CAPITAL UNIVERSITY OF SCIENCE AND TECHNOLOGY, ISLAMABAD

Impact of High Penetration of PV Systems on Fault Current Levels in Conventional Distribution System

by

Yasir Ahmed

A thesis submitted in partial fulfillment for the degree of Master of Science

in the

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Department of Electrical Engineering

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I am dedicating this thesis to my Parents, Family, Friends and Teachers for their limitless love, care and inspiration.

CAPITAL UNIVERSITY OF SCIENCE & TECHNOLOGY
ISLAMABAD

CERTIFICATE OF APPROVAL

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Abstract

World is facing a major problem of energy crises and pollution. Renewable energy resources are practical solution and alternative to fossil fuel to make the future pollution free. Photovoltaic (PV) as distributed generation is a practical solution to renewable energy resources. However as PV integration is increasing, it is predicted that it has effects on conventional distribution systems. PV-system as distributed generation has multiple effects on voltage profile, line losses, harmonics, power network operation and fault current level. One of the effect is that fault current level can shift which can effect the existing system fault protection equipment and overall infrastructure of distribution system. There are two opinions, regarding to this effect of change in fault current level due to PV penetration. One opinion states that as PV penetration increases fault current level will increase which has negative effect on the fault protection equipment and overall infrastructure. The reason behind increase in fault current level by integration of PV systems with conventional distribution grid is that, total power of the grid's fault is increased when new sources of power like PV systems are added to the grid and these sources are near to the fault location due to this fault current level can increase. The other opinion states that the change in fault current level will be insignificant with PV penetration. In proposed thesis, it is investigated that which of the above mentioned two opinions is correct. Fault current analysis is performed for two models of (500 kVA and 1 MVA) grid without and with PV system, for different PV penetration levels. It was investigated by comparing results for grid without and with PV system, where two three-phase (LLLG) faults were generated independently in distribution networks. There is an insignificant change in fault current levels for both 500 kVA and 1 MVA systems. The reason behind no effect of PV penetration on fault current levels is that grid tied inverters are capable of fast disconnection (i.e., in less than four cycles); interrupts the inverter current contribution immediately during a fault event. As response time of inverters is in milliseconds so inverter is able to instantly cease operation after a disturbance is detected. Therefore, the duration of the fault current contributions is also limited. It is typically assumed that the total fault contribution for a PV inverter is less than twice the inverters rated output current. Results shows that high penetration of PV system with conventional distribution system is not problematic with respect to fault current levels in distribution systems.

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List of Abbreviations

AC	Alternate Current
CdTe	Cadmium Telluride
CIGS	Copper Indium Gallium Selenide
DC	Direct Current
DG	Distribution Generation
DT	Distribution Transformer
FCL	Fault Current Limiters
FACTS	Flexible AC Transmission Systems
FC	Fault Current
IGBT	Insulated-Gate Bipolar Transistor
LV	Low Voltage
LLLG	Line-Line-Line To Ground
MPPT	Maximum Power Point Tracking
MV	Medium Voltage
PV	Photovoltaic
PVP	PV-Penetration
PL	Penetration Level
PC	Percentage Chnage
TP	Total Power
VSC	Voltage Source Converter

Chapter 1

Introduction

1.1 Introduction

World is facing major problem related to energy nowadays. Problems related to energy can be overcome by integrating renewable resources with conventional grid. Using fossil fuels for power generation cause air pollution which is one of the major issues nowadays [1].

Researchers are doing research in this field to get an optimal solution for this problem. As the demand for energy is growing rapidly from past centuries, world totally rely on fossil fuels. Using fossil fuels for electricity generation is major cause of global warming and greenhouse gas emission due to which environment is getting worse. For all kinds of modern mean and generation of electricity, fossil fuels are being used. As population increasing rapidly demand of electricity exceeds, for which extra fuel is required. By increase in demand, energy dependent world has begun to search for other energy alternates. Reasonable alternates for electricity generation are coal, gas and hydroelectric generation. These alternates are deployed all over the globe, but hydroelectric generation needs high initial investment as compared to gas and coal based thermal power generations. Hydroelectric generation totally rely on water level and not stable like thermal generation. To reduce demand of fossil fuels for generation of electricity, the world

adopts new technology which is generation of electricity through reactor based on nuclear fission. The best part of this technology is that it is very efficient and does not produce greenhouse gases. This technology needs high level of safety, as an emission of nuclear radiation from reactor reported harmful. It is difficult to control reactions in nuclear reactor and chance of failure is high. As past encounters of failure of nuclear reactors at Fukushima Daiichi reactors in Japan 2011 and at Chernobyl in Russia have emphasized the major issues that may be triggered due to nuclear reactor failure. The other clean and environment friendly methods of generation of electricity in alternate of thermal and hydro generations are wind energy, solar energy, tidal energy. These alternates are an unlimited source of energy as compare to fossil fuels. As solar power is available all over the globe, so this technology can cause massive reduction of greenhouse gases as this method of generation of electricity is totally clean and environment friendly.
Photovoltaic is among one of the clean energy possibility for pollution free future [2]. But there are also many issues by using renewable resources for generation of electricity. For generation of electricity from sun solar panels are used, solar panel converts solar energy into electricity by converting solar radiations directly into electricity. Factors like temperature and irradiance are important for solar panels. By using large scale photovoltaic system for generation of electricity, greenhouse gas emission and energy crises can be controlled. In future renewable resources will replace fossil fuels which are clean and environment friendly.

1.2 Background

Population and technology is increasing rapidly worldwide, the demand for energy also increases rapidly, modern means and electricity needs high energy demand. In present century world is facing three major problems regarding energy. The first problem is that energy dependent world needs a lot of energy for which massive quantity of fossil fuel is required which cause a terrible impact on the environment. Exceed in demand of energy needs extra fossil fuels, in result of that greenhouse gases increase rapidly which is cause of global warming.

