the test current and the interpretation of results.

Apply the prescribed test voltage for the specified period of time. Reference [15-2] provides guidance for the selection of test voltage and time.

The following three general types of test can be conducted with this equipment:

2.3.1 DC Withstand Test. A voltage at a prescribed level is applied for a prescribed duration. The cable system is deemed to be acceptable if no breakdown occurs.

2.3.2 Leakage Current -- Time Tests. Total apparent leakage output current is recorded as a function of time at a prescribed voltage level. The variations of leakage current with time (rather than its absolute value) provide diagnostic information on the cable system.

2.3.3 Step - Voltage Test or Leakage Current Tip-up Tests.

The voltage is increased in small steps while the steady-state leakage current is recorded, until the maximum test voltage is reached or a pronounced nonlinear relationship between current and voltage is displayed. Such departures from linearity may denote a defective insulation system.

2.4 Summary of Advantages and Disadvantages

Some of the advantages and disadvantages of dc testing are listed below:

Advantages

- Relatively simple and light test equipment, in comparison to ac, and facilitates portability.
- Input power supply requirements readily available.
- Extensive history of successful testing of laminated dielectric cable systems and well established data base.

- Is effective when the failure mechanism is triggered by conduction or by thermal consideration.

- Purchase cost generally lower than that of non-dc test equipment for comparable kV output.

Disadvantages

- Is blind to certain types of defects, such as clean voids and cuts.

- May not replicate the stress distribution existing with power frequency ac voltage. The stress distribution is sensitive to temperature and temperature distribution.

- May cause undesirable space charge accumulation, especially at accessory cable insulation interfaces.

- May adversely affect future performance of water-tree-affected extruded dielectric cables.

3. POWER FREQUENCY TESTING

3.1 Introduction

As the name implies, these test methods are based on using alternating current at the operating frequency of the system as the test source.

These methods have the advantage, unique among all the test methods described in this chapter, of stressing the insulation comparably to normal operating conditions. It also replicates the most common method of factory test on new cables and accessories.

There is a practical disadvantage in that the cable system represents a large capacitive load, and in the past a bulky and expensive test generator was required if the cable system was to be stressed above normal operating levels. This size and bulk can be offset by the use of resonant and pulsed resonant test sources, which are described later.

A further advantage of power frequency testing is that it allows partial discharge and dissipation factor (tan delta) testing for diagnostic purposes. Some other test sources also permit these measurements, but give rise to some uncertainty in interpretation, since the measurements are then made at a frequency other than the normal operating frequency.

The factory quality tests on new cable are almost invariably made at the power frequency on which the cable will operate in service.

It would therefore seem logical that all field testing should use the same type of test voltage. However, a conventional power frequency transformer required even for full reel tests in the factory is a large and expensive device. Since a power cable may be made up of multiple reels of cable spliced together in the field, an even larger test transformer would be required to supply the heavy reactive current drawn by the geometric capacitance of the cable system.

The size of the transformer can be substantially reduced by using the principle of resonance. If the effective capacitance of the cable is resonated with an inductor, the multiplying effect of the resonant circuit (its Q factor) will allow the design of a smaller test transformer. In the ideal case of a perfect resonance, the test transformer will only be required to supply energy to balance the true resistive loss in the inductor and cable system. A further and significant reduction in size and weight of the test voltage generator can be achieved by use of the pulsed resonant circuit.

3.2 Test Apparatus Requirements

The following requirements are common to all three types of line frequency, resonant testing systems:

The apparatus may be provided with an output voltmeter which responds to the crest of the test waveform. For convenience this may be calibrated in terms of the rms voltage of the output (i.e., as 0.707 times the crest voltage.)

The output waveform is sinusoidal and should contain minimum line frequency harmonics and noise. This is of particular importance if diagnostic measurements (partial discharge, power factor, etc.) are to be performed.

Suggested maximum values for total harmonic and noise are:

☐ For withstand tests ±5% of the output voltage crest.

☐ For diagnostic tests ±1% of the output voltage crest.

It should be noted that certain types of voltage regulators using inductive methods for regulation tend to produce large amounts of harmonic distortion.

Line filters to minimize noise introduced from the power line are recommended for diagnostic measurements.

The test system should be equipped with a means of controlling the output voltage smoothly and linearly. The resolution of the voltage adjustment should be not more than one percent of the maximum output voltage.

For withstand tests, the detection and indication of breakdown of the point at which breakdown occurs is defined by the over-current protective device of the test system. For this reason it is desirable that a high speed and repeatable electronic circuit be used to operate the system circuit breaker and that the circuit breaker be as fast operating as practical. Disconnection of the cable from the test system should occur in less than two cycles of input frequency.

It is desirable that the output voltage be controlled by an automatic voltage regulator to maintain constant voltage for the duration of the test.

In resonant systems, it is convenient to have an automatic resonance control which operates initially to resonate the test system and cable system under test.

If the test system is to be used for diagnostic measurements, the internal partial discharge should be low -- less than 5 PC is normally acceptable.

3.3 Characteristics of Test Systems

The operating characteristics of a conventional test set are similar to a power transformer, although there are significant differences in the design of the source equipment.

Resonant systems operate differently than conventional transformers in that they have a specific tuning range for the capacitance of the cable under test. Capacitance outside this range cannot be energized. The minimum that can be energized can be reduced to zero, in the series resonant system, by using an auxiliary capacitor of appropriate rating in parallel with the test sample. The parallel resonant test system can be energized with no connected capacitance. The maximum value is independent of the current or thermal rating of the test system and cannot be exceeded. A typical tuning range is of the order of 20:1, maximum to minimum capacitance.

Both conventional and resonant test transformers provide an output which stresses the cable system under test identically to that under normal operations.

The output of a pulsed resonant test system consists of a power line frequency modulated at a low frequency, such as one Hz. The stress distribution in the cable system under test is therefore identical to that under normal operation. The only difference is that the magnitude of the stress varies periodically. The duration of the test must therefore be extended so that the cable under test is subjected to the same volt-time exposure as with a constant amplitude line frequency test.

3.4 Test Procedures

3.4.1 Conventional Transformers. When the cable has been prepared and appropriate safety precautions taken, the test set is energized and the voltage increased at a slow, linear way until the specified test voltage is achieved. It is then held constant for the specified test period. At the conclusion of the test period, it is reduced to zero at the same rate as that used for raising the voltage.

3.4.2 Resonant Systems. Proceed as in 3.4.1 except that the voltage is first raised to approximately 5% of the specified test voltage, and the system tuned, either manually or automatically if the facility is available. The tuning may also require minor adjustment when specified voltage is achieved.

3.4.3 Testing with System Voltage (Medium Voltage). It has been the utility practice for field crews to reclose an overhead circuit after a visual patrol is made of the circuit. The visual patrol is important in order to verify that any damaged equipment has been removed, downed lines have been restored, and feeds from alternate circuits have been disconnected. Fusing used in these operations are normally the size and type that was originally found in the switch.

This practice has been carried over to the Underground Residential Distribution (URD) circuits by the same operating crews that switched the overhead system. URD circuits have been re-energized either by the overhead fuse connection or by the use of a separable connector (elbow). In some cases continual re-closing and sectionalizing have been used to isolate a failure. This practice should be used sparingly since it may be damaging to the underground system. Reclosing in this manner may cause high voltage transients to be generated, and hence subject the circuit to excessive current surges. Both of those conditions may reduce the life and reliability of the underground circuit.

Devices have been developed to eliminate the need to re-energize a faulted underground circuit. With the use of a standard operating tester, a high voltage rectifier, the correct adapters, and an ac system source, a test can be applied to the underground circuit that will indicate whether a circuit is suitable for re-energization. A voltmeter phasing tester, in common use for overhead testing, can be modified to test underground circuits with the application of a high voltage rectifier and proper adapters. The voltmeter indicates the amount of charging current that is on the circuit being tested. Since the underground cable is a good capacitor, an un-faulted circuit would give a high reading when the tester is first connected to the circuit. As the capacitance charges, the reading on the voltmeter will decrease. If the reading fails to decrease, a faulted circuit is indicated.

When any of the above tests is complete, all parts of the circuit should be grounded and the system made secure.

The recommended rate-of-rise and rate-of-decrease of the test voltage is approximately 1 kV per second.

The duration of an acceptance test on a new cable system is normally 15 minutes at specified voltage. Maintenance tests may be 5 to 15 minutes. Any diagnostic tests (such as partial discharge) may be performed during this period. The voltage should be maintained at the specified value to within ±1%

4. PARTIAL DISCHARGE TESTING

4.1 Introduction

Partial discharge measurement is an important method of assessing the quality of the insulation of power cable systems, particularly for extruded insulation materials.

This chapter considers partial discharge from two points of view: the measurement of all partial discharges occurring within the cable system and the location of individual partial discharge sites.

4.2 Measurement of Partial Discharge

Perhaps the most significant factory test made on the insulation of full reels of extruded cable is the partial discharge test. This is usually done at power frequency, but can also be carried out at very low frequency and at some voltage significantly higher than normal working voltage to ground. Experience has shown that this test is a very sensitive method of detecting small imperfections in the insulation such as voids or skips in the insulation shield layer.

It would therefore seem logical to repeat this test on installed cables to detect any damage done during the shipping or laying or any problems created by jointing and terminating the cable. Unfortunately this is a difficult measurement to perform in the field due to the presence of partial discharge signals. However, in spite of the difficulty, this test has been performed in the field where some special circumstances suggest it is worth the time and expense involved. Typically this may be when damage or faulty installation is suspected or the cable route requires it to be of the highest possible reliability.

Once the necessary steps are taken to reduce the noise level below the partial discharge level to be measured, the test can provide a great deal of useful diagnostic data. By observing the magnitude and phase of the partial discharge signals and how they vary with increasing and then decreasing test voltage, results will disclose information on the type and position of the defects and their probable effect on cable life.

Noise reduction methods necessary for field tests of partial discharge usually include the use of an independent test voltage source such as a motor-generator, power line and high voltage filters, shielding and sometimes the use of bridge detection circuits.

Partial discharges can also be detected at system voltage with special sensors connected to the splice or termination, using the frequency spectrum of the discharges.

In summary, if the cable system can be tested in the field to show that its partial discharge level is comparable with that obtained in the factory tests on the cable and accessories, it is the most convincing evidence that the cable system is in excellent condition.

5. VERY LOW FREQUENCY (VLF, < 1 HZ.) TESTING

5.1 Introduction

Medium and high voltage power cables are carefully tested by the manufacturer before shipment with ac and/or dc voltages to ensure conformance with published specifications and industry standards. During transport, installation, and backfilling, cables are vulnerable to external damage. Therefore, cables may be tested prior to placing them in service to locate any external mechanical damage and to ensure that jointing and terminating work has been satisfactory. Periodic testing of service-aged cables may also be performed with the desire to determine system degradation and to reduce or eliminate service failures. Very low frequency (VLF) testing describes a testing technique for field testing of service-aged systems with extruded cable insulations.

Very low frequency (VLF) testing methods can be categorized as withstand or diagnostic. In withstand testing, insulation defects are caused to break down (fault) at the time of testing. Faults are repaired and the insulation is retested until it passes the withstand test. The withstand test is considered a destructive test. Diagnostic testing allows the identification of the relative condition of degradation of a cable system and establishes, by comparison with figures of merit, if a cable system can or cannot continue operation. Diagnostic testing is considered as non-destructive.

In extreme cases, when the cable system insulation is in an advanced condition of degradation, the diagnostic tests can aggravate the condition of the cable and cause of breakdown before the test can be terminated.

The VLF Withstand Test Methods for Cable Systems are:

- VLF Testing with Cosine -- Pulse Waveform
- VLF Testing with Sine Waveform
- VLF Testing with Square Wave with Programmable Slew Rate

The VLF Diagnostic Test Methods for Cable Systems are:

- VLF Dissipation Factor (tan δ) Measurement
- VLF Partial Discharge Measurement

Field testing techniques frequently employ a combination of diagnostic and withstand test methods. They are selected based on their ease of operation and cost/benefit ratio. The various VLF test methods described are in commercial use and are accepted as alternate test methods in international standards.

5.2 VLF Testing with Cosine-Pulse Waveform

5.2.1 Method. The VLF cable test set generates a 0.1 Hz bipolar pulse wave which changes polarity sinusoidal. Sinusoidal transitions in the power frequency range initiate a partial discharge at an insulation defect, which the 0.1 Hz pulse wave develops into a breakdown channel. Within minutes, a defect is detected and forced to become a failure. It can then be located with standard, readily available cable fault locating equipment. Cable systems can be tested in preventive maintenance programs or after a service failure. Identified faults can be repaired immediately and no new defects will be initiated during the testing process. When a cable system passes the VLF test, it can be returned to service.

5.2.2 Measurement and Equipment. A dc test set forms the high voltage source. A dc to ac converter changes the dc voltage to the very low frequency ac test signal. The converter consists of a high voltage choke and a rotating rectifier that changes the polarity of the cable system being tested every five seconds. This generates a 0.1 Hz bipolar wave. A resonance circuit, consisting of a high voltage choke and a capacitor in parallel with the cable capacitance, assures sinusoidal polarity changes in the power frequency range. The use of a resonance circuit to change cable voltage polarity preserves the energy stored in the cable system. Only leakage losses have to be resupplied to the cable system during the negative half of the cycle.

The 0.1 Hz test set is easily integrated in a standard cable fault-locating and cable-testing system by making use of available dc hipot sets. Stand-alone VLF systems should be supplemented by cable fault locating equipment.

The cable system to be tested is connected to the VLF test set. In five to six steps, the test voltage is regulated to the test voltage level of 3 V_0 (V_0 is phase to ground voltage). The recommended testing time is 15 to 60 minutes. When the cable system passes the VLF voltage test, the test voltage is regulated to zero and the cable and test set are discharged and grounded. When a cable fails the test, the VLF test set is turned off to discharge the system. The fault can then be located with standard cable fault locating equipment.

5.2.3 Advantages

- The VLF test uses a 0.1 Hz pulse wave which changes polarity sinusoidal. The sinusoidal transitions in the power frequency range may initiate a partial discharge at a defect which the 0.1 Hz pulse wave may develop into a breakthrough channel.

- Due to sinusoidal transitions between the HV pulses, traveling waves are not generated.

- Due to continuous polarity changes, dangerous space charges cannot develop. Cables can be tested with an ac voltage up to three times the conductor to ground voltage with a device comparable in size, weight, and power requirements to a dc test set.

- The VLF test can be used on extruded as well as oil impregnated paper insulations.

- The VLF test with cosine-pulse wave form works best when eliminating a few singular defects from an otherwise good cable insulation. The VLF test is used to "fault" the cable defects without jeopardizing the cable system integrity.

- When a cable passes the recommended 0.1 Hz VLF test, it can be returned to service.

- Disadvantages. When testing cables with extensive water tree damage or ionization of the insulation, VLF testing alone is often "not conclusive". Additional tests which measure the extent of insulation losses will be necessary.

- Present limitations are the maximum available test voltage of 54 kV.

5.3 VLF Testing With Sinusoidal Waveform

5.3.1 Method. The VLF test set generates sinusoidal changing waves which are less than 1 Hz. When the local field strength at a cable defect exceeds the dielectric strength of the insulation, partial discharge starts. The local field strength is a function of applied test voltage, defect geometry, and space charge. After initiation of partial discharge, the partial discharge channels develop into breakthrough channels within the recommended testing time. When a defect is forced to break through, it can then be located with standard, readily available fault locating equipment. Cable systems can be tested in preventative maintenance programs of after failure. Identified faults can be repaired immediately. When a cable passes the VLF test, it can be returned to service.

5.3.2 Measurement and Equipment. The VLF test set is connected to the cable or cable system to be tested. The test voltage is regulated to the test voltage level of 3 V_0. The recommended testing time is 60 minutes or less that can be found in VLF testing guides. VLF sets have to have sufficient capacity to be able to supply and dissipate the total cable system charging energy. When the cable system passes the VLF voltage test, the test voltage is regulated to zero and the test set and cable system are discharged and grounded. When a cable fails the test, the VLF test is turned off to discharge the cable system and test set and the cable fault can then be located with standard cable fault locating equipment.

In addition to standard 0.1 Hz sinusoidal very low frequency test sets, which have been in use for many years for VLF testing of electrical machines, see ANSI-IEEE 433 [8-2], several variations are also available to meet specific cable system test requirements:

(1) VLF, less than 0.1 Hz, high-voltage generator with programmable test voltage wave forms for cable systems with mixed insulation:

- Sine wave test voltage.
- Bipolar pulse wave with defined slew rate.
- Regulated dc test voltage with positive and negative polarity.
- Programmable step test for all voltage waveforms.

(2) VLF, 0.1 Hz, high voltage generator with loss factor (tan δ) measurement capability.

(3) Partial discharge free, VLF, 0.1 Hz high voltage generator for

partial discharge testing.

4) Partial discharge free, VLF, bi-polar pulse with defined slew rate, high voltage generator for partial discharge testing.

5.3.3 Advantages

- Cables are tested with an ac voltage up to three times the conductor to ground voltage. After initiation of a partial discharge, a breakthrough channel at a cable defect develops.

- Due to continuous polarity changes, dangerous space charges do not develop in the cable insulation.

- Test sets are transportable and power requirements are comparable to standard cable fault locating equipment.

- The VLF test can be used on extruded as well as paper type cable insulations. The VLF test with sinusoidal wave form works best when eliminating a few defects from an otherwise good cable insulation. The VLF test is used to "fault" the cable defects without jeopardizing the cable system integrity. When a cable passes the recommended 0.1 Hz VLF test, it can be returned to service.

- VLF test sets with 0.1 Hz loss factor measurement capability for diagnostically identifying cables with highly degraded cable insulations are available and can be used with a 0.1 Hz withstand test.

5.3.4 Disadvantages

- When testing cables with extensive water tree damage or ionization of the insulation, VLF withstand testing alone is often "not conclusive." Additional tests which measure the extent of insulation losses will be necessary.

- Limitations are the maximum available test voltage of 36 kV rms and the maximum capacitive load of approximately 3 μF at 0.1 Hz (30 μF at 0.01 Hz). The total charging energy of the cable has to be supplied and dissipated by the test in every electrical period. This limits the size of the cable system which can be tested. A long testing time must be seen as an inconvenience rather than a limitation.

5.4 Tan Delta Test With VLF Sinusoidal Waveform

5.4.1 Method. Bahder et al., first used dissipation factor (tan δ) measurements to monitor aging and deterioration of extruded dielectric cables. Bach, et al., reported a correlation between an increasing 0.1 Hz dissipation factor and a decreasing insulation break-down voltage level at power frequency. The 0.1 Hz loss factor is mainly determined by water tree damage of the cable insulation and not by water along the conducting surfaces. The measurement of the loss factor with a 0.1 Hz sinusoidal waveform offers comparative assessment of the aging of PE, XLPE, and EPR type insulations. The test results permit differentiation between new, defective, and highly degraded cable insulations. The loss factor with a 0.1 Hz sinusoidal waveform can be used as a diagnostic test. Cables can be tested in preventative maintenance programs and returned to service after testing. The loss factor measurements at VLF can be used to justify cable replacement or cable rejuvenation expenditures.

5.4.2 Measurement and Equipment. A programmable, high voltage VLF, 0.1 Hz test generator with loss factor measurement capability is connected to the cable system under test. The loss factors of tan δ at V_0, tan δ at 2 V_0, and the differential loss factor Δ tan δ (tan δ at 2 V_0 minus tan δ at V_0) are measured. The measured values are used as figures of merit to grade the condition of the cable insulation as good, defective, or highly deteriorated.