Increase in greenhouse gas emissions will have a terrible impact on the environment and cause of climate change [3]. For low voltage AC grid photovoltaic is famous renewable resource and cost of electricity generated by PV system is expected to become cheaper as compare to conventional energy source [4] [5] [6] [7]. The second problem is that using fossil fuels for centuries and which is not unlimited source like sun and wind renewable resources. The third problem is that large population still do not have enough energy to even boil water other than all the generations of energy by fossil fuels. Comparison of power capacity of different renewable energies and hydropower worldwide is shown in Figure 1.1. As power capacity of PV is exponential at the beginning capacity of PV was not in large amount but suddenly installation growth increases as the demand of energy increases. As installation

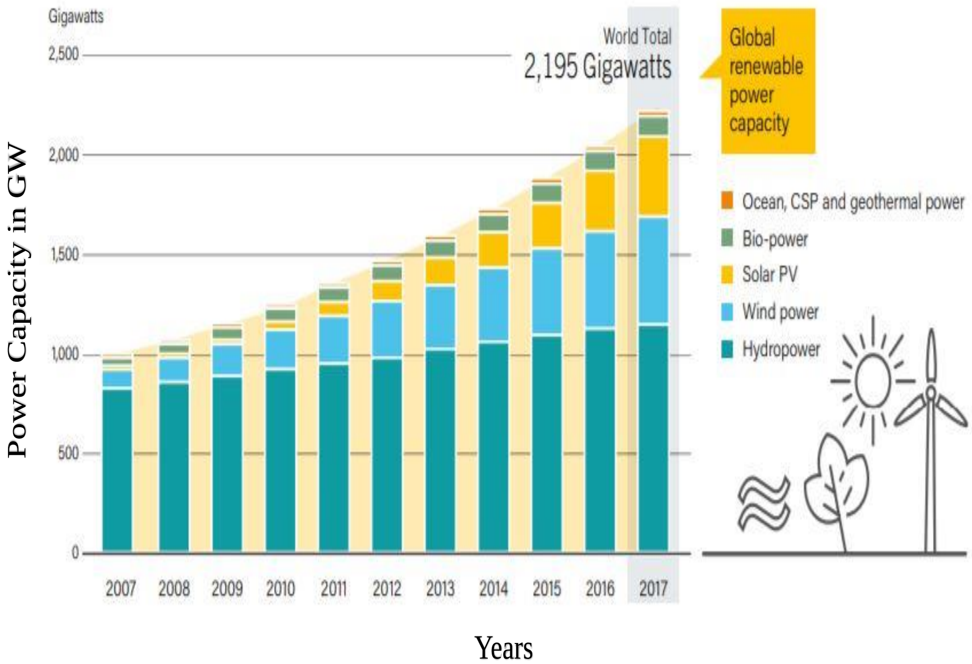

FIGURE 1.1: Comparison between Renewable and Hydro Power Capacity Worldwide [8]

of PV increases which means penetration level of PV to grid will increase, this research will conclude either PV integration is problematic or not.

1.3 Motivation

The renewable resources integration has been a topic of interest for the researchers over the last two decades. World is facing problems related to energy and environmental problems are increasing rapidly due to generation of electricity by using fossil fuels. To overcome these major problems, integration of renewable resources to the conventional grid is the best solution. To overcome the main problem of greenhouse gases, we can integrate PV systems in large scale within distribution network and can make the environment clean. According to study and research, integration of large scale PV system may cause problem related to fault current levels. Protection system requires, intelligent protection devices and circuits. A lot of work and study is done for effective deployment of PV systems in present grid easily. The effect of PV systems in case of a fault current level, low voltage networks are not investigated in detail. As existing grid was designed with an idea of centralized network and not intelligent to overcome protection issues. To overcome this problem an intelligent and efficient monitoring structure across the system could be very effective. Stability of grid highly depends on communication link between network and system.

Owners of PV system usually get benefit from utilities by fixing reasonable charges for electricity generated by their PV system [9]. PV system has plus points for both consumer and utility. As consumers of electricity, installed PV system on buildings or houses which will supply power to grid or directly to building load. Transfer of units occurs in one condition when the power of PV is generated greater then load consumed power. Power from grid can be reduced when PV generation is high and it supplies all building. This will help in reduction of electricity bill [10].

1.4 Components of PV System

In this section fundamental components used in PV system are discussed.

(i) PV Modules

(ii) Inverters

(iii) Batteries

(iv) Charge Controller

1.4.1 PV Modules

PV modules work on simple phenomena photovoltaic, we can generate electricity using PV modules directly from solar energy. Photovoltaic cells convert solar energy into DC supply this is done via an electronic process. Semiconductors are used in PV modules, this material plays an important role in PV modules. When sunlight falls on these modules, present electrons in semiconducting material get excited and move freely through electrical circuit due to which electricity is generated and penetrated to the grid [11].

1.4.2 Inverters

In PV system inverters are used because, PV modules generate output as DC supply where conventional distribution networks work on AC supply. Integration of PV system with grid directly without using inverter is not possible. An inverter is a device which converts DC to AC power as shown in Figure 1.2. An inverter can be classified by size, mode of operation and topology [12]. Three modes of operations of inverter are discussed in section (1.5) grid connected inverters, stand-alone inverters and bi-modal inverters.