For example, XLPE insulation is tested at a 0.1 Hz test voltage of V_0 and the tan $\delta > 2 \times 10^{-3}$, the service aged cables should be replaced. The test voltage should not be raised above V_0 in order to prevent an insulation breakdown. If for a 0.1 Hz test voltage of V_0 , and the tan $\delta >> 1.2 \times 10^{-3}$, the service aged cables should additionally be tested with VLF 3 x V_0 for 60 minutes. When cable passes this test, it can be returned to service.

If for a 0.1 Hz test voltage at V_0 and 2 V_0, the loss factors are $1.2 \times 10^{-3} <$ tan $\delta < 2 \times 10^{-3}$ and the differential loss factor Δ tan $\delta < 0.6$, the cable should be returned to service but monitored semi-annually.

If for a 0.1 Hz test voltage at V_0 and 2 V_0, the loss factors are $1.2 \times 10^{-3} <$ tan $\delta < 2 \times 10^{-3}$ and the Δ tan $\delta > 1.0$, the cable should be replaced.

It must be understood that, for different insulations, installations, and cable types, tan δ figures of merit can vary significantly from the values listed above. The test gives the best results when comparing present measurements against established historical figures of merit for a particular cable.

5.4.3 Advantages

- This test is a diagnostic, non-destructive test. Cable systems are tested with an ac voltage equal to the conductor to ground voltage.

- Cable system insulation can be graded between good, defective, and highly deteriorated.

- Cable system insulation condition can be monitored over time and a cable system history developed. Cable replacement and cable rejuvenation priority and expenditures can be planned.

- Test sets are transportable and power requirements are comparable to standard cable fault locating equipment.

5.4.4 Disadvantages

- For a 0.1 Hz VLF test set, the maximum available test voltage is 36 kV rms and the maximum capacitive load in approximately 3 μF.

- The test becomes useful after historical comparative cable system data have been accumulated.

The suitability, practicality, and effectiveness of these testing methods for service aged power cables with extruded dielectric insulation will have to be determined based on several criteria:

It is known that dc testing of extruded dielectric insulated cables is not very useful. In fact, it may cause cables to fail after having been returned to service. At this time, VLF test techniques are effective alternates for testing of service aged power cables with extruded dielectric insulation.

6. DISSIPATION FACTOR TESTING

6.1 Introduction

Note: *Some of this material is also included in Section 5 above, but is left here to aid in an understanding of this method.*

Periodic testing of service-aged cables is practiced with the desire to determine system degradation and to reduce or eliminate service failures. Dissipation factor testing describes a diagnostic testing technique for field testing of service-aged shielded cable systems.

6.2 Dielectric Loss

Service-aged, shielded cable can be described by an equivalent circuit as shown in Fig. 14-1. The cable capacitance per unit length, C, is:

$$C = 7.354\,\varepsilon / \log_{10}(d_i/d_c) \qquad (15.1)$$

Where ε = dielectric constant of the insulation
d_i = the diameter over the insulation
d_c = the diameter under the insulation (over the conductor shield)

If the space between the coaxial conductors is filled with a conventional insulating material, the cable conductance per unit length, G, is:

$$G = 2\,\pi\,k\,e_v f C \tan\delta \qquad (15.2)$$

The quantity tan δ is used to designate the lossyness of the insulating dielectric in an ac electric field. This is called loss factor or the tangent of the loss angle δ of the material. Typical values of e_V and tan δ are shown in Table 15-1.

For an applied voltage, V, the current through the loss-free dielectric is I_C and the current due to the lossyness of the material is I_G, see Fig. 15.2. The angle formed by the current, $I = I_C + I_G$ and the current I_C, is δ. The angle formed by the current, $I = I_C + I_G$ and the voltage, V, is q and cos q is the power factor. I, I_C, I_G are phasor quantities.

6.3 Method

The tan δ test is a diagnostic test that allows an evaluation of the cable insulation at operating voltage levels. The test is conducted at operating frequency or at the VLF frequency of 0.1 Hz. When the tan δ measurement exceeds a historically established value for the particular insulation type, the cable is declared defective and will have to be scheduled for replacement. If the tan δ measurements are below an historically established value for a particular insulation type, additional tests have to be performed to determine whether the cable insulation is defective.

Tests conducted on 1,500 miles of XLPE insulated cables have established a figure of merit for XLPE, tan δ = 4 x 10^{-3}. If the cable's measured tan δ > 4 x 10^{-3}, the cable insulation is contaminated by moisture (water trees). The cable may be returned to service, but should be scheduled for replacement as soon as possible. If the cable's measured tan δ < 10^{-3}, it is not possible to predict the integrity of the cable insulation. The cable insulation could have many small defects, in which case the cable may operate satisfactorily for many more years. The tan δ should be monitored regularly, and upon further deterioration of the dissipation factor, proper action taken. However, the cable could have only a few isolated large defects, which could cause it to fail upon returning it to service or within days after it has been re-energized. Therefore, if the measured tan δ < 4 x 10^{-3}, it is recommended that a VLF test at $3V_0$ be performed to identify the large defects, remove and repair them.

6.4 Measurement and Equipment

Bridge type circuits are used to measure cable capacitance and tan δ. The most common are a Schering bridge and transformer ratio arm bridge. Both test sets require an ac HV source and a loss-free capacitor standard. For balanced bridges, the dissipation factor and cable capacitance is:

Schering Bridge $$\tan\delta = 2\pi f C_1 R_1 \tag{15.3}$$

$$C_X = C_N R_1 / R_2 \tag{15.4}$$

Transformer Ratio Arm Bridge $$\tan\delta = 2\pi f C_1 R_1 \tag{15.5}$$

$$C_X = C_N W_1 / W_2 \tag{15.6}$$

6.5 Advantages

- Tan δ measurements are diagnostic tests which permit assessment of the state of aging or damage of the cable insulation.
- Cables are tested with an ac voltage at operating voltage levels.
-
- The tests are performed at operating or at VLF frequencies.

- The tan δ test can be used on plastic and rubber as well as on fluid impregnated paper type insulations.

- When a cable fails the tan δ test, it can still be returned to service until repair or replacement has been scheduled.

- Monitoring of the tan δ will establish a cable history and a deterioration will be noticed.

6.6 Disadvantages

- When a cable passes the tan δ test, it is not possible to declare the cable insulation sound.

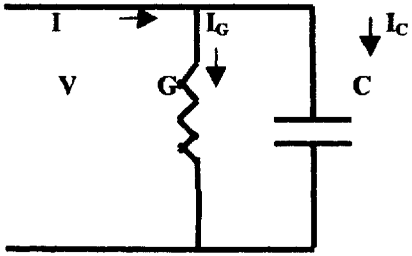
- A VLF or breakdown test will have to be performed to identify any large defects in the cable system insulation.

Table 15.1

Typical Values of Dissipation Factor

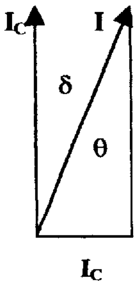
Type of Insulation	ε_V	**10^{-3} x tan δ**
Impregnated paper	3.5	2.3
Impregnated PPP	2.7	0.7
XLPE	2.3	0.1
TR-XLPE	2.3	0.2
HDPE	2.3	0.1
EPR	2.8 to 3.5	3.5

Figure 15-1



Equivalent circuit of a lossy portion of a power cable.

Figure 15-2



Phasor diagram for lossy dielectric

6.7 Dissipation Factor With VLF Sinusoidal Wave Form

6.7.1 Method. Bach, et al., reported that loss factor (tan δ) measurements at VLF (0.1 Hz sinusoidal) can be used to monitor aging and deterioration of extruded dielectric cables. The 0.1 Hz loss factor is mainly determined by water tree damage of the cable insulation and not by water along the conducting surfaces. The measurement of loss factor with 0.1 Hz sinusoidal wave form offers comparative assessment of the aging condition of PE, XLPE, and EPR type insulations. The test results permit differentiating between new, defective, and highly degraded cable insulations. The loss factor with a 0.1 Hz with sinusoidal wave form is a diagnostic test. Cables systems can be tested in preventative maintenance programs and returned to service after testing. The loss factor measurements at VLF can form the basis for the justification of cable replacement or cable rejuvenation expenditures.

6.7.2 Measurement Equipment. A programmable high voltage VLF test generator with loss factor measurement capability is connected to the cable under test. If for a test voltage of V_0 the tan $\delta > 4 \times 10^{-3}$, the service aged cables should eventually be replaced. The test voltage should not be raised above V_0 in order to prevent insulation breakdown. If for test voltage of V_0 the tan $\delta <<$ than 4×10^{-3}, the service aged cables should additionally tested with VLF at 3 V_0 for 60 minutes. When the cables passes this test, it can be returned to service without reservation. Loss factor measurements at VLF can form the basis for the justification of cable replacement or cable rejuvenation expenditures.

6.7.3 Advantages

- The test is a non-destructive, diagnostic test.
- Cables are tested with an ac voltage equal to the phase-to-ground voltage at which they operate.
- Cable system insulation can be graded as excellent, defective, or highly deteriorated.
- Cable system insulations can be monitored and history developed. Cable replacement and rejuvenation priority can be planned.
- Test sets are transportable and power requirements are comparable to standard cable fault locating equipment.

6.8.4 Disadvantages

- The maximum available test voltage is 36 kV rms and the maximum capacitive load is about 3 μF.
- The test works best after comparative cable system data have been developed.

7. OSCILLATING WAVE TESTING

7.1 Introduction

Oscillating wave testing was selected by a CIGRE task force "alternative tests after laying" as an acceptable compromise using the following criteria:

- The ability to detect defects in the insulation that will be detrimental to the cable system under service conditions, without creating new defects or causing any aging.
- The degree of conformity between the results of tests and the results of 50 or 60 Hz tests.
- The complexity of the testing method
- The commercial availability and costs of the testing equipment.

The purpose of the Oscillating Wave (OSW) testing method is to detect defects that may cause failures during service life without creating new defects that may threaten the life of the cable system.

Although OSW testing does not have a wide reputation with respect to cable testing, it is already used for testing in metal-clad substations and is being recommended for CGI cable testing.

7.2 General Description of Test Method

The test circuit consists basically of a dc voltage supply which charges a capacitance C_1, and a cable capacitance C_2. After the test voltage has been reached, the capacitance is discharged over an air coil with a low inductance. This causes an oscillating voltage in the kHz range. The choice of C_1 and L depends on the value of C_2 to obtain a frequency between 1 and 10 kHz.

7.3 Advantages

- The OW method is based on an intrinsic ac mechanism.
- The principal disadvantages of dc (field distribution, space charge) do not occur.
- The method is easy to apply.
- The method is relatively inexpensive.

7.4 Disadvantages

- The effectiveness of the OSW test method in detecting defects is better than with dc but worse when compared with ac (60 Hz).
- In particular for medium voltage cable systems, the factor f* OSW / 60 Hz voltage is approaching 1, indicating the mutual equivalence.
- For HV cable systems f * OSW / 60 Hz is significantly higher (1.2 to 1.9) which means that OSW is less effective than 60 Hz.
- For both HV and MV cable systems, f* OSW / DC is low (0.2 to 0.8) indicating the superiority of OSW over dc voltage testing.

{Note *: f OSW / 60 Hz is the ratio of breakdown values for a dielectric containing a standard defect when using respectively OSW voltage and 60 Hz voltage.}

7.5 Test Apparatus

The cable is charged with a dc voltage and discharged through a sphere gap into an inductance of appropriate value so as to obtain the desired frequency. The voltage applied to the cable is expressed by:

$$V(t) = V_1 e^{-\alpha t / \sqrt{LC}} \cos 2\pi f t \qquad (15.7)$$

where V_1 = charging voltage provided by the generator

α = damping ratio

C = $C_1 + C_2$

$$f = 1/2\pi\sqrt{LC}$$

Other test circuits are possible and give alternative solutions using different circuit configurations.

7.6 Test Procedure

Many tests carried out so far are of an experimental nature. Artificial defects like knife cuts, wrong positions of joints and holes in the insulation were created and subjected to different testing procedures of which one method was the OSW testing method.

These test procedures were intended to obtain breakdown as a criterion for comparison. The general testing procedure is as follows:

- Start to charge the cable with a dc voltage of about 1 or 2 times operating voltage.
- Increase with steps of 20 to 30 kV.
- Produce 50 shots at each voltage level.
- Time interval between shots 2 to 3 minutes.
- Proceed until breakdown occurs.

In one case, the Dutch testing specification for HV extruded cables, the OSW method is mentioned as a withstand test to be used as an after laying (installation) test. The test procedure is as follows:

- Charge the cable slowly, using the dc power supply.
- After reaching the value of 3 V_0, the dc source will be disconnected and the rapid closer activated.
- The cable circuit will be discharged through a reactor, causing the OSW testing voltage.
- This procedure should be repeated 50 times.

In the Netherlands the OSW testing method is applied several times as an after laying test for HV extruded cable systems.

7.7 Further Development Work

Since the effectiveness of the OSW testing method is not as high as would be desired, it might be very attractive to combine OSW with partial discharge (PD) site detection as an additional source of information. In the literature, details are given of an automatic PD measurement system, enabling statistical analysis and generating phase, time and amplitude resolved PD finger prints. Compared to ac 50/60 Hz generated PD finger prints, additional information results from the decreasing voltage amplitude of each OSW pulse. For medium voltage cable systems according to [14-8], this measuring system looks feasible.

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CHAPTER 16

TREEING

William A. Thue

1. INTRODUCTION

Treeing in extruded dielectric cable insulation is the term that has been given to a type of electrical deterioration that has the general appearance of a tree-like path through the wall of insulation. This formation is radial to the cable axis and hence is in line with the electrical field.

Trees that form in insulations such as polyethylene, crosslinked polyethylene, and ethylene propylene rubber cables are considered as two distinct types:

☐ Electrical trees
☐ Water trees (also known as electro-chemical trees)

They are differentiated by these and other parameters:

Electrical Trees

○ Hollow tubes
○ Water not required
○ Rapid growth (hours, weeks)

Water Trees

○ Discreet voids separated by insulation
○ Moisture is required
○ Slow growth (months, years)
○ Must be stained to see them. This may be from chemicals in or around the cable or be stained as cable is examined.

2. BACKGROUND

The phenomenon known as treeing in cables was first described by Raymer in 1912. He had been investigating electrical breakdown in the presence of discharges in paper insulated cables. The tree-like appearance of Lichtenberg figures was well known during the 1920s. These "trees" are totally different from what is seen in extruded dielectric cables because those older trees were carbon paths burned into the paper insulation that proceed concentrically around the insulating wall.

Treeing in extruded dielectric cables was described by Whitehead in 1932 in his work on electrical breakdown. The development of corona detection equipment in 1933 by Tykociner, Brown, and Paine made quantitative studies possible. Kreuger thoroughly described methods for detection and measurement of discharges in 1965.

The announcements by Vahlstrom and Lawson in 1971 and 1972 that direct buried HMWPE cables in URD systems contained trees made a significant impact on the cable industry. Previously reported results, especially by the Japanese, now became required reading.

3. FACTORS INFLUENCING ELECTRICAL TREES

Partial discharges that decompose the organic material in insulations are generally considered the common factor in the formation of electrical trees. The intrinsic electrical strength of the commonly used material is many times higher than the electrical stresses that are encountered in actual service. How can these excellent materials fail at such low stresses? The presence of internal voids, contaminants and external stress points leads to electrical stress enhancements that are sufficiently high to originate water trees.

Impulses, surges, and dc stresses seem to create hollow channels through the insulation that we know as electrical trees. When seen in wafers, electrical trees are distinct and opaque. They usually do not have to be stained to see them, but staining is certainly a recommended practice. Electrical trees require high stress but not water, and they grow quickly.

4. FACTORS INFLUENCING WATER TREES

Water (also called electro-chemical or chemical) trees grow at a slower rate than electrical trees that may take years to propagate and grow. Their appearance is sometimes obvious upon cutting wafers from aged cables, but their visibility stems from the staining of the interior of the tree wall by some form of chemical staining. Non-stained water trees disappear when the sample is dried. Staining techniques are discussed later in this Chapter.

Water treeing is influenced by the following:

Moisture
Voids
Contaminants
Ionic impurities
Temperature
Temperature gradient
Aging time
Voltage stress
pH

5. LABORATORY TESTING

Treeing was considered to be a laboratory "trick" until the 1970s. Some of the earliest work was done by Simplex Wire & Cable. Kitchens, Pratt, Ware, Crowdes, and others reported on work done with one needle embedded in small slabs of polyethylene beginning in 1956. From this work, they developed the first commercial tree retardant HMWPE insulation. They reported in 1958 that moisture was an inhibitor to tree growth. What was not known at that time was that they were looking only at electrical trees. They confidently predicted in 1958 that "HMWPE may last more than 40 years in water at operating stress up to 45 volts per mil." They were not aware of the existence of water trees as we now understand them nor did they repeat that statement made in that first paper that "...at the end of 40 years, half the lengths of cable will have failed."

Other researchers in that same time period began using two embedded needles. They came up with similar conclusions. McMahon and Perkins reported in 1960 that "corona life of a specimen of HMWPE in air is a strong function of humidity. A relative humidity of 95 to 100% gives approximately 15 times longer life than dry air." They were also only looking at electrical trees.

After the reported findings of Lawson and Vahlstrom and the Japanese reports in 1972 of "sulfide trees" in cables removed from the field, laboratory work moved towards wet testing of insulating materials such as the pie plate test of McMahon, and Perkins. By 1975, AEIC had developed an accelerated water treeing test on actual full sized cable samples placed in water filled pipes.

6. TECHNICAL DISCUSSION OF TREEING

Treeing has been demonstrated as one of the most important factors involved in loss of life for medium voltage cables. Electrical trees are considered to be associated with the final cable failure and do not exist for a long period of time. Water trees are the slower growing variety. They can extend from one electrode to the other without a service failure. Once they have formed, water trees seem to be converted to electrical trees for part or all of their length by dc, surges, and impulses. Conclusions in recent research work show that treed cables that are subjected to dc, surges, or impulses have shorter life in service after that application than cables not subjected to those stresses.

There are several possible explanations for this "conversion" of a water tree to an electrical tree, but the more commonly accepted explanation is that charges are trapped in the insulation wall. When these trapped charges are disturbed by heat or mechanical motion, they can literally bore a hole through the insulation wall. A likely scenario is that the trapped charges bore a tunnel from one void or contaminant to the next one. The insulation between these voids may be in a deteriorated condition, thus speeding up the damaged from the trapped charges. This continues until the wall has been virtually destroyed and the cable can't hold even line voltage.

Inception of water trees is likely to be the result of voltage enhancements at voids, contaminants, or other imperfections in the cable. Another significant factor is the presence of ionic impurities have shown to be especially deleterious to cables. At one time it was thought that the source of these ions was from ground water or the like. It is now established that the frequent source of these impurities is the materials in the cable -- basically contaminants in the older semiconducting shield materials. Microscopically small "chunks" of sand make the insulation/shield interface another source of voltage enhancement. Growth or propagation of the water tree is apparently quite slow -- several years in a well made cable. Bow tie trees may stop propagating as they grow large enough to decrease the voltage stress at their extremities.

We know that voltage stress and temperature accelerate this propagation of water trees. Crosslinked and thermoplastic polyethylene are adversely effected by temperatures above about 75 °C -- as demonstrated by laboratory aging studies [16-10].