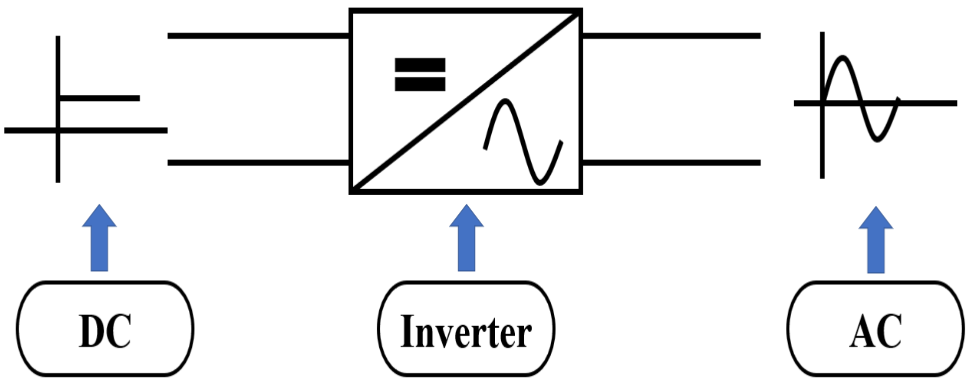

FIGURE 1.2: Inverter is use to Convert DC Supply from PV System to AC Supply for Grid [12]

1.4.3 Batteries

As PV cells are totally depended on the sun and we know that during the night PV cell do not generate power for which we need backup supplies such as battery storage systems [13]. Batteries are key technology and important for PV system and also for all renewable resources. Batteries convert chemical energy into electrical energy. Different types of batteries are shown in Figure 1.3, energy and power characteristics for different types of batteries are shown in Table 1.1. Mainly divided into two categories, primary batteries which can be used only for one time not rechargeable and on other hand secondary batteries which are rechargeable and used in PV systems for this feature [14].

FIGURE 1.3: Different Type of Batteries used for Backup in PV System[15]

TABLE 1.1: Energy and Power Characteristics for Batteries Being Considered for Storage Applications [15]

Battery Type	**Voltage Range V**	**Energy Density Wh/L**	**Specific Energy Wh/kg**	**Specific Power W/kg**	**Cycles**
Nickel Cadmium	0.8-1.3	60-75	30-40	60-110	100-500
Nickel Metal Hydride	0.9-1.3	250-330	70-100	70-200	1000
Lead Acid	1.8-2.1	60-75	30-40	60-110	100-500
Lithium ion	2.5-4.2	200-250	120-160	200-300	300-1000

1.4.4 Charge Controller

Battery life is an important factor in PV system for the long life of battery it must work within quantified limits. Charge controller plays an important role on battery life, charge controller used widely in stand alone PV systems and it is an electronic device with intelligent algorithms and power electronics. Most of the charge controllers have maximum power point tracking technique embedded by default. To get maximum output efficiency from PV cells system should work on conditions of maximum power point tracking [16] [17]. Charge controller is shown in Figure 1.4. Perturb and observe technique is an efficient technique which is used in proposed research work for maximum power tracking [18].

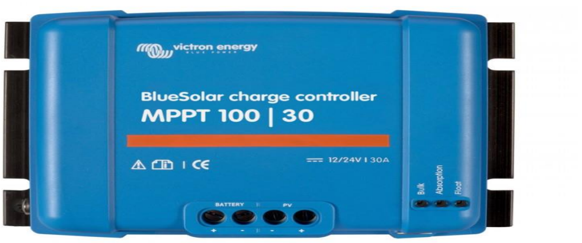

FIGURE 1.4: Charge Controller Plays an Important Role on Life of Battery [19]

1.5 PV System Topologies

There are different types of topologies in PV systems, three major topologies of PV systems are discussed below;

1.5.1 Standalone System

As PV cells are totally depended on the sun and we know that during the night PV cells do not generate power for such kind of scenario stand alone system is the best solution. The stand alone system is used when grid power is not available. Stand alone inverters are stable and supply fixed voltage and frequency for the AC load.

In Figure 1.5 PV array converts solar energy from the sun into electrical energy. For back up batteries are used to store charge, the controller manages battery charging and MPPT technique is also embedded in it. Inverter used for converting DC power from panels to AC power for AC load [20] [21].

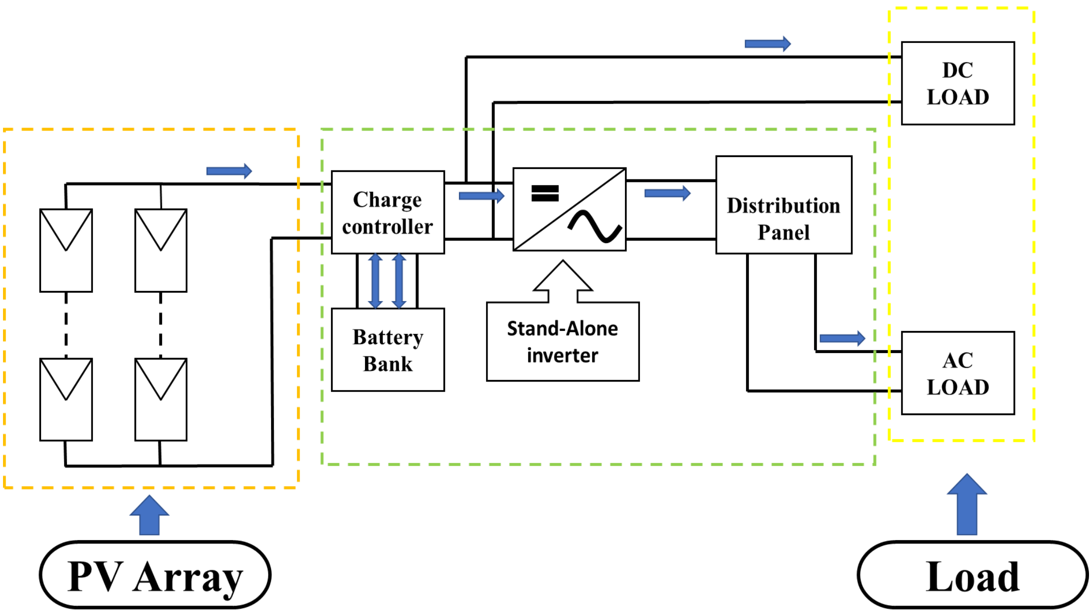

Figure 1.5: Topology of Standalone PV System [21]

1.5.2 Grid Tied System

The grid tied system is independent of batteries and intelligent grid tied inverter is used in this type of system as shown in Figure 1.6. Load is not totally dependent on the grid it is dependent on both grid and PV system. The concept of net metering is also introduced in this type of system where two way of communication can be done between consumer and utility. Consumer can reduce electricity bill by generating electricity by PV system [22]. This topology is used in proposed research work.