It is well established that moisture penetrates polymers. What has only been demonstrated in the past 20 years or so is that ac brings moisture toward the point of higher electrical stress. This is known as dielectrophoresis. Tanaka in 1974 presented this important concept that helps explain the growth of water trees.

As briefly mentioned previously, there is only a small distinction between water and electrochemical trees that results from a "natural" staining of the interior or the voids. Pre-1970 HMWPE insulation was formulated with a staining antioxidant. These cable did not require any dying to see the trees. The change to non-staining antioxidant around 1970 resulted in water trees that could not be seen unless the wafers were put in a dye solution. In the transition period, it was thought that possibly the staining antioxidant was what had caused the trees! The dying procedure is given at the end of this section.

Trees also exist and are visible in EPR insulated cable but they can only be seen at the surface of the cut. A similar dying procedure is used for EPR but the staining time must be increased considerably. There are also proprietary methods for staining EPR cable samples. Tree counts in EPR are lower than for the non-opaque types because of not being able to see down into the material, but they also may be lower because they simply don't tree the same as XLPE cables.

Trees positively initiate at defects within the cable such as at discontinuities between the interfaces of the insulation and the two shields, and at voids and contaminants -- metal particles, threads, oxidized bits of insulation (ambers) and even at chunks of undispersed antioxidant.

Trees that have one of their points of origin at the insulation / shield interface are called "vented" trees. They always show up as the dangerous trees as compared to ones that stay completely within the wall of insulation -- the non-vented tree. The probable explanation here is that pressure can build up within the non-vented tree and this suppresses the partial discharge.

7. METHYLENE BLUE DYING PROCEDURE

In a 500 ml beaker with watch glass cover, place:

A. 250 ml distilled water
B. 0.50 gm methylene blue
C. 8 ml concentrated aqueous ammonia

Heat to boiling with continuous stirring. Use a fume hood or other adequate ventilation.

Place the specimens to be stained in the solution using a wire for installation and removal.

Remove specimens from hot solution from time to time to be certain that the staining is neither too light nor too dark.

When the specimens are adequately stained, remove from the hot solution, rinse in hot water, and wipe dry.

A thin film of oil on the surface of the sample makes observation with a microscope much less confused by scratches.

8. OBSERVATION IN SILICONE OIL

An excellent method of observing several inches of insulation at one time is to place a one foot sample on the insulated cable (the semiconducting insulation shield must be removed!) in a glass beaker with silicone oil that has been heated to about 130 ^{0}C. At about this temperature, all of the crystallinity is gone and the insulation becomes quite clear. The surface of the conductor shield can be observed for smoothness. Voids or contaminants in the insulation wall can be readily seen. Note: "voids" can be created during the test by moisture in the insulation resulting from service conditions.

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CHAPTER 17

LIGHTNING PROTECTION OF DISTRIBUTION CABLE SYSTEMS

William A. Thue

1. INTRODUCTION

Distribution cable systems have peak failure rates during the summer months throughout North America. Research work has shown that impulse surges to cables shortens their service life [17-1]. It is also well documented that water trees reduce the impulse level of extruded dielectric insulated cables.

Most of the effort that has been spent in the past on lightning protection of distribution system components has been on overhead transformers. This is logical when you consider that the companies that build transformers are also the ones that sell arresters.

The older paper insulated cables were manufactured with an inherently high impulse level and that level was maintained over the 40 plus years of life of the system. Today, the extruded dielectric insulated cables that are used so extensively in underground systems, exhibit a dramatic drop in electrical strength in just a few months of service. It is important to note that crosslinked polyethylene (XLPE) cables start with a much higher impulse level than ethylene propylene (EPR) or paper cables. EPR cables have initial impulse strengths less than the others, but their impulse level doesn't drop as quickly and levels out. With time, both XLPE and EPR have impulse levels that are much nearer the basic impulse level (BIL) of the system than for paper cables. Because of this, lightning protection is a significant consideration for these newer cables.

2. SURGE PROTECTION TERMINOLOGY

2.1 Protective Margin

This is defined as being:

$$\frac{\text{Insulation Withstand Level}}{\text{Arrester Protection Level}} \times 100$$

Another form of this equation for protective margin is:

$$\left[\frac{\text{Equipment BIL in kV}}{\text{Arrester Discharge Voltage in kV + Discharge Voltage of Arrester Leads in kV}} - 1\right] \times 100$$

A minimum protection margin of 20% over BIL has usually been recommended for transformers.

2.2 Voltage Rating

Voltage rating of an MOV arrester is based on its duty-cycle test. The duty-cycle test defines the maximum permissible voltage that can be applied to an arrester and allow it to discharge its rated current. Another way to consider this is that it is the voltage level at which power follow current can be interrupted after a surge discharge has taken place. At voltage levels above this, power follow current interruption is doubtful. The safe arrester rating is usually determined by the highest power voltage that can appear from line to ground during unbalanced faults and shifting of the system ground.

2.3 Highest Power Voltage

The highest power voltage can be calculated by multiplying the maximum system line-to-line voltage by the coefficient of grounding at the point of arrester placement.

2.4 Coefficient of Grounding

This is defined as the ratio, expressed in percent, of the highest rms line-to-ground voltage on an unfaulted phase during a fault to ground. Systems have historically been referred to as being effectively grounded when the coefficient of grounding does not exceed 80%.

2.5. Sparkover

This refers to the initiation of the protective cycle that occurs when the surge voltage reaches the level at which an arc develops across the device's electrodes to complete the discharge circuit to ground. In terms of voltage across gapped arresters, this is somewhat indefinite since sparkover of a simple gap structure is a function of both the wave front and the voltage of the incoming surge.

The essential requirement of a proper sparkover level is the speed of response to steep fronts such as natural lightning yet give a consistent response to waves with slower rates of rise which are typical of indirect strokes and system generated surges.

Sparkover of an arrester should not be confused with "flashover". Flashover refers to the exterior arcing which can occur, for instance, when surfaces become contaminated.

2.6 Surge Discharge

Surge discharge refers to the situation where the arrester must handle the power frequency line current as well as the momentary surge current. This power follow current continues to flow until the arrester can extinguish the arc.

2.7 IR Discharge Voltage

The IR discharge voltage of an arrester is the product of the discharge current and the resistance or inductance of the discharge path. While the resistance may be very low, the discharge current can be very high and the IR discharge voltage can reach levels that equal or exceed the arrester sparkover voltage. The inductance of the combined line and ground leads must be kept as short as possible. This is accomplished by placing the arrester as close as practical to the cable termination and always connecting the arrester closer to the incoming line than the termination. See Fig. 17-5.

3. WAVE SHAPE AND RATE OF RISE

Natural lightning must be simulated in the laboratory to test and evaluate lightning protection devices and equipment. This is accomplished with a surge generator. A group of capacitors, spark gaps and resistors are connected so that the capacitors are charged in parallel from a relatively low voltage source and then discharged in a series arrangement though the device being tested.

The terms used to describe both natural and artificial lightning are "wave shape" and “rise time”. The wave crest is the maximum value of voltage reached. Wave shape is expressed as a combination of the time from zero to crest value for the front of the wave and the time from zero to one-half crest of the wave tail. Both values of time are expressed in microseconds. The rate of rise is determined by the slope of a line drawn through points of 10 and 90 percent of crest value.

Testing of surge arresters has historically been done with an 8 x 20 microsecond wave, but more recent work has been done at 4 x 10 even though a direct stroke of natural lightning is more nearly 1 x 1000. See Figure 17-1 to see how these times are defined.

Figure 17-1
Wave Shape

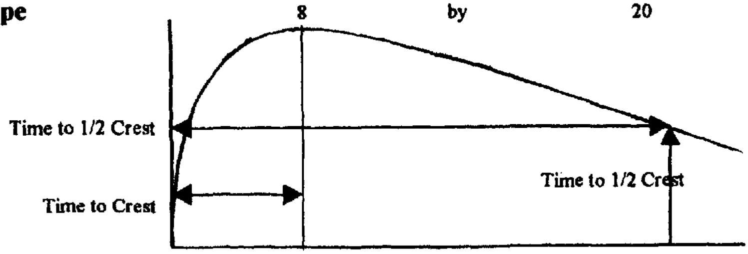
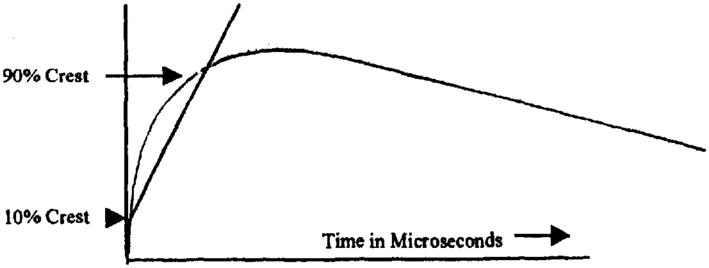


Figure 17-2
Rate of Rise



4. OPERATION OF A SURGE ARRESTER

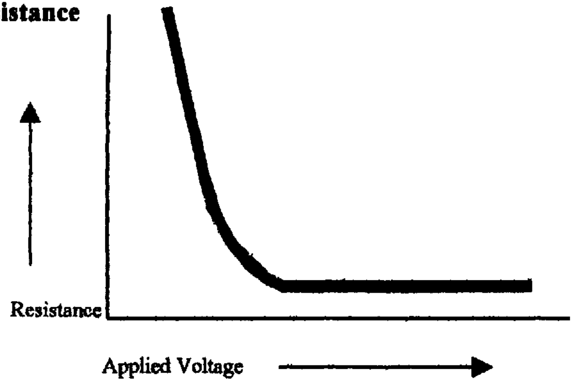
4.1 Air Gaps

The original surge arrester was a simple air gap. They were made of a simple rod or spheres installed between line and ground that were far enough apart to keep the line voltage from sparking over but close enough to discharge when a surge occurred. Air gaps have the disadvantage of allowing system short circuit current to continue to flow until the breaker, fuse or other backup device operates.

Air gaps have another disadvantage. Electrically speaking they are sluggish and their response varies as stated above. Sparkover may not occur until a considerable portion of a rapidly rising lightning surge has been impressed on the system. The short gap spacing necessary to provide adequate protection against steep front lightning waves may result in frequent and unnecessary sparkovers on minor power frequency disturbances.

Non-linear resistance can best be considered as resistance that varies inversely with applied voltage. Under normal voltage conditions, the resistance is high; under unusual voltages the resistance is low.

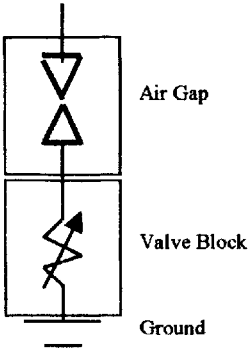
Figure 17-3
Non-Linear Resistance



The material that, in the past, has been used so extensively in valve arresters is silicon carbide. It is blended with a ceramic binder, pressed into blocks under high pressure and fired in kilns at temperatures of over 2000 °F. This component is the valve block. The number of valve blocks used in an arrester is determined resistance requirement for the rating of the system.

For silicone carbide blocks, it is essential that an air gap be in series with the blocks. This gap must ionize the atmosphere in the arc chamber to break down that gap before the blocks encounter any voltage. After the air gap breaks down, the valve blocks begin to conduct the combination of surge current and power current. The high voltage of the lightning surge decreases the resistance of the valve blocks and the current flows to ground. The voltage now across the blocks is approximately the line-to-ground voltage of the system. The valve blocks revert to their normal high resistance. This forces the power flow current to be reduced to a value that the series blocks can interrupt at the next system current zero.

Figure 17-4
Schematic of a Silicone Carbide Arrester



4.3 Metal Oxide Arresters

Commonly known as MOVs, metal oxide varistors, became available for distribution systems in about 1978. Their first use on distribution systems were on terminal poles, hence the riser pole arrester term.

Gaps are not required because the material is extremely non-linear. The lower half of the schematic shown in Figure 17-4 represents a MOV arrester. A voltage increase of just over 50% results in a conduction current change of 1 to 100,000. The absence of gaps allows these devices to operate much faster than the older gapped silicone carbide arresters. The absence of gaps is a major factor in allowing MOVs to be used in load break elbow arresters.

Grounding resistance / impedance must be treated more seriously now that the URD systems are using conduit and/or jacketed neutral wires. With bare neutral wires, the stroke energy was dissipated along the cable run. The insulation provided by the jacket or conduit makes low resistance grounds at the terminals an essential factor.

5. NATURAL LIGHTNING STROKES

The understanding of natural lightning has increased tremendously since the early 1980s. EPRI efforts led to the construction of antennas throughout the United States to record lightning strokes. These systems are now capable of pinpointing the time, location, magnitude, and polarity of strokes that occur between clouds and ground. What has been determined is that the rate of rise and the current magnitudes of natural lightning is much more severe than previously assumed.

From this information, we now have recorded strokes of over 500,000 amperes.

Although these high stroke currents do occur, examination of arresters removed from service do not show that they have discharged such high values of current. One possible explanation is the division of stroke currents into multiple paths. Another is that the majority of strokes terminate to buildings, trees, or the ground without directly striking the electrical system. Recent research indicates that indirect strokes may be the biggest cause of failures on today's distribution systems.

Rate of rise is extremely important because the faster the rate, the higher the discharge voltage will be for all types of arresters. Recorded data shows that natural lightning strokes have rise times between 0.1 and 30 μs with 17% of the recorded strokes having rise times of 1 μs or faster and 50% are less than 2.5 μs. For the same wave shape, the average rate of rise increases with the crest magnitude. Using the "standard" 8 x 20 microsecond wave and a 9 kV gapped arrester, the discharge voltage is about 40 kV. For the same 20 kA stroke but rising to crest in one microsecond, the arrester would have a 54.4 kV discharge, or a 36% increase. Metal oxide arresters (without gaps, of course) commonly exhibit a 12 to 29% increase under similar circumstances.

The inductance (hence length and shape) of the arrester leads becomes more pronounced with the faster rate of rise. Applying the generally used value of 0.4 microhenries per foot, the lead voltage is 8 kV per foot of total lead length at 20 kA per microsecond and 16 kV per foot at 40 kA. Assuming new arresters and two feet of total lead length, the total voltage at 20 kA and 40 kA would be 70 and 96 kV respectively. Saying this in a different way, a stroke having a 40 kA per microsecond rate of rise would add 32 kV to the arrester discharge voltage given in a typical manufacturer's literature.

Prudent engineering suggests that the level of protection should be calculated for a family of possible values of current and rates of rise for the anticipated lightning activity in the service area under study. This suggests currents such as 40 kA for parts of central Florida but only 10 kA or lower for California. Rates of rise of 1 to 3 microseconds are commonly used in calculations.

For an interesting note, these systems are of use to many organizations. Lightning stroke information is used by the forest service to warn of fires. Antennas near Anchorage, Alaska, warn of volcano eruptions that produce lightning.

6. TRAVELING WAVE PHENOMENA

Whenever a lightning stroke encounters an electric system, energy is propagated along the circuit from the point of origin in the form of a traveling wave. The current in the wave is equal to the voltage divided by the surge impedance of the circuit. Surge impedance is approximately equal to the square root of the ratio of the self inductance to the capacitance to ground of the circuit. Both the inductance and capacitance are values per given unit length making the surge impedance of a circuit independent of the actual length of the circuit.

A traveling wave will keep moving without change in a circuit of uniform surge impedance except for the effects of attenuation. As soon as the wave reaches a point of change in impedance, reflections occur.

A wave reaching an open circuit is reflected without change in shape or polarity. The resultant voltage at the open end will be the vector sum of the incident wave and the reflected wave. This is the source of the voltage doubling circumstance. If an arrester is located at the open point, this doubling does not occur after the arrester begins to discharge.

When a wave arrives at a ground or other value of impedance that is lower than the surge impedance of the circuit, the incident wave is reflected without change in shape but with a reversal in polarity.

No reflections will occur on a circuit that is connected to ground through a resistance / impedance that is equal to the surge impedance of the circuit since there is no change in impedance.

It is convenient to think of traveling waves as having square shapes to illustrate the points just mentioned, but since real surges have a finite time to crest, the results of the superposition of the actual wave shapes are quite different than the square waves, which are the worst case scenario.

7. VELOCITY OF PROPAGATION

For practical purposes, a traveling wave on an overhead line travels at the speed of light -- 984 feet per microsecond. The velocity of propagation of a traveling wave in cables commonly used today is about half the speed of light, or 500 to 600 feet per microsecond. This can be derived from the fact that, in an insulated and shielded cable, the speed is reduced depending on the specific inductive capacity, or permativity, of the insulating material.

$$V = 1 \Big/ \sqrt{LC} \quad = \quad 984 \text{ ft per } \mu\text{sec.} \tag{17.1}$$

This calculates out to 659 ft/μsec for TR-XLPE and 577 ft/μsec for an EPR.

Velocity of propagation becomes important to the protection of distribution cables because the travel time from the junction arrester to the end of the cable run is very short as compared to the conduction time of the arrester. Consider a typical 5,000 foot long loop that is open at the midpoint. At 500 feet per microsecond, the travel time to the end is only 5 microseconds to the end and 10 microseconds for the round trip. The arrester conduction time for an 8 x 20 microsecond wave is about 50 microseconds. This means that the junction arrester still has 90% of its conduction time left when the wave has traveled to the end of the cable. If the end does not have an arrester, the reflected wave will travel back towards the junction point and add to the incoming voltage wave throughout the length of the cable. Thus the entire cable is exposed to the "doubled" wave. The amount of time the incoming wave is maintained becomes an important consideration as to the exposure of the cable to this full doubling of voltage.

Attenuation has a negligible effect on the reflected voltage because the low loss insulations that are in use today do not attenuate the wave appreciably in the relatively short runs used for distribution systems.

8. PROPER CONNECTION OF ARRESTERS

There are several extremely important installation rules for arresters:

☐ Keep both the line and ground side leads as short and straight as possible. (It is the sum of the two lead lengths that must be used in the calculations).

☐ The lead from the line should go to the arrester FIRST -- then to the termination.

☐ The ground resistance should be as low as practical. This means ten ohms if the cable has an insulating jacket or is in a conduit.

8.1 Lead Lengths

The issue of lead length on the voltage that will be impressed on a cable has been discussed earlier in this chapter. All of that is correct. There is, however, one more issue here. Does that lead carry the lightning current? If the lightning current flows in that lead, its length is a factor. If, on the other hand, the lead does not carry lightning current its length and impedance are not factors. In the real world, the current generally flows through all the paths that are available. The amount of current times the length of each lead establishes the voltage that is impressed on the cable. The practical point is that the circuit must be analyzed in its entirety.

8.2 Route of Current Flow

In the beginning of this section, it was stated that the lead from the incoming line should first be attached to the arrester -- then to the termination. Wait a minute. This isn't the way we have always done it! Are you certain of that?

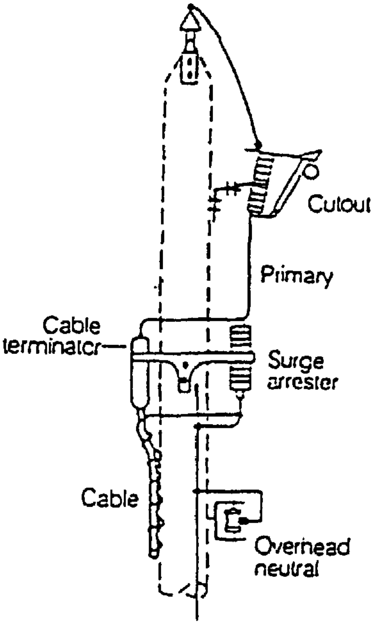
Yes. If we can visualize the flow of lightning current as a flood of water, we can easily recognize that we would be much better off if we could divert that flood around our house - not through it. That is why the arrester is the first connection point. The bulk of the current flows through the arrester and through its ground. The termination lead length is not very significant because it isn't carrying that much current.

8.3 Ground Resistance / Impedance

Why is the ground resistance / impedance important? We are concerned about voltage and voltage is the product of current and impedance (length). Almost all of the current that goes through the arrester must flow to ground at the arrester location. Remember that the impedance of an overhead line (the neutral for our purposes) is about 50 to 60 ohms. If the ground at the arrester is very high, then all of that lightning current must flow along those neutrals. That means that the "footing" resistance is 60 ohms. The voltage that is developed is the current multiplied by 60 ohms. Even if there are two directions for the ground current to flow, this can be a very high voltage.

The voltage build-up through the arrester is increased by the voltage build-up in the ground circuit.

Figure 17-5
Correct Arrester Connection Diagram



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CHAPTER 18

CABLE PERFORMANCE

William A. Thue [18-1]

1. INTRODUCTION

Cable failure reporting in the United States had its beginning by action of the Edison Electric Institute and its predecessor the National Electric Light Association. A significant early report covered the performance of paper insulated, lead covered cables, splices, and terminations beginning in 1923. Failure rates of cable were reported in units per 100 installed miles for a variety of causes. Splice and termination reports were based on failures per 1000 units that were in service. These reports were continued through 1966 and served both as a useful performance guide as well as a barometer of the effectiveness of the cable specifications in effect. The National Electric Light Association prepared the first U.S. paper cable specification in 1920 for cables rated up to 15 kV. The Association of Edison Illuminating Companies upgraded this to 45 kV in 1930.

The advent of underground residential distribution (URD) systems with the extensive use of extruded dielectric cable convinced the U.S. utility group to become involved in specifications for this evolving type of cable. Later usage in conventional urban duct and manhole systems to take the place of the backbone paper insulated cables finalized this requirement.

During the early 1970s, isolated reports of early cable failures on the extruded dielectric systems began to be documented in many parts of the world. "Treeing" was re-introduced to the cable engineer's vocabulary, but with an entirely new meaning from the paper cable use of the word.

The Edison Electric Institute's last attempt to report distribution cable failures was in 1973. A vacuum was therefore developed in the U.S. for distribution cable failure reporting. No system for similar reporting existed in the world.

2. CABLE FAILURE DATA

The data coming from a few U.S. utilities and work funded by EPRI by 1975 [18-2] showed that thermoplastic polyethylene insulated cables were failing at a rapidly increasing rate and that XLPE and EPR cables had a lower failure rate.

The next compilation of data began in 1976 with 16 and later 21 utilities in North America reporting their failure rates on an annual basis for both polyethylene and crosslinked polyethylene insulated cables [18-3].

Failure data kept by the utilities was rather meager. It was decided to only request data based on type of insulation, number of failures for each year and the total amount of each of those insulation types were in service at the end of the year. It was also decided to only ask for failures of known electrical causes, such as defective cable, insulation deterioration, lightning, etc., and then include all "unknown" causes since treeing analysis was not easily obtainable.

3. PERFORMANCE

Comparable data from EEI for paper insulated, medium voltage power cables installed in the United States is included as Figure 18-1 for the years of 1923 through 1966 -- when the data was no longer collected. Similar data showing the electrical failures of polyethylene and crosslinked polyethylene for 21 North American utilities is shown in Figure 18-2. AEIC then began to collect and report similar data in 1984 except that data was requested from all utilities. A major future step was to request information on jackets, ducts, voltage stress levels, etc. The old 21 company base was not separately recorded, however. They also began to collect data for tree retardant XLP as well as EPR. See Figures 18-3, 18-4, 18-5 and 18-6.

AEIC strongly suggests that this data be carefully analyzed and understood. This is important since the age of the cables were not known and could skew the results. For instance, jacketed cable is probably newer than non-jacketed cable and hence the failure rate of the older cables may not be entirely the result of a jacket.

The European community also began to collect data and their results were published as UNIPEDE-DISCAB that represents most of the European countries. Their data includes PE, XLP, EPR and PVC.

4. ANALYSIS OF DATA

Cable failure rates in the U.S. have historically been calculated on the basis of failures per 100 miles of installed cable. The rest of the world reports failures per 100 kilometers. All data is shown as rates per 100 miles for ease of comparison.

The most frequently used form for the data shows the number of failures per 100 miles for each year. The disadvantage of such depiction is that older cable is looked at in the same light as new cable. This data is more readily available, but a preferred method is to take into account the years in service for all cables. This is accomplished by integrating the miles installed with the years of service. The expression is:

Service Index $A_j = \Sigma \; i \, (M_i N_j - i)$ (18.1)

where A = system age in year j in terms of service mile-years,
M_i = the number of miles of cable installed in year i,
N_{j-i} = the number of years from i to j.

Years	Miles of Cable Multiplied by Age					
A	a					
B	2a	b				
C	3a	2b	c			
D	4a	3b	2c	d		
E	5a	4b	3c	2d	e	
F	6a	5b	4c	3d	2e	f, etc.

At the end of the year F, the age of the system is:

$$A_F = 6a + 5b + 4c + 3d + 2e + f \qquad (18.2)$$

where a, b, c, etc. represent the number of miles of cable installed in year A, B, C....

This analysis can be shown as a summation of failures per 1,000 mile-years, this is:

Year	Cumulative Miles of Cable at End of Year	Summation
A	a	a
B	b	a + b
C	c	a + b + c
D	d	a + b + c + d
E	e	a + b + c + d + e
	Σ =	5a+4b+3c+2d+e

It is only necessary to add the miles of cable installed each year to the summation of cable installed in all previous years to obtain updated mile-years from this equation.

5.0 PRESENT SITUATION

There is no new data to report regarding cable failure statistics. This is the result of two factors:

- ☐ New cable performance is very good. The few problems with new cable makes collecting data seem unnecessary.
- ☐ There are not enough people to do the essential work.

The last North American data was collected for 1991 performance by AEIC. The data shows an extremely low failure rate for TR-XLPE and EPR. The XLPE rate is not escalating to a troublesome level. The European collection of data has also been discontinued.

This is certainly an indication of the effort that has been directed toward improved cables - both from the material suppliers standpoint as well as the cable manufacturers.

Figure 18-1
PILC Cable Failures in the United States

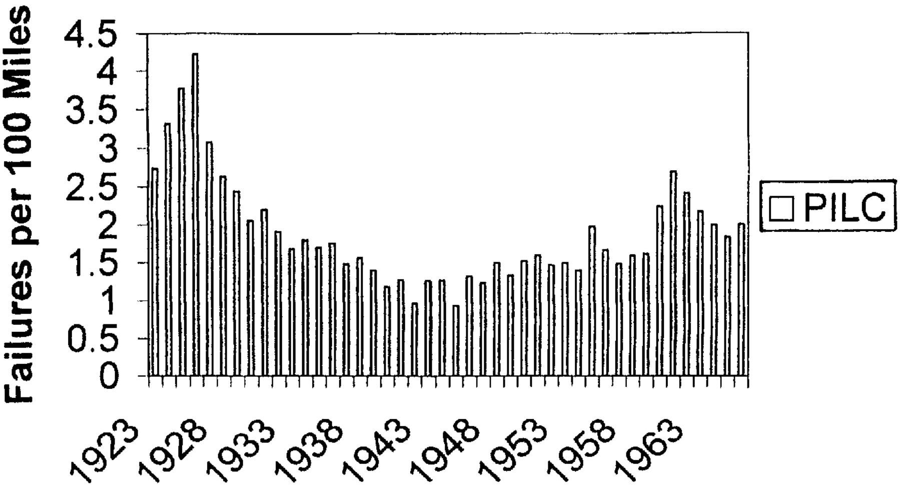


Figure 18-2
Electrical Failures of Extruded Dielectric Cables

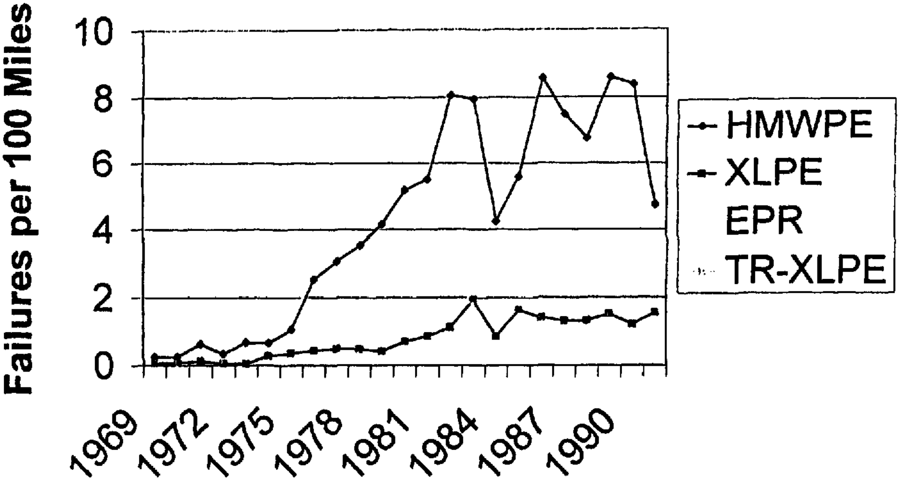


Figure 18-3
AEIC Cable Failure Data, High and Low Electrical Stress

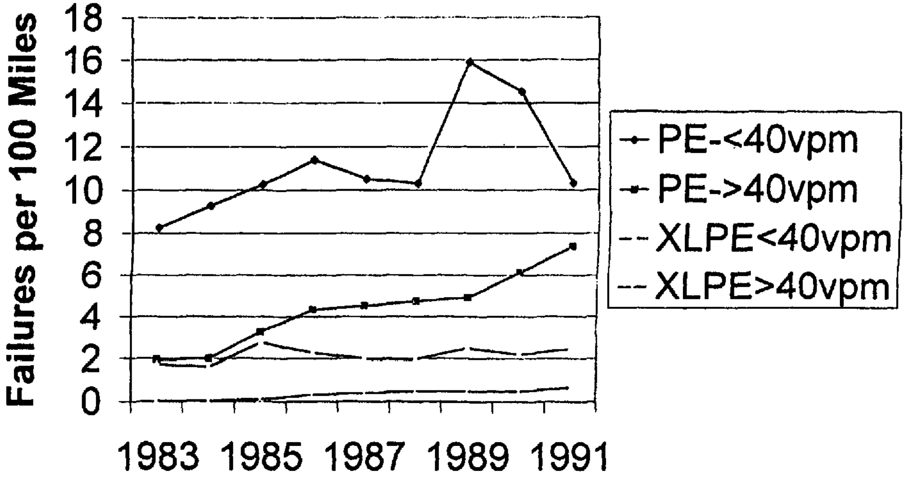


Figure 18-4
AEIC Cable Failure Data, Duct versus Direct Buried

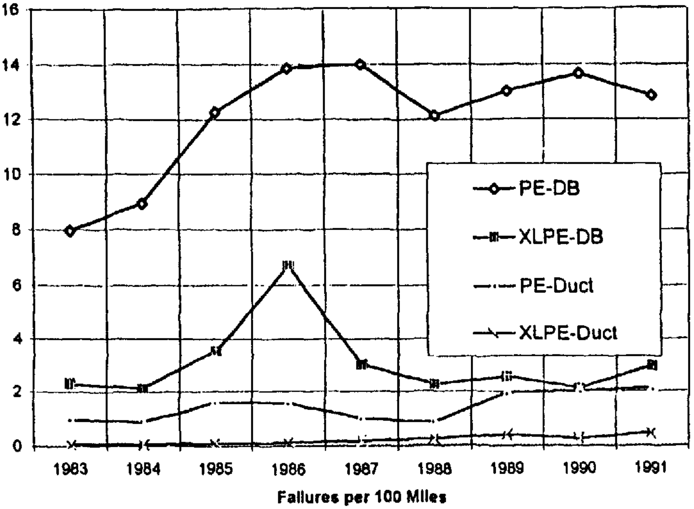


Figure 18-5
AEIC Cable Failure Data, Jacket versus Non-Jacket Construction

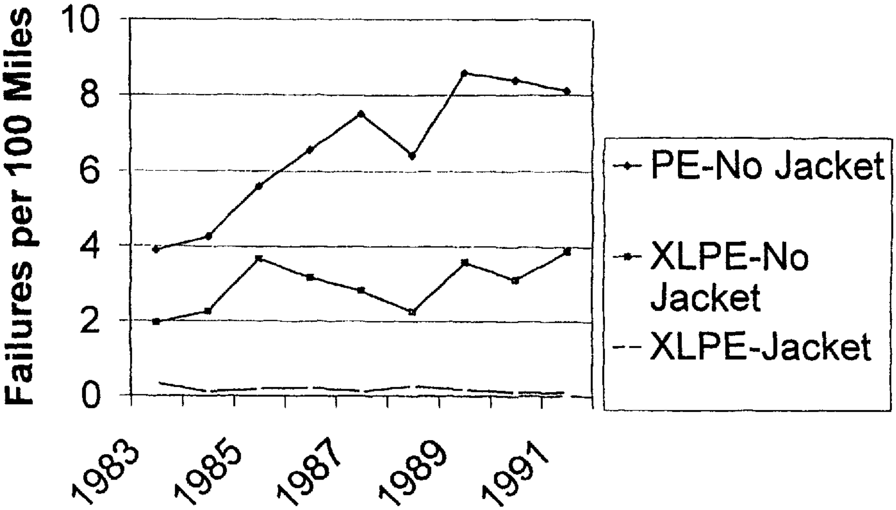
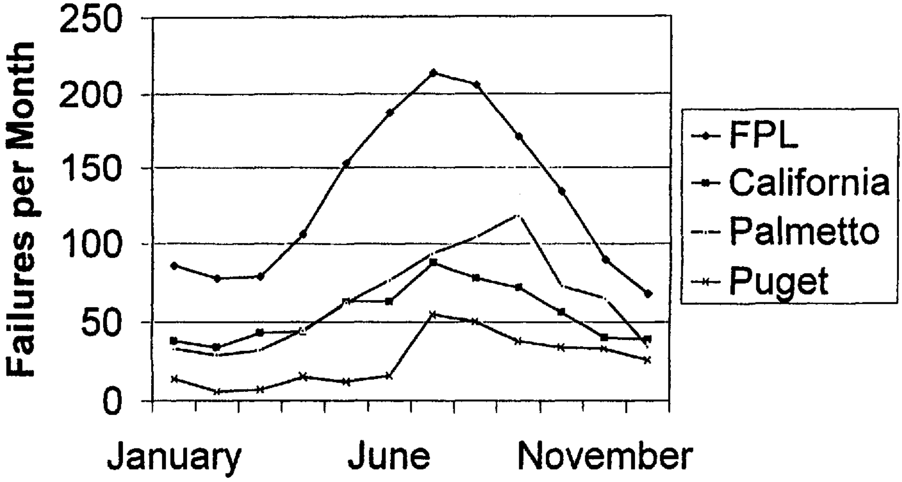


Figure 18-6
Cable Failure Data, Seasonal Pattern



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CHAPTER 19

CONCENTRIC NEUTRAL CORROSION

William A. Thue

1. INTRODUCTION

In nature, metals are usually found in combinations such as oxides or sulfides, not as a pure metal. Nature wants to change those pure metals back to their original state after we have refined them to an almost pure metal. That process is known as corrosion [19-1, 19-2, 19-3].

Corrosion may be defined as the destruction of metals by chemical or electrochemical reaction with the environment. The fundamental reaction involves a transfer of electrons where in a moist or wet environment some positive ions lose electrical charges. These positive charges are acquired by the metallic member and a portion of the metal surface goes into solution, hence is corroded. The entire process may be divided into an anodic reaction (oxidation) and a cathodic reaction (reduction). The anodic reaction represents acquisition of charges by the corroding metal and the cathodic reaction represents the loss of charges by hydrogen ions that are discharged. The flow of electricity between the anodic and cathodic areas may be generated by local cells set up either on a single metallic surface, or between dissimilar metals.

1.1 Electromotive Series

The tendency for metals to corrode by hydrogen ion displacement is indicated by their position in the electromotive series shown in Table 19-1. To achieve these precise voltages, the metals must be in contact with a solution in which the activity of the ion indicated is one mol per 1,000 grams of water and at 77°F (25°C). Different values of voltage will be obtained in other solutions.

Metals above hydrogen displace hydrogen more readily than do those below hydrogen in this series. A decrease in hydrogen ion concentration (acidity), tends to move hydrogen up relative to other metals. An increase in the metal ion concentration tends to move the metals down relative to hydrogen. Whether or not hydrogen evolution will occur in any case is determined by several other factors besides the concentration of hydrogen and metallic ions.

Table 19-1
Electromotive Series

(Anodic End)

Metal	Ion	Volts
Magnesium	Mg + 2e*	-2.34
Aluminum	Al + 3e	-1.67
Zinc	Zn + 2e	-0.76
Chromium	Cr + 3e	-0.71
Iron	Fe + 2e	-0.44
Cadmium	Cd + 2e	-0.40
Nickel	Ni + 2e	-0.25
Tin	Sn + 2e	-0.14
Lead	Pb + 2e	-0.13
Hydrogen	H + e	Arbitrary 0.00
Copper	Cu + 2e	+0.34
Silver	Ag + e	+0.80
Palladium	Pd + 2e	+0.83
Mercury	Hg + 2e	+0.85
Carbon	C + 2e	+0.90
Carbon	C + 4e	+0.90
Platinum	Pt + 2e	+1.2
Gold	Au + 3e	+1.42
Gold	Au + e	+1.68

(Cathodic End)

* Note: "e" stands for electrons (negative charges)

1.2 Electrochemical Equivalents

The electrochemical equivalent of a metal is the theoretical amount of metal that will enter into solution (dissolve) per unit of direct current transfer from the metal to an electrolyte. Table 19-2 shows that theoretical amount of metal removed in pounds per year with one ampere of direct current flowing continuously from the material.

Table 19-2
Electrochemical Equivalents

Metal	Pounds Removed per Amp per Year
Carbon (C++++)	2.16
Carbon (C ++)	4.23
Aluminum	6.47
Magnesium	8.76
Chromium	12.5
Iron	20.1
Nickel	21.1
Cobalt	21.2
Copper (Cu++)	22.8
Zinc	23.5
Cadmium	40.5
Tin	42.7
Copper (Cu +)	45.7
Lead	74.2

1.3 Hydrogen Ion Concentration

A normal solution is one that contains an "equivalent weight" (in grams) of the material dissolved in sufficient water to make one liter of the solution. The equivalent weight of hydrogen is 1 and therefore one gram of hydrogen ions in a liter of water is a normal acid solution. The hydroxyl ion has an equivalent weight of 17 (1 for the hydrogen and 16 for oxygen). Therefore, 17 grams in a liter is equal to the normal alkaline solution.

Since acids produce hydrogen ions when dissolved in water, the concentration of the hydrogen ions is a measure of the acidity of the solution. The hydrogen ion concentration is expressed in terms of pH. Stated mathematically, the pH value is the logarithm of the reciprocal of the hydrogen ion concentration in terms of the normal solution. A change of one in pH value is equivalent to a change of ten times in concentration.