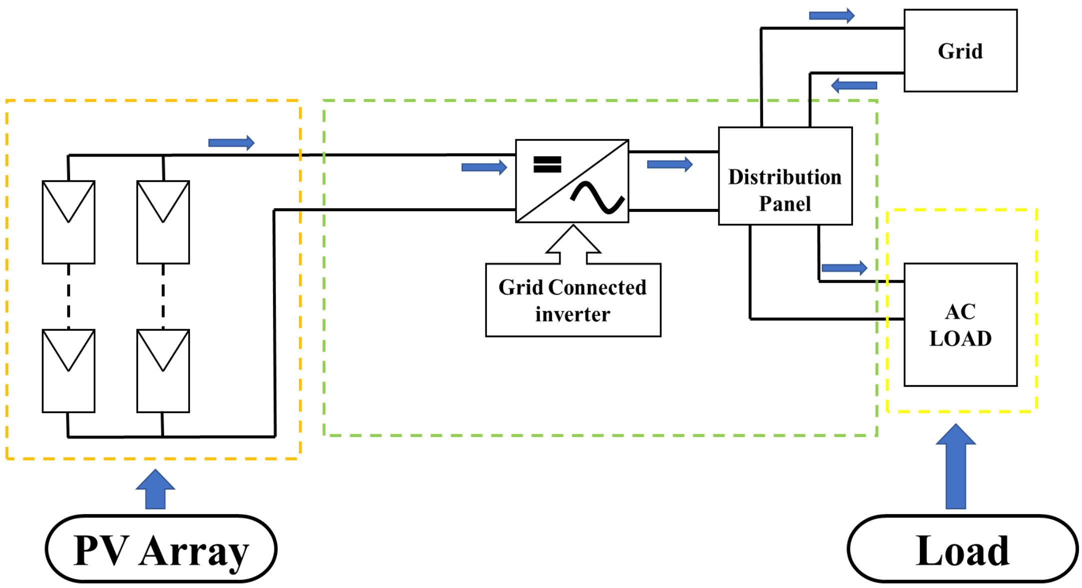

FIGURE 1.6: Topology of Grid tied PV System [22]

1.5.3 Hybrid System

As from the name of this topology, this system is hybrid form of both stand alone and grid tied system as shown in Figure 1.7, it can behave like stand alone or grid tied system. An important part of this system is bi-modal inverter which is an intelligent and efficient, works in both modes of operations. It is useful in those areas where blackout occurs for a long time. This system is much more expensive than stand alone and grid tied system.

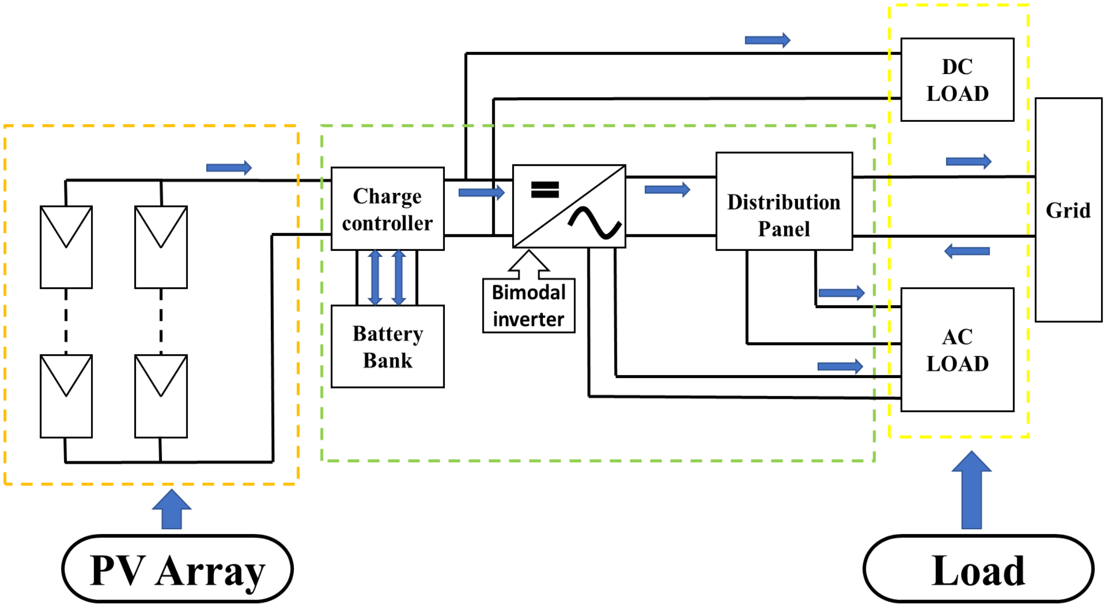

FIGURE 1.7: Topology of Hybrid PV System [22]

1.6 Objective

Following are the key points of given thesis:

(i) To design distribution network and modeling of (500 kVA and 1 MVA) systems without and with PV.

(ii) To investigate whether integration of PV system with conventional grid is problematic or not at different level of penetrations.

(iii) Fault current analysis for both (500 kVA and 1 MVA) systems without and with PV.

(iv) Comparison between fault current levels for both (500 kVA and 1 MVA) systems without and with PV.

(v) Modifications, recommendations and necessary review process for both (500 kVA and 1 MVA) systems without and with PV.

1.7 Thesis Overview

In this section, complete thesis overview is presented, short summary of five chapters are discussed.

Chapter 1 -Introduction

In this chapter introduction, background, motivation, components of PV-system, objective, and thesis overview are discussed.

Chapter 2 - Literature Review

In this chapter a detailed literature review, problem statement and methodology are discussed.

Chapter 3 -System Modeling

This chapter presents single line diagrams and system modeling. Different types of MATLAB models are discussed in this chapter.

Chapter 4 -Results and Simulations

This chapter present results and simulations of MATLAB models. Grid without PV and with PV are discussed with fault current results.