In any aqueous solution, the hydrogen ion concentration multiplied by the hydroxyl ion concentration is always a constant. When the concentrations are expressed in terms of normal solution, the constant is equal to 10^{-14}. It follows that a solution having a pH equal to 7 is neutral, less than 7 has an acidic reaction, and more than 7 has an alkaline reaction

Table 19-3
Significance of Hydrogen Ion Concentration

pH	Hydrogen Ion Concentration	Hydroxyl Ion Concentration	Reaction
0	1.0×10^{-0}	1.0×10^{-14}	Acidic
1	1.0×10^{-1}	1.0×10^{-13}	Acidic
2	1.0×10^{-2}	1.0×10^{-12}	Acidic
3	1.0×10^{-3}	1.0×10^{-11}	Acidic
4	1.0×10^{-4}	1.0×10^{-10}	Acidic
5	1.0×10^{-5}	1.0×10^{-9}	Acidic
6	1.0×10^{-6}	1.0×10^{-8}	Acidic
7	1.0×10^{-7}	1.0×10^{-7}	Neutral
8	1.0×10^{-8}	1.0×10^{-6}	Alkaline
9	1.0×10^{-9}	1.0×10^{-5}	Alkaline
10	1.0×10^{-10}	1.0×10^{-4}	Alkaline
11	1.0×10^{-11}	1.0×10^{-3}	Alkaline
12	1.0×10^{-12}	1.0×10^{-2}	Alkaline
13	1.0×10^{-13}	1.0×10^{-1}	Alkaline
14	1.0×10^{-14}	1.0×10^{-0}	Alkaline

2. TYPES OF CORROSION

There are numerous types of corrosion, but the ones that are discussed here are the ones that are most likely to be encountered with underground power cable facilities.

In this initial explanation, lead will be used as the referenced metal. Copper neutral wire corrosion will be discussed as a separate topic later.

2.1 Anodic Corrosion (Stray dc Currents)

Stray dc currents come from sources such as welding operations, flows between two other structures, and -- in the days gone by -- street railway systems.

Anodic corrosion is due to the transfer of direct current from the corroding facility to the surrounding medium--usually earth. At the point of corrosion, the voltage is always positive on the corroding facility. In the example of lead sheath corrosion, the lead provides a low resistance path for the dc current to get back to its source. At some area remote from the point where the current enters the lead, but near the inception point of that stray current, the current leaves the lead sheath and is again picked up in the normal dc return path. The point of entry of the stray current usually does not result in lead corrosion, but the point of exit is frequently a corrosion site.

Clean sided corroded pits are usually the result of anodic corrosion. The products of anodic corrosion such as oxides, chlorides, or sulfates of lead are carried away by the current flow. If any corrosion products are found, they are usually lead chloride or lead sulfate that was created by the positive sheath potential that attracts the chloride and sulfate ions in the earth to the lead.

In severe anodic cases, lead peroxide may be formed. Chlorides, sulfates, and carbonates of lead are white, while lead peroxide is chocolate brown.

2.2 Cathodic Corrosion

Cathodic corrosion is encountered less frequently than anodic corrosion--especially with the elimination of most street railway systems.

This form of corrosion is usually the result of the presence of an alkali or alkali salt in the earth. If the potential of the metal exceeds -0.3 volts, cathodic corrosion may be expected in those areas. In cathodic corrosion, the metal is not removed directly by the electric current, but it may be dissolved by the secondary action of the alkali that is produced by the current. Hydrogen ions are attracted to the metal, lose their charge, and are liberated as hydrogen gas. This results in a decrease in the hydrogen ion concentration and the solution becomes alkaline.

The final corrosion product formed by lead in cathodic conditions is usually lead monoxide and lead / sodium carbonate. The lead monoxide formed in this manner has a bright orange / red color and is an indication of cathodic corrosion of lead.

2.3 Galvanic Corrosion

Galvanic corrosion occurs when two dissimilar metals in an electrolyte have a metallic tie between them. One metal becomes the anode and the other the cathode. The anode corrodes and protects the cathode as current flows in the electrolyte between them. The lead sheath of a cable may become either the anode or the cathode of a galvanic cell. This can happen because the lead sheath is grounded to a metallic structure made of a dissimilar metal and generally has considerable length. Copper ground rods are frequently a source of the other metal in the galvanic cell.

The corrosive force of a galvanic cell is dependent on the metals making up the electrodes and the resistance of the electrolyte in which they exist. This type of corrosion can often be anticipated and avoided by keeping a close watch on construction practices and eliminating installations having different metals connected together in the earth or other electrolyte.

2.4 Chemical Corrosion

Chemical corrosion is damage that can be attributed entirely to chemical attack without the additional effect of electron transfer. The type of chemicals that can disintegrate lead are usually strong concentrations of alkali or acid. Examples include alkaline solutions from incompletely cured concrete, acetic acid from volatilized wood or jute, waste products from industrial plants, or water with a large amount of dissolved oxygen.

2.5 AC Corrosion

Until about 1970, ac corrosion was felt to be an insignificant, but possible, cause of cable damage [19-5]. In 1907, Hayden [19-6], reporting on tests with lead electrodes, showed that the corrosive effect of small ac currents was less than 0.5 percent as compared with the effects of equal dc currents.

Later work using higher densities of ac current has shown that ac corrosion can be a major factor in concentric neutral corrosion. See Section 3.2.4.

2.6 Local Cell Corrosion

Local cell corrosion, also known as differential aeration in a specific form, is caused by electrolytic cells that are created by an inhomogenious environment where the cable is installed. Examples include variations in the concentration of the electrolyte through which the cable passes, variations in the impurities of the metal, or a wide range of grain sizes in the backfill. These concentration cells corrode the metal in areas of low ion concentration.

Differential aeration is a specific form of local cell corrosion where one area of the metal has a reduced oxygen supply as compared with nearby sections that are exposed to normal quantities of oxygen. The low oxygen area is anodic to the higher oxygen area and an electron flow occurs through the covered (oxygen starved) material to the exposed area (normal oxygen level).

Differential aeration corrosion is common for underground cables, but the rate of corrosion is generally rather slow. Examples of situations that can cause this form of corrosion include a section of bare sheath or neutral wires that are laying in a wet or muddy duct or where there are low points in the duct run that can hold water for some distance. A cable that is installed in a duct and then the cable goes into a direct buried portion is another good example of a possible differential aeration corrosion condition.

Differential aeration corrosion turns copper a bright green.

2.7 Other Forms of Corrosion

There are numerous other forms of corrosion that are possible, but the most probable causes have been presented. An example of another form of corrosion is microbiological action of anaerobic bacteria which can exist in oxygen-free environments with pH values between 5.5 and 9.0. The life cycle of anaerobic bacteria depends on the reduction of sulfate materials rather than on the consumption of free oxygen. Corrosion resulting from anaerobic bacteria produces sulfides of calcium or hydrogen and may be accompanied by a strong odor of hydrogen sulfide and a build-up of a black slime. This type of corrosion is more harmful to steel pipes and manhole hardware than to lead sheaths.

3. CONCENTRIC NEUTRAL CORROSION

This section will concentrate on the corrosion mechanisms associated with concentric neutral, medium voltage power cables. [19-10]. The most probable causes of concentric neutral corrosion include:

- Differential aeration.
- Stray dc current flow.
- DC current generated through ac rectification.
- AC current flow between neutral and earth.
- Galvanic influence with semiconducting layer (unjacketed cables).
- Galvanic influence of alloy coating and copper neutral wires and other action from dissimilar metals.
- Soil contaminants.

Electric power systems had used copper directly buried in the ground for over 60 years without problems being experienced. Most of the applications consisted of butt wraps under poles and substation ground grids. The successful operation led to a complacency when underground residential distribution cables began to be installed in vast quantities after 1965.

Although the number of cable failures caused by neutral corrosion were very small, when these cables did fail for other reasons it became clear that neutral corrosion was taking place in situations that were not anticipated.

3.1 Research Efforts

EPRI funded a series of projects to study the problem and to suggest remedies: [19-8]--[19-14]. The subjects include mechanisms of corrosion, cathodic protection methods, procedures for locating corrosion sites, and step-and-touch potential data for jacketed as well as unjacketed cable.

3.2 Mechanisms of Concentric Neutral Corrosion

Differential aeration is one specific type of local cell corrosion and is probably the most frequent cause of neutral corrosion. Fortunately, this is a relatively slow form of attack. This type of corrosion is caused when metal is exposed to soils or water having a difference in oxygen content. Examples of this are:

- Soils with different grain sizes.
- Cable going from a direct buried environment to a conduit.
- A conduit run that has a section with standing water and another section that has an unlimited supply of oxygen.
- Jacketed cable spliced to unjacketed cable.

The key concept here is the dissimilar environment and oxygen supply for a run of cable. It can occur in a small crevice made by a large grain of sand or stone in contact with the copper neutral conductor. Areas of low aeration change to an area that is well aerated. This form of corrosion is frequently caused when special backfills are brought in to replace the native soil. The native soil usually has a consistent grain size while the imported material may have quite a different grain size. Pockets are thereby formed.

Another very frequent cause of this form of corrosion is where an unjacketed cable leaves a conduit (such as under a street) and enters the earth. The same sort of cell is created by having a low section of conduit that is filled with water while the adjacent section is in a dry conduit The use of an overall jacket (either insulating or semiconducting) eliminates this condition.

Stray dc current flow problems are very similar to the lead sheath condition previously described. This situation is frequently encountered when an anode that is used to protect a gas pipeline that is installed in close proximity to an unjacketed cable. This damage occurs very rapidly.

Stray dc current causes dissolution of the copper where anions are present that contribute to the reaction. The rate of dissolution may not follow Faraday's law precisely because of other electrochemical oxidation reactions that occur in parallel.

DC current flow can be generated through ac rectification across a film of copper oxide. Copper neutral wires quickly develop an oxide coating. This coating provides a rectification boundary so that ac current is restricted from flowing back to the neutral wires. This is similar to the situation in 3.2.4.

AC corrosion was not recognized as a serious problem in the initial URD systems. The opinion was that while ac current flow might take off metal during one half cycle, the other half cycle would bring it back. The concept of rectification was commonly discussed as a possible explanation for ac corrosion in the 1960s. It was not until the 1970s that ac corrosion was recognized as a major concern for copper neutrals. The Final Report of EPRI EL-4042 [19-12] published in 1985 stated that the effect of high ac current density was creating this rapid corrosion mechanism on bare URD and UD cables.

Above some threshold of ac current density, the positive cycle tends to dissolve more metal than the negative cycle can plate back. Especially in cables with large conductors that are heavily loaded (such as feeder cables), the amount of current that can flow off the neutral wires at one point and then back on at another is quite large. Another explanation of this flow of current off and then back on the neutral wires is that shifts in potential exist along the cable length due to the differences in the current densities.

Galvanic influence with the semiconducting insulation shield material and bare or tinned copper is another form of concentric neutral corrosion. A voltage differential exists between the carbon in the semiconducting layer and the neutral wires. Corrosion, although not a widespread cause of failure, must be considered.

Dissimilar metal corrosion is probable if plating is used on the neutral wires and no jacket is applied over these wires. Areas of bare copper may exist during the factory plating process or are created by mechanical scraping during handling and field installation efforts. The result is a local cell corrosion due to the two different metals.

Research has shown that bare wires out perform plated wires in the field. When jackets are used, bare copper wires are recommended and are almost always specified.

Soil contaminants and other direct chemical action is another source of problems for URD cables. Examples of this are high quantities of chemicals in the soil such as from fertilizers, peat, cinders and decaying vegetation. Decaying vegetation produces hydrogen sulfide that reacts rapidly to deteriorate copper.

Combinations of the previously discussed corrosion mechanisms do occur in the real world. Multiple sources of corrosion accelerate the problem.

4. JACKETS

An overall jacket is the preferred construction for new cable. Both insulating and semiconducting jackets have demonstrated their ability to virtually eliminate corrosion of the neutral wires. An encapsulated jacket made with linear low density polyethylene is the type most frequently specified. See Chapter 8 for a complete discussion of jackets.

5. CATHODIC PROTECTION

Cathodic protection [19-7] can be applied to the copper neutral wires of existing cable that did not have a jacket or where the jacket may be damaged. An obvious place where cathodic protection should be considered is where a bare neutral cable goes from a direct buried environment to a conduit as under a road. Another is where a long section of jacketed cable is spliced onto a short section of existing bare neutral cable. Here the short section will be even more vulnerable to corrosion.

Noteworthy efforts have been expended towards solving this concern and the reference section contains excellent sources of advice regarding design and installation recommendations.

6. LOCATION OF CORROSION SITES

The existence of deteriorated copper neutral wires is an unwelcomed fact. How to identify their existence and then locate the precise site of the corrosion has shown great advancement in recent years. Several technologies are presently available.

6.1 Resistivity Measurements of Neutral Wires

Resistive techniques are used to measure the resistance of neutral wires of installed cables. Instruments are available for testing the resistance of the neutral wires while the cable is energized. This value is compared with the original resistance for that length of cable and the size and number of original wires. A new or undamaged cable would show a resistance ratio of 1 while a cable that has half of the wires remaining would have a ratio of 2.

6.2 Location of Deteriorated Sites

If the reading of the resistance ratio warrants, the precise location of the corroded area can be obtained by using a form of time domain reflectometry (TDR). This equipment is similar to that used for locating cable faults. [19-15].

Damage to the a neutral wire must be great enough so that a reflection can be seen on the screen of the TDR. This may mean that a wire with only pitting may not be identifiable, and the cable would appear to be sound. The reflection of that wave from the end of the cable has a lower amplitude than intact wires. A cable with uniform corrosion may not be seen, but discreet sites cause reflections and are readily detected.

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CHAPTER 20

GLOSSARY

James D. Medek

This Glossary contains many of the cable terms used throughout this book and is furnished as an aid to understanding the text. The reader is encouraged to utilize the more complete definitions that may be found in the *IEEE Standard Dictionary of Electrical and Electronics Terms,* IEEE Standard 100-1996.

Abrasion Resistance Ability to resist surface wear.

Accelerated Life Test Subjecting a product to test conditions more severe than normal operating conditions, such as voltage and temperature, to accelerate aging and thus to afford some measure of probable life at normal conditions or some measure of the durability of the equipment when exposed to the factors being aggravated.

Acceptance Test A test to demonstrate the degree of compliance with specified requirements. A test demonstrating the quality of the units of a consignment. The term "conformance test" is recommended by ANSI to avoid any implication of contractual relations.

Aging The irreversible change of material properties after exposure to an environment for an interval of time.

Ampacity The current carrying capacity of a cable, expressed in amperes. The current that a cable can carry under stated thermal conditions without degradation.

Ampere (Amp) The basic SI unit of the quantity of electric current. That constant current that if maintained in two straight parallel conductors of infinite length, or negligible cross section, and placed one meter apart in vacuum, would produce a force equal to 2×10^{-7} newton per meter of length.

Amplitude The maximum value of a sinusoidally varying wave form.

Annealing The process of removing or preventing mechanical stress in materials by controlled cooling from a heated state, measured by tensile strength.

Asymmetrical Not identical on both sides of a central line; not symmetrical.

Backfill The materials used to fill an excavation, such as sand in a trench.

Bedding A layer of material that acts as a cushion or inter-connection between two elements of a device, such as the jute or polypropylene layer between the sheath and wire armor in a submarine cable.

Bending Radius The inner radius of a cable, such as when it is trained or being installed.

BIL (Basic Impulse Level) The impulse voltage that electrical equipment is required to withstand without failure or disruptive discharge when tested under specified conditions of temperature and humidity. BILs are designated in terms of the crest voltage of a 1.2 x 50 microsecond full-wave voltage test.

Braid An interwoven cylindrical covering usually of fiber or wire.

Bridge A circuit that measures by balancing a number of impedances through which the same current flows.

Butt Lap Complete turn of tape where the adjacent layers are next to each other but do not overlap.

Cable, Aerial An assembly of one or more insulated conductors that are lashed or otherwise fastened to a supporting messenger.

Cable, Belted A multi-conductor cable having a layer of insulation over the assembled insulated conductors.

Cable, Spacer An aerial cable system made of covered conductors supported by insulating spacers; generally for wooded areas.

Cable, Submarine A cable designed for crossing under bodies of water; having mechanical strength for installation and removal, and limited protection from anchors, debris, and other mechanical damage.

Cable, Triplexed A helical assembly of three covered or insulated conductors; sometimes with one bare conductor used as a neutral.

Cable Tray A rigid structure to support cables. A type of raceway normally having the appearance of a ladder. May be open at the top (or side) to facilitate changes, or be covered with a ventilated or solid cover.

Cambric A fine weave of linen, cotton, or other fiber that is used as an insulation base.

Capacitance The storage of electricity in a capacitor. The opposition to voltage change, measured in Farads.

Capacitor Any device having two conductors separated by insulation with the conductors having opposite electrical charges.

Capstan A rotating drum used to pull cables or ropes by friction as they are wrapped around the drum.

Carbon Black A black pigment produced by the incomplete burning of natural gas or oil; used for semiconducting purposes.

Catenary The natural curve assumed by a completely flexible material hanging freely between two supports. A cable curing tube having a catenary curvature.

Corona Extinction Voltage (CEV) The voltage at which partial discharge is no longer detectable within the dielectric structure when measured with instrumentation having specific sensitivity, following the application of a higher voltage to achieve corona inception.

Charge The quantity of positive or negative ions in or on an object; unit: coulomb.

Corona Inception Voltage (CIV) The voltage at which partial discharge is initiated within the dielectric structure with instrumentation having specific sensitivity.

Coefficient of Friction The ratio of the tangential force needed to start or maintain relative motion between two contacting surfaces to the perpendicular force holding them in contact.

Conduit Fill. The percentage of cross-sectional area used in a conduit as compared with the cross-sectional area of the conduit.

Continuous Vulcanization A system utilizing heat, and frequently pressure, to vulcanize materials after extrusion onto a conductor.

Corona An electrical discharge caused by ionization of a gas by an electrical field.

Corrosion The deterioration of a substance (usually a metal) as a result of a chemical reaction with its environment.

Current, Charging The current needed to bring a cable, or other capacitor, up to voltage; determined by capacitance of the cable. After withdrawal of voltage, the charging current returns to the circuit. For ac circuits, the charging current will be 90 degrees out of phase with the voltage.

Current, Induced Current in a conductor due to the application of a time-varying electromagnetic field.

Current, Leakage That small amount of current that flows through insulation whenever a voltage is present. The leakage current is in phase with the voltage and is a power loss.

Density (physics) The ratio of mass to volume at a specified temperature.

Dielectric Absorption The storage of charges within an insulation (dielectric); evidenced by the decrease of current flow after application of dc voltage.

Dielectric Constant The capacitance of a dielectric in comparison with the capacitance of a vacuum where both capacitors have identical geometry. Also referred to as specific inductive capacity (SIC).

Dielectric Loss. The time rate at which electrical energy is transformed into heat when a dielectric is subjected to a changing electric field.

Dielectric Strength The maximum voltage that an insulation can withstand without breaking down; usually expressed as a gradient—volts per mil or kilovolts per millimeter.

Direction of Lay The longitudinal direction in which the components of a cable (stands) run over the top of the cable as they recede from an observer looking along the axis of a cable; expressed as left-hand or right-hand.

Dissipation Factor The energy lost when voltage is applied across an insulation due to reactive current flow. Also known as power factor and tan delta.

Drain Wires A group of small gage wires helically applied over a semiconducting insulation shield that is designed as a path for leakage current return—as opposed to fault current or a system neutral.

Eccentricity A measure of the centering of an item within a circular area. The ratio, expressed as a percentage, of the difference between the maximum and minimum thickness (or diameter) of an annular area.

Eddy Currents Circulating currents induced in conducting materials by varying magnetic fields; usually considered undesirable because they represent loss of energy and create heat.

Elongation The fractional increase in length of a material as it is stressed under tension. The amount of stretch of a material in a given length before breaking.

Endosmosis The penetration of water into a cable insulation by osmosis. Aggravated and accelerated by dc and ac voltage across the insulation where it is also known as electro-endosmosis.

Filler A relatively inert and low-cost material added to a compound to improve physical properties and make it less costly.

Flame Retardant Does not support or spread flame. An additive that enhances the flame resistance of a compound.

Hard Drawn A relative measure of temper; drawn to obtain maximum tensile strength.

Hardness Resistance to plastic deformation; stiffness or temper; resistance to scratching, abrasion, or cutting.

Hypalon Trade name for chlorosulphanated polyethylene.

Impedance (Z) The opposition to current flow in an ac circuit; impedance consists of resistance, capacitive reactance, and inductive reactance.

Insulated Separated from other surfaces by a substance permanently offering a high resistance to the passage of energy through that substance.

Insulation Level The thickness of insulation for circuits having ground fault detectors which interrupt fault currents within one minute (100% level), one hour (133% level), or over one hour (173% level).

Intercalated Tapes Two or more tapes applied simultaneously so that each tape overlays a portion of the other. Example: copper and carbon shielding tapes in paper insulted cables.

Interstices A space between strands of a conductor or between individual phases of a multi-conductor cable.

Ionization (1) The process or the result of any process by which a neutral atom or molecule acquires charge. (2) A breakdown that occurs in gaseous phases of an insulation when dielectric stress exceeds a critical value without initiating a complete breakdown of the insulation system.

Ionization Factor The difference between dissipation factors at two specified values of electrical stress. The lower of the two stresses is usually selected that the effect of the ionization on dissipation factor is negligible.

Insulation Resistance The measurement of dc or ac resistance of a dielectric at a specified temperature. May be either volume or surface resistivity.

Irradiation Bombardment with a variety of subatomic particles that usually causes changes in physical properties. A form of crosslinking by bombardment with high-energy electrons.

Jacket A non-metallic polymeric protective covering over cable insulation or shielding.

Jamming The wedging of three or more cables in a conduit such that they can no longer be moved during cable pulling.

Jam Ratio The ratio of the overall diameter of one cable to the inner diameter of the conduit I which they are being pulled. For three cables in a conduit, the critical jam ratio is between 2.8 and 3.2.

Lay The axial length of one turn of the helix of any component of a cable.

Lay Length Distance along the axis for one turn of a helical component.

Load Factor The ratio of the average to the peak load over a specified period of time.

Magnetic Field The force field surrounding any current carrying conductor.

MCM Old form of “thousand circular mils” for conductor size in English system; presently kcmil.

mil Unit of measure of a conductor equal to 0.001 inch.

mm Millimeter. Unit of measure equal to 0.001 meter.

Monomer A term denoting a single property or ingredient. A molecule of low molecular weight used as a starting material to produce molecules of larger molecular weight called polymers.

Mouse A device that is attached to one end of a line and blown into a duct or pipe for use in installation of a pulling line. Usually consists of a series of rubber gaskets sized to fit the duct or pipe.

Mutual Inductance The common property of two electric circuits whereby an electromotive force in induced in one circuit by a change of current in the other circuit.

MW Megawatt, equal to 1,000 kilowatts and 1,000,000 watts.

Nominal A term used to describe functional behavior as being within expected norms or as designed.

Ohm The SI unit of electrical resistance; one ohm equals one volt per ampere.

Organic Matter originating from plant or animal life; composed of chemicals—such as carbon and hydrogen.

Oscillation The variation, usually with time, of the magnitude of a quantity which is alternatively greater or smaller than a reference.

Oscillograph An instrument for recording or making visible the oscillations of a electrical quantity.

Osmosis The diffusion of fluids through a membrane.

Oxidize (1) To combine with oxygen, (2) to remove one or more electrons, (3) to dehydrogenate.

Oxygen Index A test to rate flammability of materials in a mixture of oxygen and nitrogen.

Ozone A form of oxygen, O^3, produced by a high electrical stress; active molecules of oxygen.

Parameter The characteristic of a circuit from which other voltages or currents are referenced with respect to magnitude and time displacement—usually under steady-state conditions.

Permeability (1) The passage or diffusion of a vapor, liquid, or solid through a barrier without physically or chemically affecting either, (2) the rate of such passage.

pH An expression of the degree of acidity or alkalinity of a substance on a scale of one to ten. Acid is less than 7.0, neutral is 7.0, and alkaline is over 7.0.

Phase Angle The measure of the progression of a periodic wave in time or space from a chosen instant or position.

Phase Conductor Any of the main conductors of a cable other than the neutral.

Phase Sequence The order in which the successive members of a periodic wave reach their positive maximum values.

Pig (1) A device to isolate a portion of a pipeline to permit the local application of a test pressure. (2) An ingot of metal, such as lead.

Pilot Wire An auxiliary insulated conductor in a circuit used for control or data transmission.

Plasticizers Chemical agents added during compounding of plastics to make them more flexible and pliable.

Polarization Index Typically the ratio of insulation resistance after ten minutes to the measured value at one minute.

Polymer A high molecular weight compound whose structure can usually be represented by a repetition of small units of that compound.

Pothead (1) A termination of a cable (potential head). (2) A device for sealing the end of a cable while providing insulated egress for the conductor or conductors. Most commonly associated with the porcelain housings for paper insulated cables.

Power Factor (power) The cosine of the phase angle between the voltage and the current. Power factor is of interest because it is the measure of useful work. A unity power factor means that all of the current is used for useful work.

Power Factor (cable) A typical cable has a power factor of about 0.1 or less—meaning that it is almost a perfect capacitor and the majority of the current consumed by the charging current of the cable is not "useful" power. For cable purposes, the power factor is expressed as the tangent of the angle delta between the current and the voltage. For the small angles found in typical medium voltage power cables, the $\sin \delta$, $\tan \delta$, and $\cos \Theta$ are essentially equal.

Power Loss Losses due to internal cable impedances, such as the conductor I^2R and the dielectric losses in the insulation. These losses create heat.

Pulling Compound The lubricating compound applied to the surface of a cable to reduce the coefficient of friction during installation in conduits and ducts.

Pulling Eye A device attached to the end of a cable to facilitate field connection of the pulling ropes.

Quadruplexed Four conductors twisted together.

Relative Capacitance The ratio of the material's capacitance to that of a vacuum of the same configuration. Also known as specific inductive capacitance (SIC).

Reverse Lay Reversing the direction of lay. For multiple conductor aerial cables, a reversal in lay at a specified distance to facilitate field connections.

Rockwell Hardness A measure of hardness of a material to indentation by a diamond or steel ball under pressure at two levels of stress.

Screen Pack A series of metal screens used in an extruder for straining out impurities.

Semiconducting A conducting medium where conducting is by electrons. The resistance of these materials is generally in the range between that of conductors and insulators.

Shield An electrically conducting layer that provides a smooth surface with the surface of the insulation. In Europe, this is called a "screen."

Sidewall Bearing Pressure The normal force on a cable under tension at a bend. This is a force that tends to flatten or crush the cable and is usually given as an allowable force for a given distance.

Skin Effect The tendency of current to crowd toward the outer surface of a conductor that increases with conductor diameter and frequency of the applied current.

Specific Inductive Capacitance The energy lost when voltage is applied across an insulation due to the reactive current flow. Also known as dissipation factor.

Strand, Sector A stranded conductor formed into sectors of a circle to reduce the overall diameter of the cable.

Strand, Segmental A stranded conductor formed of sectors that are insulated from one another to reduce the ac resistance of the conductor.

Strand, Unilay A stranded conductor having a unidirectional lay of the various wires. Frequently used in low voltage power cables.

Stress Relief Cone A mechanical component of a termination to reduce electrical stress levels on a shielded cable, originally in the shape of a cone.

Tandem Extrusion Extruding two or more layers on a conductor where the extruders are in close proximity to one another.

Thermoplastic (1) A plastic that is thermoplastic in behavior. (2) Having the quality of softening when heated and of returning to its original state when cooled below that range.

Thermosetting Materials that, upon curing, undergo an irreversible chemical and physical property change so that subsequent heating does not return them to their original state.

Tinned A strand having a thin coating of pure tin or an alloy of tin and lead. Used over copper to reduce the effect of sulfur from certain rubber compounds and to facilitate solder connections. Many aluminum connectors are also tin plated to minimize the formation of aluminum oxide.

Triplexed Three conductors or cables that are twisted together.

Voltage Rating The designated maximum permissible phase-to-phase ac (or direct current) voltage at which a cable is designed to operate.

Vulcanize To cure by chemical reaction. Produces changes in the physical properties of the material by the reaction of an additive (originally sulfur) at an elevated temperature.

CHAPTER 21

TABLES AND DATA

1. Tables

The tables in this chapter have been copied by permission of the groups that are specifically mentioned. It did not seem wise to abridge those tables since they are the basis for most North American cable designs, especially in the power field.

Figure 21-1

Stress Concentration at Tip of a Conductive Ellipsoid Placed in a Uniform Electrical Field

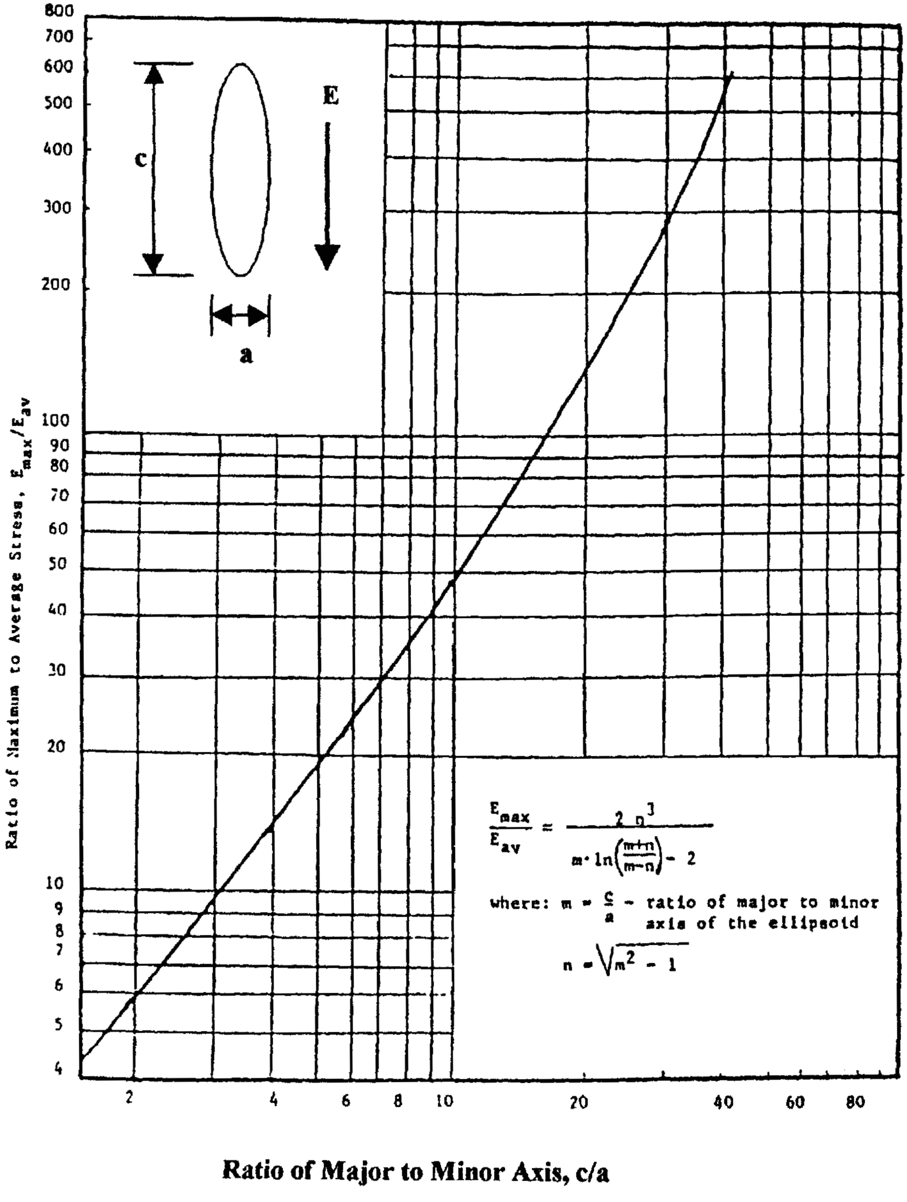

Figure 21-2

Typical Leakage Curve of dc Current, Assuming Constant Voltage

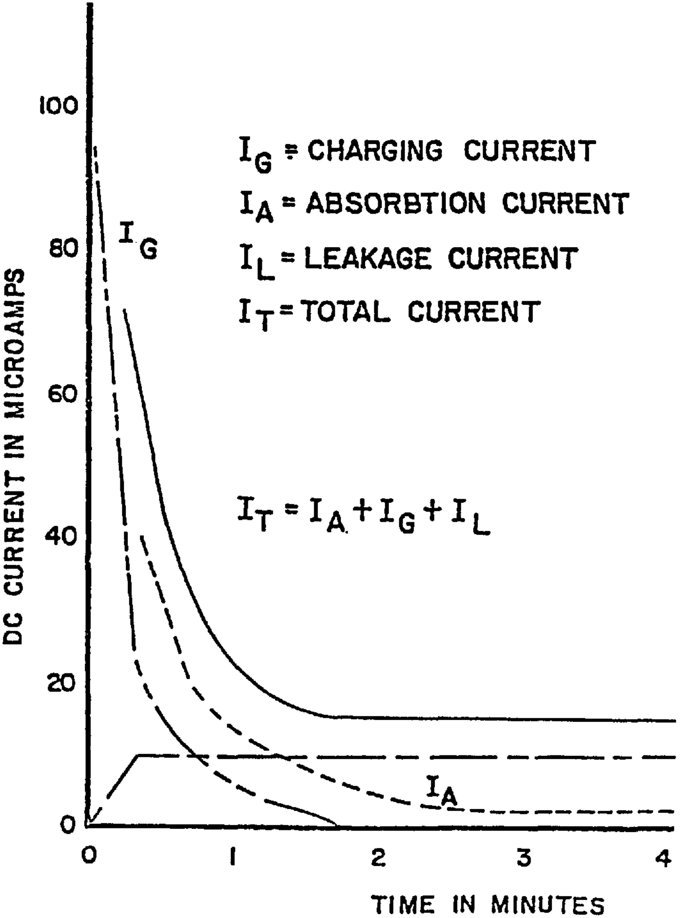

Table 21-1

Nominal Direct Current Resistance In Ohms Per 1000 Feet** at 25°C (77°F) of Solid and Concentric Lay stranded Conductor

Conductor	Solid			Concentric Lay Stranded*				
Size	Aluminum	Copper		Aluminum	Copper			
AWG or kcmil		Uncoated	Coated	Class, B, C, D	Uncoated	Coated		
					Class B, C, D	Class B	Class C	Class D
22	27.1	16.5	17.2	27.4	16.7	17.9	...	...
20	16.9	10.3	10.7	17.3	10.5	11.1	...	...
19	13.5	8.20	8.52	13.7	8.33	8.83	...	...
18	10.7	6.51	6.76	10.9	6.67	7.07	...	...
17	8.45	5.15	5.35	8.54	5.21	5.52	...	...
16	6.72	4.10	4.26	6.85	4.18	4.43	...	...
15	5.32	3.24	3.37	5.41	3.30	3.43	...	...
14	4.22	2.57	2.67	4.31	2.63	2.73	2.79	2.83
13	3.34	2.04	2.12	3.41	2.08	2.16	2.21	2.22
12	2.66	1.62	1.68	2.72	1.66	1.72	1.75	1.75
11	2.11	1.29	1.34	2.15	1.31	1.36	1.36	1.39
10	1.67	1.02	1.06	1.70	1.04	1.08	1.08	1.11
9	1.32	0.808	0.831	1.35	0.825	0.856	0.856	0.874
8	1.05	0.640	0.659	1.07	0.652	0.678	0.678	0.680
7	0.833	0.508	0.522	0.851	0.519	0.538	0.538	0.538
6	0.661	0.403	0.414	0.675	0.411	0.427	0.427	0.427
5	0.524	0.319	0.329	0.534	0.325	0.338	0.339	0.339
4	0.415	0.253	0.261	0.424	0.258	0.269	0.269	0.269
3	0.329	0.201	0.207	0.336	0.205	0.213	0.213	0.213
2	0.261	0.159	0.164	0.266	0.162	0.169	0.169	0.169
1	0.207	0.126	0.130	0.211	0.129	0.134	0.134	0.134
1/0	0.164	0.100	0.102	0.168	0.102	0.106	0.106	0.106
2/0	0.130	0.0794	0.0813	0.133	0.0810	0.0842	0.0842	0.0842
3/0	0.103	0.0630	0.0645	0.105	0.0642	0.0667	0.0669	0.0669
4/0	0.0819	0.0500	0.0511	0.0836	0.0510	0.0524	0.0530	0.0530
250	0.0694	...	...	0.0707	0.0431	0.0448	0.0448	0.0448
300	0.0578	...	...	0.0590	0.0360	0.0374	0.0374	0.0374
350	0.0495	...	...	0.0505	0.0308	0.0320	0.0320	0.0320
400	0.0433	...	...	0.0442	0.0269	0.0277	0.0280	0.0280
450	0.0385	...	...	0.0393	0.0240	0.0246	0.0249	0.0249
500	0.0347	...	...	0.0354	0.0216	0.0222	0.0224	0.0224
550	...	...	...	0.0321	0.0196	0.0204	0.0204	0.0204
600	...	...	...	0.0295	0.0180	0.0187	0.0187	0.0187
650	...	...	...	0.0272	0.0166	0.0171	0.0172	0.0173
700	...	...	...	0.0253	0.0154	0.0159	0.0160	0.0160
750	...	...	...	0.0236	0.0144	0.0148	0.0149	0.0150
800	...	...	...	0.0221	0.0135	0.0139	0.0140	0.0140
900	...	...	...	0.0196	0.0120	0.0123	0.0126	0.0126
1000	...	...	...	0.0177	0.0108	0.0111	0.0111	0.0112
1100	...	...	...	0.0161	0.00981	0.0101	0.0102	0.0102
1200	...	...	..	0.0147	0.00899	0.00925	0.00934	0.00934
1250	...	...	...	0.0141	0.00863	0.00888	0.00897	0.00897
1300	...	...	...	0.0136	0.00830	0.00854	0.00861	0.00862
1400	...	...	...	0.0126	0.00771	0.00793	0.00793	0.00801
1500	...	...	...	0.0118	0.00719	0.00740	0.00740	0.00747
1600	...	...	...	0.0111	0.00674	0.00694	0.00700	0.00700
1700	...	...	...	0.0104	0.00634	0.00653	0.00659	0.00659
1750	...	...	...	0.0101	0.00616	0.00634	0.00640	0.00640
1800	...	...	...	0.00982	0.00599	0.00616	0.00616	0.00622
1900	...	...	...	0.00931	0.00568	0.00584	0.00584	0.00589
2000	...	...	...	0.00885	0.00539	0.00555	0.00555	0.00560
2500	...	...	...	0.00715	0.00436	0.00448	...	..
3000	...	...	...	0.00596	0.00363	0.00374	...	...
3500	...	...	...	0.00515	0.00314	0.00323	...	...
4000	...	...	...	0.00451	0.00275	0.00283	...	...
4500	...	...	...	0.00405	0.00247	0.00254	...	...
5000	...	...	...	0.00364	0.00222	0.00229	...	...