Chapter 5 -Conclusion and Future Work

This chapter accomplishes the outcomes of this study and future recommendations for new research.

Chapter 2

Literature Review and Problem Formulation

This chapter presents detail overview of the literature. Problem statement and methodology are also discussed in this chapter.

2.1 Literature Survey

Worldwide PV system is used for generation of electricity as solar energy is available everywhere. Rooftops, parking lots and windows are used for PV system in case of low voltage network, which seems environment friendly and attractive [23] [24]. To make existing centralized grid economical we should move towards decentralized grid by adding renewable resources to the grid to fulfill the demand for electricity worldwide. As all renewable resources being used to fulfill the electricity requirement but generation through photovoltaic cells increasing rapidly from past years. However, problems occur by integrating photovoltaic system to the grid [23].

Integration of PV system with conventional distribution system has negative impacts, research is done for evaluating these effects in term of voltage profile [25] [26] [27] [28] [29], line losses [30], harmonics [31], power network operation [32] [33] and short circuit current [34] [35].

As large scale PV system may be a significant source of fault current, so the question comes in mind that precautions should be taken for protection system for such kind of power source, protection required from utility and vendors. Inverter fault contributions are limited by the maximum current carrying capability of the power switching device used in the inverter. It is typically assumed that the total fault contribution for a PV inverter is less than twice then inverters rated output current, it is observed that effect is insignificant from short circuit on MV protection [36] [37] [38].

Yet, in grid connected PV power plants several protection problems are still stated [39]. To limit fault current, electronic switched (FCL) fault current limiters have been used efficiently [40] [41]. The author of [42] found that, integration of PV system have some advantages however may have negative effects on the grid. One of the major problems is related to the fault current, which can cause severe damage. This fault current depends on penetration level of PV, location and type of distribution generation. Adding new distribution generation to existing grid may cause problems, several analysis have been done on effects of connecting PV with the grid.

The author of [43] investigated that new standards for power quality, protection and safety operation of the grid is required. Worldwide integration of PV systems with conventional distribution system is increasing rapidly. The mentioned paper focus on fault current contribution by decentralized generation, specifically PV grid connected system. According to this research paper greater the penetration level of PV in grid, greater will be fault current which will affect protective devices such as relays, circuit breakers etc. To overcome the damage of electrical components, improvement and possibility of selecting protective devices is required for distribution system introduced.

In the literature, the author of [44] investigated and found that, contribution of fault current from small scale PV system is not high as compared to large scale PV system connected to the network. As penetration level of PV system increases an amplitude of fault current also increases which can cause damage at both ends customer and grid. The fault current contributions from utility is 490 A, from single PV system is 16.5 A and form network where 14 residences are connected to the same phase of network is 14 x 16.5=231 A. Where 2.5kW PV system is connected to each residence , this shows that by adding more PV systems to conventional grid fault current level can increases.

The author of [45] proposed that integration of PV system to conventional distribution grid has many advantages such as, reliability is increased and peak demand is full filled. When PV system is integrated despite of it advantages it has some negative impact on protection system, integration of PV system with grid can increase fault current and severely effect protection system. When penetration of PV power increases, the fault current level increases. Comparison between system without injecting any PV power and system when PV power is injected on the bus is done in this research paper. From results it is concluded that, fault current level increases when PV power is injected.

The author of [46] found that, fault current contribution by PV systems is insignificant as compare to synchronous and induction machines due to the inverter operation and PV system characteristics. Low fault is contributed by PV system as compare to synchronous and induction machine based distribution generation.

The author of [47] proposed that fault current contribution of grid tied PV system is insignificant. Large number of simulations are done using dynamic model of a PV system coupled to radial distribution network. Results shows that integration of PV systems with the grid have insignificant impact on fault current level.

In the literature, the author of [48] done fault current analysis of grid without PV system and grid with PV system. Large scale PV system integrated with distribution system contributes fault current insignificantly. No significant effect of PV system on fault current level, difference between values of fault current with and without PV integration is minor.

Author of [49] investigate and compare results of fault current level of system without PV and system with PV for two level of penetrations. First results are compared when 15 MW PV system is connected, after that 200 MW system is

connected to distribution system fault current level slightly increases, but PV integration does not influence the design of the system protection. In the literature, the authors of [50] found that there is an insignificant difference between fault current values for system without PV and system with PV. This concludes that PV had insignificant effect on the fault current level of distribution system.
Author of [51] discussed fault current analysis of distribution system without PV system and with PV system. By Adding PV system to distribution network on different feeders. Increasing PV penetration by adding additional PV systems on different feeders, results shows that fault current contribution from PV is insignificant.

2.2 Problem Statement

As PV installation is increasing exponentially, PV penetration level is also increasing and it can have negative effects on grid such as effect on switch gear, stress level of overall infrastructure can increase. The increase in fault current with integration of PV system with grid depends on many factors. It depends on the size and generating capacity of PV, location of the PV and distance between the generating source. As from literature review according to some researchers PV integration is problematic as discussed in papers [34], [35], [42], [43], [44], [45]. They claim that fault current level increases when PV system is integrated with conventional distribution system. The reason behind increase in fault current level by integration of PV systems with conventional distribution grid is that, total power of the grid's fault is increased when new sources of power like PV systems are added to the grid and these sources are near to the fault location due to this fault current level can increase.
While others are in support of PV integration with distribution system as discussed in papers [47], [48], [49], [50], [51]. They claim that change in fault current level is insignificant when PV system is integrated with conventional distribution system. The reason behind no effect of PV penetration on fault current levels is that grid tied inverters are capable of fast disconnection (i.e., in less than four

cycles); interrupts the inverter current contribution immediately during a fault event. As response time of inverters is in milliseconds so inverter is able to instantly cease operation after a disturbance is detected. Therefore, the duration of the fault current contributions is also limited. It is typically assumed that the total fault contribution for a PV inverter is less than twice the inverters rated output current. There is a contradiction between these two opinions and our objective is, to determine which opinion is correct among the above mentioned two opinions.