* Concentric lay stranded includes compressed and compact conductors.

** Resistance values in milliohms per meter shall be obtained by multiplying the above values by 3.28.

Table 21-2

Nominal Direct Current Resistance in Ohms Per 1000 Feet* At 25°C (77°F) For Flexible Aluminum Conductors

Conductor Size AWG or kcmil	Class G	Class H	Class I
8	...	...	1.07
7	0.858	...	0.850
6	0.681	...	0.687
5	0.540	...	0.545
4	0.428	...	0.432
3	0.340	...	0.343
2	0.269	0.272	0.272
1	0.216	...	0.216
1/0	0.171	0.172	0.172
2/0	0.136	0.136	0.137
3/0	0.107	0.108	0.109
4/0	0.0852	0.0857	0.0861
250	0.0725	0.0728	0.0735
300	0.0604	0.0607	0.0613
350	0.0518	0.0520	0.0525
400	0.0453	0.0455	0.0460
450	0.0403	0.0405	0.0409
500	0.0363	0.0364	0.0368
550	0.0331	0.0334	0.0334
600	0.0304	0.0306	0.0306
650	0.0280	0.0283	0.0286
700	0.0260	0.0263	0.0265
750	0.0243	0.0245	0.0247
800	0.0228	0.0230	0.0232
900	0.0202	0.0204	0.0206
1000	0.0182	0.0184	0.0186
1100	0.0166	0.0167	0.0169
1200	0.0152	0.0153	0.0155
1250	0.0146	0.0147	0.0148
1300	0.0140	0.0141	0.0143
1400	0.0130	0.0131	0.0133
1500	0.0121	0.0123	0.0124
1600	0.0115	0.0115	0.0116
1700	0.0108	0.0108	0.0109
1750	0.0105	0.0105	0.0106
1800	0.0102	0.0102	0.0103
1900	0.00968	0.00968	0.00977
2000	0.00919	0.00919	0.00928

*Resistance values in milliohms per meter shall be obtained by multiplying the above values by 3.28.

Table 21-3

Nominal Direct Current Resistance in Ohms Per 1000 Feet* At 25°C (77°F) For Flexible Annealed Copper Conductors

Conductor Size	Uncoated					Coated				
	Class G	Class H	Class I	Class K	Class M	Class G	Class H	Class I	Class K	Class M
AWG or kcmil										
20	...	...	...	10.6	10.6	...	...	...	11.4	11.4
18	...	...	...	6.66	6.66	...	...	...	7.15	7.15
16	...	...	...	4.18	4.18	...	...	...	4.49	4.49
14	2.65	...	...	2.62	2.62	2.81	...	...	2.82	2.82
12	1.67	...	...	1.65	1.68	1.77	...	...	1.77	1.81
10	1.05	...	1.04	1.04	1.06	1.11	...	1.08	1.12	1.14
9	0.832	...	0.824	0.840	0.840	0.884	...	0.857	0.902	0.902
8	0.660	0.666	0.653	0.666	0.666	0.701	0.708	0.679	0.715	0.715
7	0.523	0.528	0.518	0.528	0.533	0.544	0.561	0.539	0.567	0.573
6	0.415	0.419	0.419	0.419	0.423	0.432	0.445	0.436	0.450	0.454
5	0.329	0.332	0.332	0.332	0.336	0.342	0.353	0.346	0.357	0.360
4	0.261	0.263	0.263	0.263	0.266	0.271	0.280	0.274	0.283	0.286
3	0.207	0.209	0.209	0.211	0.213	0.215	0.222	0.217	0.227	0.227
2	0.164	0.166	0.166	0.167	0.169	0.171	0.172	0.172	0.180	0.181
1	0.131	0.132	0.131	0.133	0.134	0.137	0.140	0.137	0.142	0.144
1/0	0.104	0.105	0.105	0.105	0.106	0.108	0.109	0.109	0.113	0.114
2/0	0.0826	0.0830	0.0834	0.0842	0.0850	0.0859	0.0863	0.0868	0.0904	0.0913
3/0	0.0655	0.0659	0.0662	0.0668	0.0674	0.0682	0.0685	0.0688	0.0717	0.0724
4/0	0.0520	0.0522	0.0525	0.0530	0.0535	0.0541	0.0543	0.0546	0.0569	0.0574
250	0.0442	0.0444	0.0448	0.0448	0.0453	0.0460	0.0462	0.0466	0.0481	0.0486
300	0.0368	0.0370	0.0374	0.0374	0.0377	0.0383	0.0385	0.0389	0.0401	0.0405
350	0.0316	0.0317	0.0320	0.0323	0.0323	0.0328	0.0330	0.0333	0.0347	0.0347
400	0.0276	0.0278	0.0280	0.0283	0.0283	0.0287	0.0289	0.0291	0.0304	0.0304
450	0.0246	0.0247	0.0249	0.0251	0.0251	0.0255	0.0257	0.0259	0.0270	0.0262
500	0.0221	0.0222	0.0224	0.0226	0.0226	0.0230	0.0231	0.0233	0.0243	0.0243
550	0.0202	0.0204	0.0204	0.0206	0.0206	0.0210	0.0212	0.0212	0.0221	0.0221
600	0.0185	0.0187	0.0187	0.0189	0.0189	0.0192	0.0194	0.0194	0.0203	0.0202
650	0.0171	0.0172	0.0174	0.0174	0.0174	0.0178	0.0179	0.0181	0.0187	0.0187
700	0.0159	0.0168	0.0162	0.0162	0.0162	0.0165	0.0167	0.0168	0.0174	0.0174
750	0.0148	0.0149	0.0151	0.0151	0.0151	0.0154	0.0155	0.0157	0.0162	0.0162
800	0.0139	0.0140	0.0141	0.0141	0.0141	0.0144	0.0146	0.0147	0.0152	0.0152
900	0.0123	0.0125	0.0126	0.0126	0.0126	0.0128	0.0130	0.0131	0.0135	0.0135
1000	0.0111	0.0112	0.0113	0.0113	0.0113	0.0115	0.0117	0.0118	0.0122	0.0121
1100	0.0101	0.0102	0.0103	...	...	0.0105	0.0106	0.0107	...	...
1200	0.00925	0.00934	0.00943	...	...	0.00962	0.00971	0.00981	...	...
1250	0.00888	0.00897	0.00905	...	...	0.00924	0.00933	0.00941	...	...
1300	0.00854	0.00862	0.00870	...	...	0.00888	0.00897	0.00905	...	...
1400	0.00793	0.00801	0.00808	...	...	0.00825	0.00833	0.00841	...	...
1500	0.00740	0.00747	0.00754	...	...	0.00770	0.00777	0.00785	...	...
1600	0.00701	0.00701	0.00707	...	...	0.00729	0.00729	0.00735	...	...
1700	0.00659	0.00659	0.00666	...	...	0.00686	0.00686	0.00692	...	...
1750	0.00641	0.00641	0.00647	...	..	0.00666	0.00666	0.00672	...	...
1800	0.00623	0.00623	0.00629	...	...	0.00648	0.00648	0.00654	...	...
1900	0.00590	0.00590	0.00596	...	...	0.00614	0.00614	0.00619	...	...
2000	0.00561	0.00561	0.00566	...	...	0.00583	0.00583	0.00588	...	...

Resistance values in milliohms per meter shall be obtained by multiplying the above values by 3.28.

Table 21-4

Nominal Diameters for Copper and Aluminum Conductors

Conductor Size		Nominal Diameters*					
			Concentric Lay Stranded				
		Solid	Compact	Compressed	Class B	Class C	Class D
AWG	kcmil	Inch	Inch	Inch	Inch	Inch	Inch
22	0.812	0.0253	...	...	...	...	...
20	1.02	0.0320	...	...	...	...	...
19	1.29	0.0359	...	...	...	...	...
18	1.62	0.0403	...	...	...	...	...
17	2.05	0.0453	...	...	...	...	...
16	2.58	0.0508	...	...	...	...	...
15	3.26	0.0571	...	0.0629	0.0648	...	...
14	4.11	0.0641	...	0.0704	0.0727	0.0735	0.0735
13	5.18	0.0720	...	0.0792	0.0816	0.0825	0.0826
12	6.53	0.0808	...	0.0888	0.0915	0.0925	0.0931
11	8.23	0.0907	...	0.0998	0.103	0.104	0.104
10	10.38	0.1019	...	0.112	0.116	0.117	0.117
9	13.09	0.1144	...	0.126	0.130	0.131	0.132
8	16.51	0.1285	0.134	0.141	0.146	0.148	0.148
7	20.82	0.1443	...	0.158	0.164	0.166	0.166
6	26.24	0.1620	0.169	0.178	0.184	0.186	0.186
5	33.09	0.1819	...	0.200	0.206	0.208	0.209
4	41.74	0.2043	0.213	0.225	0.232	0.234	0.235
3	52.62	0.2294	0.238	0.252	0.260	0.263	0.264
2	66.36	0.2576	0.268	0.283	0.292	0.296	0.297
1	83.69	0.2893	0.299	0.322	0.332	0.333	0.333
1/0	105.6	0.3249	0.336	0.361	0.372	0.374	0.374
2/0	133.1	0.3648	0.376	0.406	0.418	0.420	0.420
3/0	167.8	0.4096	0.423	0.456	0.470	0.471	0.472
4/0	211.6	0.4600	0.475	0.512	0.528	0.529	0.530
	250	0.5000	0.520	0.558	0.575	0.576	0.576
	300	0.5477	0.570	0.611	0.630	0.631	0.631
	350	0.5916	0.616	0.661	0.681	0.681	0.682
	400	0.6325	0.659	0.706	0.728	0.729	0.729
	450	0.6708	0.700	0.749	0.772	0.773	0.773
	500	0.7071	0.736	0.789	0.813	0.814	0.815
	550	...	0.775	0.829	0.855	0.855	0.855
	600	...	0.813	0.866	0.893	0.893	0.893
	650	...	0.845	0.901	0.929	0.930	0.930
	700	...	0.877	0.935	0.964	0.965	0.965
	750	...	0.908	0.968	0.998	0.999	0.998
	800	...	0.938	1.000	1.030	1.032	1.032
	900	...	0.999	1.061	1.094	1.093	1.095
	1000	...	1.060	1.117	1.152	1.153	1.153
	1100	...	...	1.173	1.209	1.210	1.211
	1200	...	...	1.225	1.263	1.264	1.264
	1250	...	...	1.251	1.289	1.290	1.290
	1300	...	...	1.275	1.314	1.316	1.316
	1400	...	...	1.323	1.365	1.365	1.365
	1500	...	...	1.370	1.412	1.413	1.413
	1600	...	...	1.415	1.459	1.460	1.460
	1700	...	...	1.459	1.504	1.504	1.504
	1750	...	...	1.480	1.526	1.527	1.527
	1800	...	...	1.502	1.548	1.548	1.549
	1900	...	...	1.542	1.590	1.590	1.591
	2000	...	...	1.583	1.632	1.632	1.632

• Diameters in millimeters shall be obtained by multiplying the above values in inches by 25.4.

Table 21-5

Factors** for Determining Nominal Resistance of Stranded Conductors Per 1000 Feet

	All Sizes, Uncoated		Diameter of Individual Coated Copper Wires in Inches for Stranded Conductors				
Conductivity, Percent	Aluminum	Copper	0.460 to 0.290, Inclusive	Under 0.290 to 0.103, Inclusive	Under 0.103 to 0.0201, Inclusive	Under 0.0201 to 0.0111, Inclusive	Under 0.0111 to 0.0010, Inclusive
	61	100	97.66	97.16	96.16	94.16	93.15
	25°C	25°C	25°C	25°C	25°C	25°C	25°C
Rope Stranded							
49 strands	17865	10892	11153	11210	11327	11568	...
133 strands	18038	10998	11261	11319	11437	11681	...
259 strands	18125	11051	11315	11374	11492	11737	...
427 strands	18212	11104	11370	11428	11547	11793	...
Over 427 strands	18385	11209	11478	11537	11657	11905	...
Bunch Stranded							
All sizes	17691	10786	...	...	11217	11456	11579
Rope-stranded Bunches							
7 ropes of bunched strand	18038	10998	...	...	11437	11681	11806
19, 37, or 61 ropes of bunched strand	18212	11104	...	...	11547	11793	11920
7 × 7 ropes of bunched strand	18385	11209	...	...	11657	11905	12033
19, 37, or 61 × 7 ropes of bunched strand	18559	11315	...	...	11767	12018	12147
Concentric Stranded							
Up to 2000 kcmil	17692	10786	11045	11102	11217	11456	11580
> 2000 to 3000 kcmil	17865	10892	11153	11211	11327	11568	11694
> 3000 to 4000 kcmil	18039	10998	11261	11319	11437	11680	11807
> 4000 to 5000 kcmil	18212	11104	11369	11428	11547	11792	11921

The factors given in Table 21-5 are based on the following

Resistivity

1. A volume resistivity of 10.575 Ω·cmil/ft (100 % conductivity) at 25°C for uncoated (bare) copper.
2. A 25°C volume resistivity converted from the 20°C values specified in ASTM B 33 or ASTM B 189 for coated copper.
3. A volume resistivity of 17.345 Ω·cmil/ft (61.0% conductivity) at 25°C for aluminum.

Copper Conductors, Class M
Each Individual Strand 34 AWG, 0.0063 Inch (0.160 mm)

Conductor Size, AWG or kcmil	Suggested Construction	Approximate Number of Strands	Approximate Outisde Diameter		Approximate Weight	
			inches	mm	Pounds per 1000 Feet	g/m
20	1 × 26	26	0.038	0.97	3.2	4.74
18	1 × 41	41	0.048	1.22	5.0	7.48
16	1 × 65	65	0.060	1.52	8.0	11.9
14	1 × 104	104	0.078	1.98	12.8	19.0
12	7 × 24	168	0.101	2.57	21.0	31.2
10	7 × 37	259	0.126	3.20	32.5	48.2
9	7 × 48	336	0.146	3.71	42	62.5
8	7 × 60	420	0.162	4.11	53	78.1
7	19 × 28	532	0.196	4.98	67	100.0
6	19 × 35	665	0.215	5.46	84	125
5	19 × 44	836	0.240	6.10	105	157
4	19 × 56	1064	0.269	6.83	134	200
3	7 × 7 × 27	1323	0.305	7.75	169	251
2	7 × 7 × 34	1666	0.337	8.56	212	316
1	7 × 7 × 43	2107	0.376	9.55	268	399
1/0	7 × 7 × 54	2646	0.423	10.7	337	501
2/0	19 × 7 × 25	3325	0.508	12.9	427	636
3/0	19 × 7 × 32	4256	0.576	14.6	547	814
4/0	19 × 7 × 40	5320	0.645	16.4	684	1020
250	19 × 7 × 48	6384	0.713	18.1	821	1220
300	19 × 7 × 57	7581	0.768	19.5	975	1450
350	37 × 7 × 34	8806	0.825	21.0	1130	1685
400	37 × 7 × 39	10101	0.901	22.9	1300	1930
450	37 × 7 × 44	11396	0.940	23.9	1465	2180
500	37 × 7 × 49	12691	0.997	25.3	1630	2430
550	61 × 7 × 32	13664	1.035	26.3	1755	2615
600	61 × 7 × 35	14945	1.084	27.5	1920	2860
650	61 × 7 × 38	16226	1.133	28.8	2085	3105
700	61 × 7 × 41	17507	1.183	30.0	2250	3350
750	61 × 7 × 44	18788	1.207	30.7	2415	3595
800	61 × 7 × 47	20069	1.256	31.9	2580	3840
900	61 × 7 × 53	22631	1.331	33.8	2910	4330
1000	61 × 7 × 59	25193	1.404	35.7	3240	4820

Table 21-7

ADDITIONAL CONDUCTOR INFORMATION

Solid Aluminum and Copper Conductors

Conductor Size, AWG or kcmil	Approximate Weight			
	Aluminum		Copper	
	Pounds per 1000 Feet	g/m	Pounds per 1000 Feet	g/m
22	...	...	1.94	2.88
20	...	...	3.10	4.61
19	...	...	3.90	5.81
18	...	...	4.92	7.32
17	...	...	6.21	9.24
16	...	...	7.81	11.6
15	...	...	9.87	14.7
14	...	...	12.4	18.5
13	...	...	15.7	23.4
12	6.01	8.94	19.8	29.4
11	7.57	11.3	24.9	37.1
10	9.56	14.22	31.43	46.77
9	12.04	17.92	39.62	58.95
8	15.20	22.62	49.98	74.38
7	19.16	28.52	63.03	93.80
6	24.15	35.94	79.44	118.2
5	30.45	45.32	100.2	149.0
4	38.41	57.17	126.3	188.0
3	48.43	72.08	159.3	237.1
2	61.07	90.89	200.9	298.9
1	77.03	114.6	253.3	377.0
1/0	97.15	144.6	319.5	475.5
2/0	122.5	182.3	402.8	599.5
3/0	154.4	229.8	507.8	755.8
4/0	194.7	289.8	640.5	953.2
250	230.1	342.4	...	...
300	276.1	410.9	...	...
350	322.1	479.4	...	...
400	368.2	547.9	...	...
450	414.4	616.3	...	...
500	460.2	648.8	...	...