2.3 Methodology

In this section of thesis, software tool, designing of grid model, research conclusion, future recommendations are discussed and flow diagram of methodology is shown in Figure 2.1

2.3.1 Software Tool

A selection of software is important and software which is selected for research must have optimal structures to permit modeling of PV system, fault current analysis and corresponding foundations. The software checked for suitability is MATLAB 2016b. In MATLAB 2016b Sim-scape Power Systems provides a large variety of examples and analysis tools for modeling and simulations for electrical power systems modeling. In Sim-scape Power Systems variety of electric models are present including electric drives, three-phase machines, renewable resources and different mechanisms for applications for example (FACTS) flexible AC transmission systems and renewable energy models. Analysis of load flow, and other key electrical power system analysis are automated, which help you to check the performance of your models. Thus, for the persistence of given work for investigation MATLAB 2016b is used worldwide.

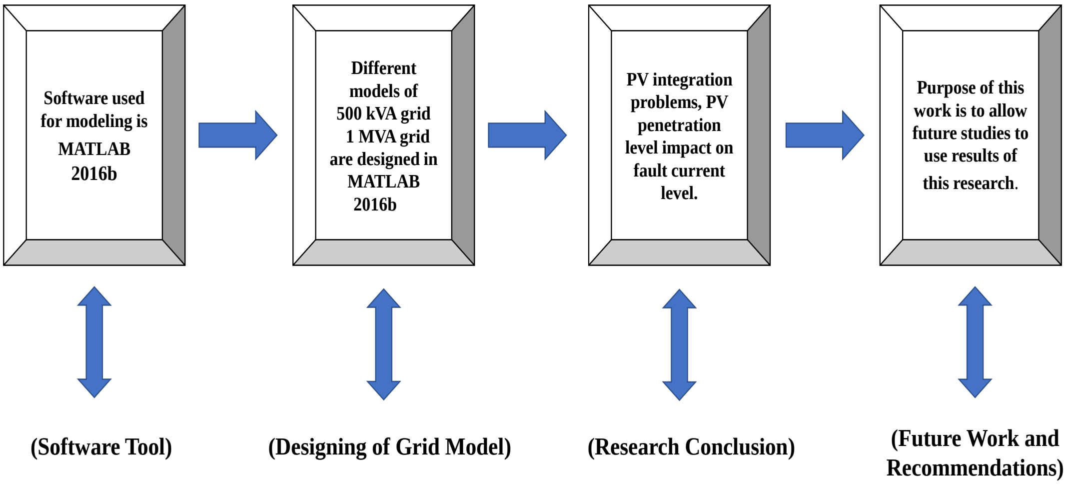

FIGURE 2.1: Flow Diagram of Methodology

2.3.2 Designing of Grid Model

A MATLAB 2016b is used to analyze the behavior of grid's current due to three-phase faults at the 11 kV bus. Model of three phases grid, 500 KVA and 1MVA grid system has been developed.MATLAB 2016b is used to analyze the behavior of PV system and current due to three phase faults at the 11 kV bus and feeder-2. Model of three phases grid, 500 KVA and 1 MVA grid system has been developed.

2.3.3 Research Conclusion

Results and consequence of this exploration work are resolved, analyzed the demand for delivering pure considerate of the PV integration problems recognized. References have been made about penetration levels of PV and problems of integration.

2.3.4 Future Work and Recommendations

When research is completed, recommendations and future work has been recognized and labeled. Purpose of this work is to allow future studies to use these results of this research and more polish and build upon this research.

Chapter 3

System Modeling

In this section system modeling, single line diagram and models of MATLAB, without and with PV systems are discussed in detail.

3.1 Conventional Distribution System without PV

Single line diagram of conventional distribution system without PV where three-phase (LLLG) fault is generated at 11 kV bus is shown in Figure 3.1. It is composed of 132 kV three-phase source, transmission lines, substation step-down transformer, three-phase (LLLG) fault, feeders, distribution lines, distribution transformers (DT) and multiple loads. The single line diagram of proposed system is shown in Figure 3.1, three-phase source (S1) generating 132 kV which is transmitted by transmission lines of 10 km, after that 132 kV is step-down in 11 kV by substation step-down transformer (T1) where on 11 kV bus (B1) three-phase (LLLG) fault is generated. Further 11 kV bus is divided in to three feeders (F1, F2, F3), on each of feeder there are two distribution transformers which step-down 11 kV to 440 V and load is connected next to each distribution transformer. Single line diagram of conventional distribution system without PV where three-phase (LLLG) fault is generated at feeder-2 is shown in Figure 3.2. It is composed of

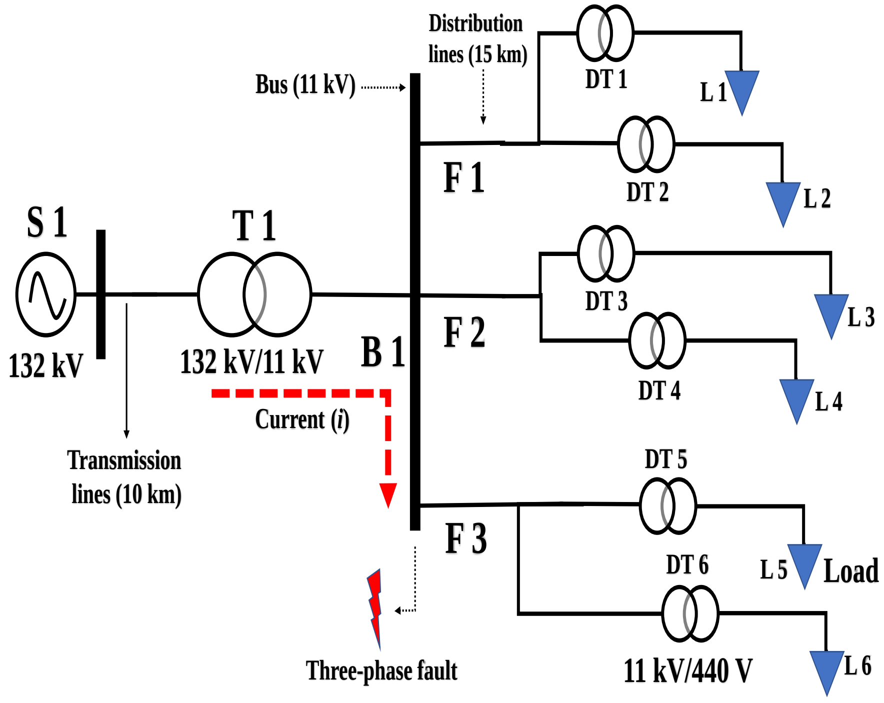

FIGURE 3.1: Single Line Diagram of Conventional Distribution System without PV System (Three-Phase (LLLG) Fault at 11kV Bus)