Table 21-8

Concentric Stranded Class B Aluminum and Copper Conductors

Conductor Size, AWG or kcmil	Number of Strands	Approximate Diameter of Each Strand		Approximate Outside Diameter		Approximate Weight			
						Aluminum		Copper	
		mils	mm	inches	mm	Pounds per 1000 Feet	g/m	Pounds per 1000 Feet	g/m
22	7	9.6	0.244	0.029	0.737	...	...	1.975	2.941
20	7	12.1	0.307	0.036	0.914	...	...	3.154	4.705
19	7	13.6	0.345	0.041	1.04	...	...	3.974	5.922
18	7	15.2	0.386	0.046	1.17	...	...	5.015	7.462
17	7	17.2	0.437	0.052	1.32	...	...	6.324	9.429
16	7	19.2	0.488	0.058	1.47	...	...	7.974	11.86
15	7	21.6	0.549	...	...	...	...	9.959	14.98
14	7	24.2	0.615	...	...	...	...	12.68	18.88
13	7	27.2	0.691	...	...	...	...	16.01	23.82
12	7	30.5	0.775	...	...	6.13	9.12	20.16	30.00
11	7	34.3	0.871	...	...	7.72	11.5	25.49	37.80
10	7	38.5	0.978	...	...	9.75	14.5	32.06	47.71
9	7	43.2	1.10	...	...	12.3	18.3	40.42	60.14
8	7	48.6	1.23	...	...	15.5	23.1	51.0	75.9
7	7	54.5	1.39	...	...	19.5	29.1	64.2	95.7
6	7	61.2	1.56	...	...	24.6	36.7	80.9	121
5	7	68.8	1.75	...	...	31.1	46.2	102	152
4	7	77.2	1.96	...	...	39.2	58.3	129	192
3	7	86.7	2.20	...	...	49.4	73.5	162	242
2	7	97.4	2.47	...	...	62.3	92.7	205	305
1	19	66.4	1.69	..	...	78.6	117	259	385
1/0	19	74.5	1.89	...	...	99.1	147	326	485
2/0	19	83.7	2.13	...	...	125	186	411	611
3/0	19	94.0	2.39	...	...	157	234	518	771
4/0	19	105.5	2.68	...	...	199	296	653	972
250	37	82.2	2.09	...	...	235	349	772	1150
300	37	90.0	2.29	...	...	282	419	925	1380
350	37	97.3	2.47	...	...	329	489	1080	1610
400	37	104.0	2.64	...	...	376	559	1236	1840
450	37	110.3	2.80	...	...	422	629	1390	2070
500	37	116.2	2.95	...	...	469	699	1542	2300
550	61	95.0	2.41	...	...	517	768	1700	2530
600	61	99.2	2.52	...	...	563	838	1850	2760
650	61	103.2	2.62	...	...	610	908	2006	2990
700	61	107.1	2.72	...	...	657	978	2160	3220
750	61	110.9	2.82	...	...	704	1050	2316	3450
800	61	114.5	2.91	...	...	751	1120	2469	3680
900	61	121.5	3.09	...	...	845	1260	2780	4140
1000	61	128.0	3.25	...	...	939	1400	3086	4590
1100	91	109.9	2.79	...	...	1032	1540	3394	5050
1200	91	114.8	2.92	...	...	1126	1680	3703	5510
1250	91	117.2	2.98	...	...	1173	1750	3859	5740
1300	91	119.5	3.04	...	...	1220	1820	4012	5970
1400	91	124.0	3.15	...	...	1313	1960	4320	6430
1500	91	128.4	3.26	...	...	1408	2100	4632	6890
1600	127	112.2	2.85	...	...	1501	2240	4936	7350
1700	127	115.7	2.94	...	...	1596	2370	5249	7810
1750	127	117.4	2.98	...	...	1643	2440	5403	8040
1800	127	119.1	3.02	...	...	1691	2510	5562	8270
1900	127	122.3	3.11	...	...	1783	2650	5865	8730
2000	127	125.5	3.19	...	...	1877	2790	6176	9190

Table 21-9

Concentric Stranded Class C and D Aluminum and Copper Conductors

Conductor Size, AWG or kcmil	Class C			Class D		
	Number of Strands	Approximate Diameter of Each Strand		Number of Strands	Approximate Diameter of Each Strand	
		mils	mm		mils	mm
22	...	...	...	...	...	...
20	...	...	...	...	...	...
19	...	...	...	...	...	...
18	...	...	...	...	...	...
17	...	...	...	...	...	...
16	...	...	...	...	...	...
15	...	...	...	...	...	...
14	19	14.7	0.373	37	10.5	0.267
13	19	16.5	0.419	37	11.8	0.300
12	19	18.5	0.470	37	13.3	0.338
11	19	20.8	0.528	37	14.9	0.378
10	19	23.4	0.594	37	16.7	0.424
9	19	26.2	0.665	37	18.8	0.478
8	19	29.5	0.749	37	21.1	0.536
7	19	33.1	0.841	37	23.7	0.602
6	19	37.2	0.945	37	26.6	0.676
5	19	41.7	1.06	37	29.9	0.759
4	19	46.9	1.19	37	33.6	0.853
3	19	52.6	1.34	37	37.7	0.958
2	19	59.1	1.50	37	42.4	1.08
1	37	47.6	1.21	61	37.0	0.940
1/0	37	53.4	1.36	61	41.6	1.06
2/0	37	60.0	1.52	61	46.7	1.19
3/0	37	67.3	1.71	61	52.4	1.33
4/0	37	75.6	1.92	61	58.9	1.50
250	61	64.0	1.63	91	52.4	1.33
300	61	70.1	1.78	91	57.4	1.46
350	61	75.7	1.92	91	62.0	1.57
400	61	81.0	2.06	91	66.3	1.68
450	61	85.9	2.18	91	70.3	1.79
500	61	90.5	2.30	91	74.1	1.88
550	91	77.7	1.97	127	65.8	1.67
600	91	81.2	2.06	127	68.7	1.74
650	91	84.5	2.15	127	71.5	1.82
700	91	87.7	2.23	127	74.2	1.88
750	91	90.8	2.31	127	76.8	1.95
800	91	93.8	2.38	127	79.4	2.02
900	91	99.4	2.53	127	84.2	2.14
1000	91	104.8	2.66	127	88.7	2.25
1100	127	93.1	2.36	169	80.7	2.05
1200	127	97.2	2.47	169	84.3	2.14
1250	127	99.2	2.52	169	86.0	2.18
1300	127	101.2	2.57	169	87.7	2.23
1400	127	105.0	2.67	169	91.0	2.31
1500	127	108.7	2.76	169	94.2	2.39
1600	169	97.3	2.47	217	85.9	2.18
1700	169	100.3	2.55	217	88.5	2.25
1750	169	101.8	2.59	217	89.8	2.28
1800	169	103.2	2.62	217	91.1	2.31
1900	169	106.0	2.69	217	93.6	2.38
2000	169	108.8	2.76	217	96.0	2.44

NOTE: The weights of Class C and Class D conductors are the same as for the equivalent Class B conductor

Table 21-10

Rope-Lay Aluminum and Copper Conductors, Class G

Conductor Size, AWG or kcmil	Number of Strands	Suggested Construction	Approximate Diameter of Each Strand		Approximate Outside Diameter		Approximate Weight			
							Aluminum		Copper	
			mils	mm	inches	mm	Pounds per 1000 Feet	g/m	Pounds per 1000 Feet	g/m
14	49	7×7	9.2	0.23	0.083	2.11	...	...	12.8	19.1
12	49	7×7	11.6	0.29	0.104	2.64	...	...	20.3	30.3
10	49	7×7	14.6	0.37	0.131	3.33	...	...	32.3	48.2
9	49	7×7	16.4	0.42	0.148	3.76	...	...	40.8	60.7
8	49	7×7	18.4	0.47	0.166	4.22	...	...	51	76.6
7	49	7×7	20.6	0.52	0.185	4.70	20	29.4	65	96.6
6	49	7×7	23.1	0.59	0.208	5.28	25	37.0	82	122
5	49	7×7	26.0	0.66	0.234	5.94	31	46.7	103	154
4	49	7×7	29.2	0.74	0.263	6.68	40	58.9	130	194
3	49	7×7	32.8	0.83	0.295	7.49	50	74.2	164	244
2	49	7×7	36.8	0.93	0.331	8.41	63	93.6	207	308
1	133	19×7	25.1	0.64	0.377	9.58	80	119	264	392
1/0	133	19×7	28.2	0.72	0.423	10.7	102	150	334	495
2/0	133	19×7	31.6	0.80	0.474	12.0	127	190	419	623
3/0	133	19×7	35.5	0.90	0.533	13.5	161	239	529	786
4/0	133	19×7	39.9	1.01	0.599	15.2	203	301	668	991
250	259	37×7	31.1	0.79	0.653	16.6	242	358	795	1175
300	259	37×7	34.0	0.86	0.714	18.1	287	429	945	1410
350	259	37×7	36.8	0.93	0.773	19.6	337	501	1110	1650
400	259	37×7	39.3	1.00	0.825	21.0	385	573	1265	1885
450	259	37×7	41.7	1.06	0.876	22.3	433	644	1425	2120
500	259	37×7	43.9	1.12	0.922	23.4	482	716	1585	2355
550	427	61×7	35.9	0.91	0.969	24.6	532	791	1750	2600
600	427	61×7	37.5	0.95	1.013	25.7	581	863	1910	2840
650	427	61×7	39.0	0.99	1.053	26.7	629	935	2070	3075
700	427	61×7	40.5	1.03	1.094	27.8	678	1005	2230	3310
750	427	61×7	41.9	1.06	1.131	28.7	725	1080	2385	3545
800	427	61×7	43.3	1.10	1.169	29.7	774	1150	2545	3785
900	427	61×7	45.9	1.17	1.239	31.5	869	1295	2860	4255
1000	427	61×7	48.4	1.23	1.307	33.2	967	1440	3180	4730
1100	427	61×7	50.8	1.29	1.372	34.8	1064	1580	3500	5205
1200	427	61×7	53.0	1.35	1.431	36.3	1158	1725	3810	5675
1250	427	61×7	54.1	1.37	1.461	37.1	1208	1800	3975	5910
1300	427	61×7	55.2	1.40	1.490	37.8	1257	1870	4135	6150
1400	427	61×7	57.3	1.46	1.547	39.3	1356	2015	4460	6620
1500	427	61×7	59.3	1.51	1.601	40.7	1452	2155	4775	7095
1600	703	37×19	47.7	1.21	1.670	42.4	1560	2325	5130	7640
1700	703	37×19	49.2	1.25	1.722	43.7	1660	2470	5460	8115
1750	703	37×19	49.9	1.27	1.747	44.4	1709	2540	5620	8355
1800	703	37×19	50.6	1.29	1.771	45.0	1756	2615	5775	8595
1900	703	37×19	52.0	1.32	1.820	46.2	1854	2760	6100	9070
2000	703	37×19	53.3	1.35	1.866	47.4	1950	2905	6415	9550

NOTE: Rope-lay aluminum Class G conductors are not recommended in sizes 8 AWG and smaller and individual aluminum wires in strande conductors should not be smaller than 24 AWG.

Table 21-11

Rope-Lay Aluminum and Copper Conductors, Class H

Conductor Size, AWG or kcmil	Number of Strands	Suggested Construction	Approximate Diameter of Each Strand		Approximate Outside Diameter		Approximate Weight			
							Aluminum		Copper	
			mils	mm	inches	mm	Pounds per 1000 Feet	g/m	Pounds per 1000 Feet	g/m
8	133	19 × 7	11.1	0.28	0.167	4.24	...	...	52	77.4
7	133	19 × 7	12.5	0.32	0.188	4.78	...	...	65	97.5
6	133	19 × 7	14.0	0.36	0.210	5.33	...	...	82	123
5	133	19 × 7	15.8	0.40	0.237	6.02	...	...	105	155
4	133	19 × 7	17.7	0.45	0.266	6.76	...	...	132	196
3	133	19 × 7	19.9	0.51	0.299	7.59	...	...	167	247
2	133	19 × 7	22.3	0.57	0.335	8.51	63	94.5	208	311
2	259	37 × 7	16.0	0.41	0.336	8.53	...	...	210	312
1	259	37 × 7	18.0	0.46	0.378	9.60	...	...	266	394
1/0	259	37 × 7	20.2	0.51	0.424	10.8	102	151	334	497
2/0	259	37 × 7	22.7	0.58	0.477	12.1	128	190	422	626
3/0	259	37 × 7	25.5	0.65	0.536	13.6	162	240	533	790
3/0	427	61 × 7	19.8	0.50	0.535	13.6	...	...	532	794
4/0	259	37 × 7	28.6	0.73	0.601	15.3	204	303	670	996
4/0	427	61 × 7	22.3	0.57	0.602	15.3	205	304	675	1000
250	427	61 × 7	24.2	0.61	0.653	16.6	242	360	795	1180
300	427	61 × 7	26.5	0.67	0.716	18.2	290	431	953	1420
350	427	61 × 7	28.6	0.73	0.772	19.6	337	503	1110	1655
400	427	61 × 7	30.6	0.78	0.826	21.0	386	575	1270	1890
450	427	61 × 7	32.5	0.83	0.878	22.3	436	647	1435	2130
500	427	61 × 7	34.2	0.87	0.923	23.4	483	719	1590	2365
550	703	37 × 19	28.0	0.71	0.980	24.9	538	798	1770	2625
600	703	37 × 19	29.2	0.74	1.022	26.0	584	871	1920	2865
650	703	37 × 19	30.4	0.77	1.064	27.0	634	944	2085	3105
700	703	37 × 19	31.6	0.80	1.106	28.1	686	1015	2255	3340
750	703	37 × 19	32.7	0.83	1.145	29.1	733	1090	2410	3580
800	703	37 × 19	33.7	0.86	1.180	30.0	778	1160	2560	3820
900	703	37 × 19	35.8	0.91	1.253	31.8	880	1305	2895	4295
1000	703	37 × 19	37.7	0.96	1.320	33.5	974	1450	3205	4775
1100	703	37 × 19	39.6	1.01	1.386	35.2	1075	1595	3535	5250
1200	703	37 × 19	41.3	1.05	1.446	36.7	1169	1740	3845	5730
1250	703	37 × 19	42.2	1.07	1.477	37.5	1221	1815	4015	5970
1300	703	37 × 19	43.0	1.09	1.505	38.2	1268	1885	4170	6205
1400	703	37 × 19	44.6	1.13	1.561	39.6	1363	2035	4485	6685
1500	703	37 × 19	46.2	1.17	1.617	41.1	1464	2180	4815	7160
1600	1159	61 × 19	37.2	0.94	1.674	42.5	1564	2325	5145	7640
1700	1159	61 × 19	38.3	0.97	1.724	43.8	1658	2470	5455	8115
1750	1159	61 × 19	38.9	0.99	1.751	44.5	1710	2540	5625	8355
1800	1159	61 × 19	39.4	1.00	1.773	45.0	1754	2615	5770	8595
1900	1159	61 × 19	40.5	1.03	1.823	46.3	1854	2760	6100	9070
2000	1159	61 × 19	41.5	1.05	1.868	47.4	1946	2905	6400	9550

NOTE: Individual aluminum wires in stranded conductors should not be smaller than 24 AWG.

Table 21-12

Aluminum and Copper Conductors, Class I
Each Individual Strand 24 AWG, 0.0201 Inch (0.511 mm)

Conductor Size, AWG or kcmil	Suggested Construction	Approximate Number of Strands	Approximate Outside Diameter		Approximate Weight			
					Aluminum		Copper	
			inches	mm	Pounds per 1000 Feet	g/m	Pounds per 1000 Feet	g/m
10	1 × 26	26	0.125	3.18	...	...	32.5	48.3
9	1 × 33	33	0.138	3.51	...	...	41	61.3
8	1 × 41	41	0.156	3.96	16	23.1	51	76.1
7	1 × 52	52	0.185	4.70	20	29.3	65	96.5
6	7 × 9	63	0.207	5.26	24	36.3	80	119
5	7 × 12	84	0.235	5.97	32	48.3	105	159
4	7 × 15	105	0.263	6.68	41	60.4	134	199
3	7 × 19	133	0.291	7.39	51	76.5	169	252
2	7 × 23	161	0.319	8.10	62	92.7	205	305
1	7 × 30	210	0.367	9.32	81	121	267	397
1/0	19 × 14	266	0.441	11.2	104	155	342	508
2/0	19 × 18	342	0.500	12.7	133	199	439	654
3/0	19 × 22	418	0.549	13.9	163	243	537	799
4/0	19 × 28	532	0.613	15.6	208	309	683	1015
250	7 × 7 × 13	637	0.682	17.3	251	374	825	1230
300	7 × 7 × 15	735	0.737	18.7	290	431	955	1420
350	7 × 7 × 18	882	0.800	20.3	348	517	1145	1700
400	7 × 7 × 20	980	0.831	21.1	386	575	1270	1890
450	7 × 7 × 23	1127	0.894	22.7	444	661	1460	2175
500	7 × 7 × 25	1225	0.941	23.9	483	719	1590	2365
550	7 × 7 × 28	1372	0.980	24.9	541	805	1780	2645
600	7 × 7 × 30	1470	1.027	26.1	579	862	1905	2835
650	19 × 7 × 12	1596	1.152	29.3	635	945	2090	3110
700	19 × 7 × 13	1729	1.194	30.3	687	1025	2260	3365
750	19 × 7 × 14	1862	1.235	31.4	740	1100	2435	3625
800	19 × 7 × 15	1995	1.290	32.8	793	1180	2610	3885
900	19 × 7 × 17	2261	1.372	34.8	901	1340	2965	4405
1000	19 × 7 × 19	2527	1.427	36.2	1005	1495	3305	4920
1100	19 × 7 × 21	2793	1.495	38.0	1111	1655	3655	5440
1200	19 × 7 × 22	2926	1.537	39.0	1164	1730	3830	5700
1250	19 × 7 × 23	3059	1.564	39.7	1216	1810	4000	5955
1300	19 × 7 × 24	3192	1.605	40.8	1269	1890	4175	6215
1400	19 × 7 × 26	3458	1.674	42.5	1386	2045	4560	6735
1500	19 × 7 × 28	3724	1.715	43.6	1482	2205	4875	7250
1600	19 × 7 × 30	3990	1.797	45.6	1587	2360	5220	7770
1700	19 × 7 × 32	4256	1.852	47.0	1693	2520	5570	8290
1750	19 × 7 × 33	4389	1.880	47.8	1746	2600	5745	8545
1800	19 × 7 × 34	4522	1.921	48.8	1800	2675	5920	8805
1900	19 × 7 × 36	4788	1.976	50.2	1905	2835	6265	9325
2000	19 × 7 × 37	4921	2.003	50.9	1958	2915	6440	9585

NOTE: Aluminum Class I conductors are not recommended in sizes 8 AWG and smaller.

Table 21-13

Copper Conductors, Class K
Each Individual Strand 30 AWG, 0.0100 Inch (0.254 mm)

Conductor Size, AWG or kcmil	Suggested Construction	Approximate Number of Strands	Approximate Outside Diameter		Approximate Weight	
			Inches	mm	Pounds per 1000 Feet	g/m
20	1 × 10	10	0.038	0.97	3.2	4.59
18	1 × 16	16	0.048	1.22	5.0	7.35
16	1 × 26	26	0.060	1.52	8.0	11.9
14	1 × 41	41	0.078	1.98	12.8	18.8
12	1 × 65	65	0.101	2.57	20.3	29.9
10	1 × 104	104	0.126	3.20	32.5	47.8
9	7 × 19	133	0.150	3.81	42	62.3
8	7 × 24	168	0.157	3.99	53	78.7
7	7 × 30	210	0.179	4.55	66	98.4
6	7 × 38	266	0.210	5.33	84	125
5	7 × 48	336	0.235	5.97	106	157
4	7 × 60	420	0.272	6.91	132	197
3	19 × 28	532	0.304	7.72	169	252
2	19 × 35	665	0.338	8.59	211	315
1	19 × 44	836	0.397	10.1	266	395
1/0	19 × 56	1064	0.451	11.5	338	503
2/0	7 × 7 × 27	1323	0.470	11.9	425	632
3/0	7 × 7 × 34	1666	0.533	13.5	535	795
4/0	7 × 7 × 43	2107	0.627	15.9	676	1005
250	7 × 7 × 51	2499	0.682	17.3	802	1195
300	7 × 7 × 61	2989	0.768	19.5	960	1425
350	19 × 7 × 26	3458	0.809	20.5	1120	1665
400	19 × 7 × 30	3990	0.878	22.3	1290	1925
450	19 × 7 × 34	4522	0.933	23.7	1465	2180
500	19 × 7 × 38	5054	0.988	25.1	1635	2435
550	19 × 7 × 41	5453	1.056	26.8	1765	2630
600	19 × 7 × 45	5985	1.125	28.6	1940	2885
650	19 × 7 × 49	6517	1.166	29.6	2110	3140
700	19 × 7 × 52	6916	1.207	30.7	2240	3335
750	19 × 7 × 57	7581	1.276	32.4	2455	3655
800	19 × 7 × 60	7980	1.305	33.1	2585	3845
900	37 × 7 × 35	9065	1.323	33.6	2935	4370
1000	37 × 7 × 39	10101	1.419	36.0	3270	4870