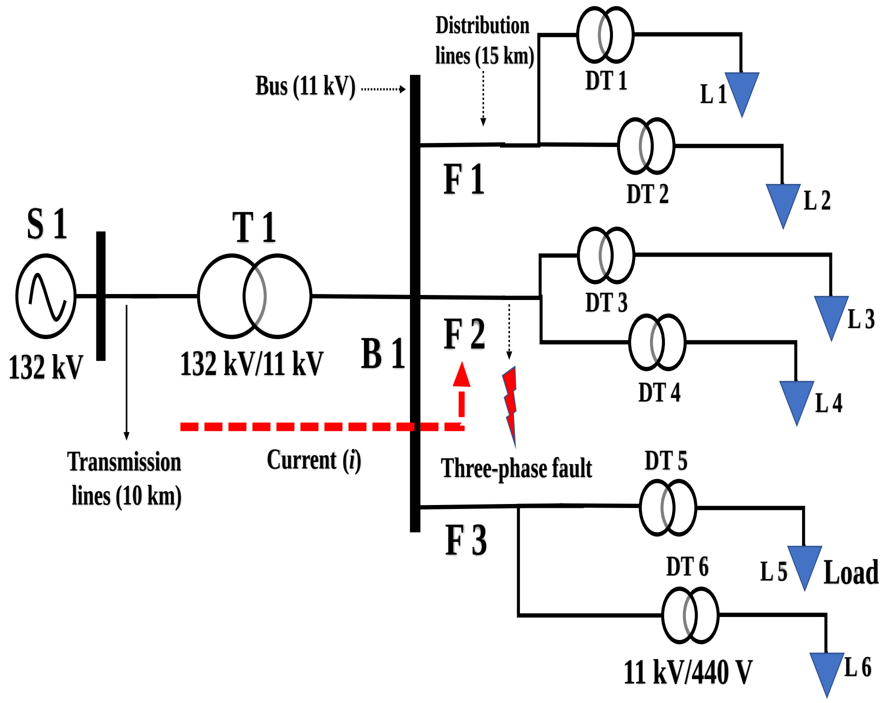

FIGURE 3.2: Single Line Diagram of Conventional Distribution System without PV System (Three-Phase (LLLG) Fault at Feeder-2)

132 kV three-phase source, transmission lines, substation step-down transformer, three-phase (LLLG) fault, feeders, distribution lines, distribution transformers and multiple loads. The single line diagram of proposed system is shown in Figure 3.2, three-phase source (S1) generating 132 kV which is transmitted by transmission lines of 10 km, after that 132 kV is step-down in 11 kV by substation step-down transformer (T1). Further 11 kV bus is divided in to three feeders (F1, F2, F3), on each of feeder there are two distribution transformers which step-down 11 kV to 440 V and load connected. Where on feeder-2 (F2) three-phase (LLLG) fault is generated.

3.2 Specifications of Transformers, Transmission Lines, Fault and Load for both Systems

Specification of substation transformer (T1), load, fault, distribution transformer (DT) and transmission lines are shown in Table 3.1, 3.2, 3.3, 3.4 and 3.5 respectively for both 500 kVA and 1 MVA systems.

TABLE 3.1: Specifications of Substation Transformer T1 132 kV/11 kV with Nominal Power (900 kVA) for 500 kVA System, with Nominal Power (1.8 MVA) for 1 MVA System

Frequency	50 Hz
Nominal Power	900 kVA/1.8 MVA
Winding-1 [V1 ph-ph(Vrms),R1(pu),L1(pu)]	[132e3 , 0.002 , 0.08]
Winding 2 [V2 ph-ph(Vrms),R2(pu),L2(pu)]	[11e3 , 0.002 , 0.08]
Magnitization resistance Rm(pu)	500
Magnitization inductance Lm(pu)	500
Confrigution	Y-Yg

TABLE 3.2: Specifications of Load for both 500 kVA and 1 MVA Systems Respectively

Frequency	50 Hz
Nominal Ph to Ph Voltage Vn (Vrms)	440 V
Load	(83*6=498) kW / (166*6=996) kW

Table 3.3: Specifications of Fault for both 500 kVA and 1 MVA Systems

Fault Type	LLLG
Switching Time	0.5 sec to 0.7 sec
Fault Resistance Ron (ohm)	0.001 (ohm)

Table 3.4: Specifications of Distribution Transformer (DT) for both 500 kVA and 1 MVA Systems Respectively

Frequency	50 Hz
Nominal Power	150 kVA/300 kVA
Winding-1 [V1 ph-ph(Vrms),R1(pu),L1(pu)]	[11e3 , 0.002 , 0.08]
Winding 2 [V2 ph-ph(Vrms),R2(pu),L2(pu)]	[440 , 0.002 , 0.08]
Magnitization resistance Rm(pu)	500
Magnitization inductance Lm(pu)	500
Confrigution	delta-Yg

Table 3.5: Specifications of Transmission Lines for both 500kVA and 1MVA Systems

Length	**1 km**	**10 km**	**15 km**
Frequency	50 Hz	50 Hz	50 Hz
Resistances [r1 r0](ohm/km)	[0.01273 0.3864] ohm/km	[0.1273 3.864] ohm	[0.19095 5.796] ohm
Inductances [l1 l0](H/km)	[0.9337e-3 4.1264e-3] H/km	[9.337e-3 41.264e-3] H	[14.0055e-3 61.896e-3] H
Capacitances [c1 c0](F/km)	[12.74e-9 7.751e-9] F/km	[127.4e-9 77.51e-9] F	[191.1e-9 116.265e-9] F

3.3 MATLAB Model of System without PV

Conventional distribution system model without PV system in MATLAB shown in Figure 3.3 it is composed of three-phase 132 kV generation after that 132 kV is step-down in 11 kV by using a step-down transformer. The three-phase (LLLG) fault is generated on the 11 Kv bus at location (A1), 11 kV bus is divided into three feeders. Each feeder has two distribution transformers as shown in Figure 3.4 which step-down 11 kV to 440 V, after that load is connected to next of each distribution transformer. Where in Figure 3.3 (M1) gives measurements for the fault at 11 kV bus, (M2) gives measurements for the fault at feeder-2. An internal model of feeder-1 without PV system is shown in Figure 3.4 load is attached to each PMT. Two (LLLG) faults are generated independently, one on 11 kV bus at location (A1) as shown in Figure 3.3 and second fault is generated in feeder-2 at location (A2) as shown in Figure 3.5

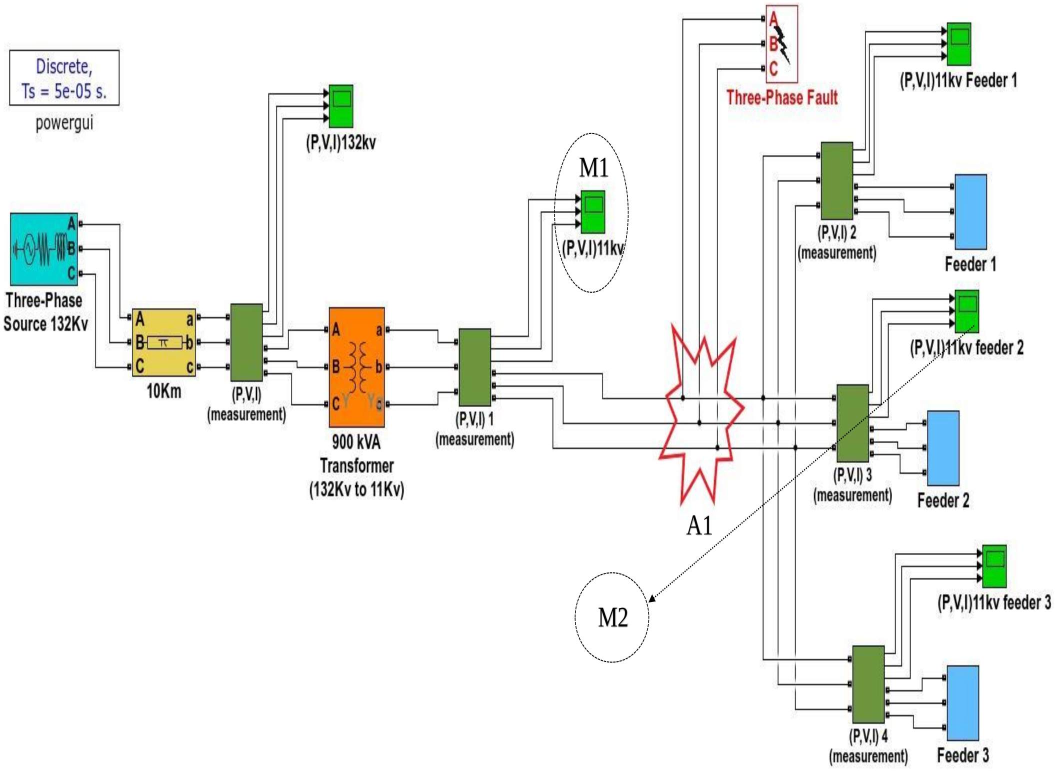

Figure 3.3: MATLAB Model of System without PV System Where M1 give Measurements for Fault Current at 11 kV Bus and M2 sive Measurements for Fault Current at Feeder-2

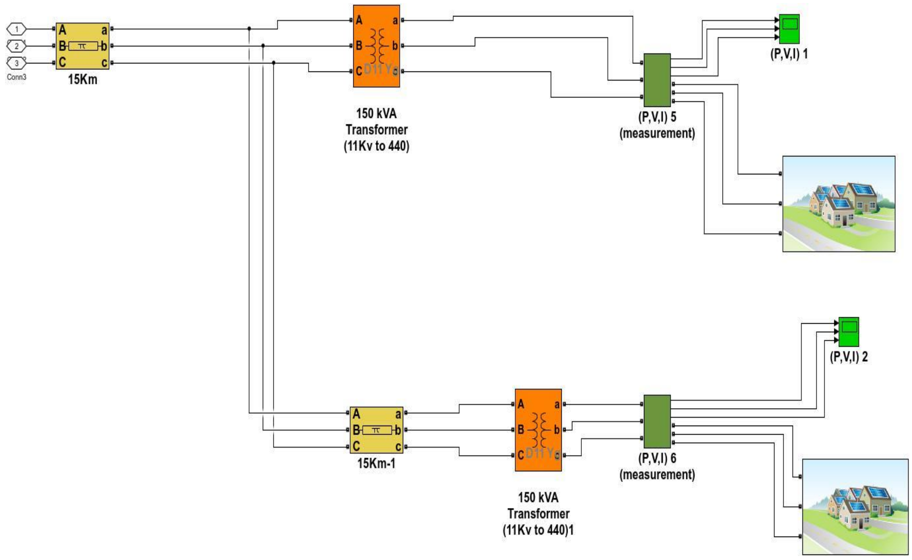

Figure 3.4: Internal Model of Feeder-1 without PV System with PMT and Load

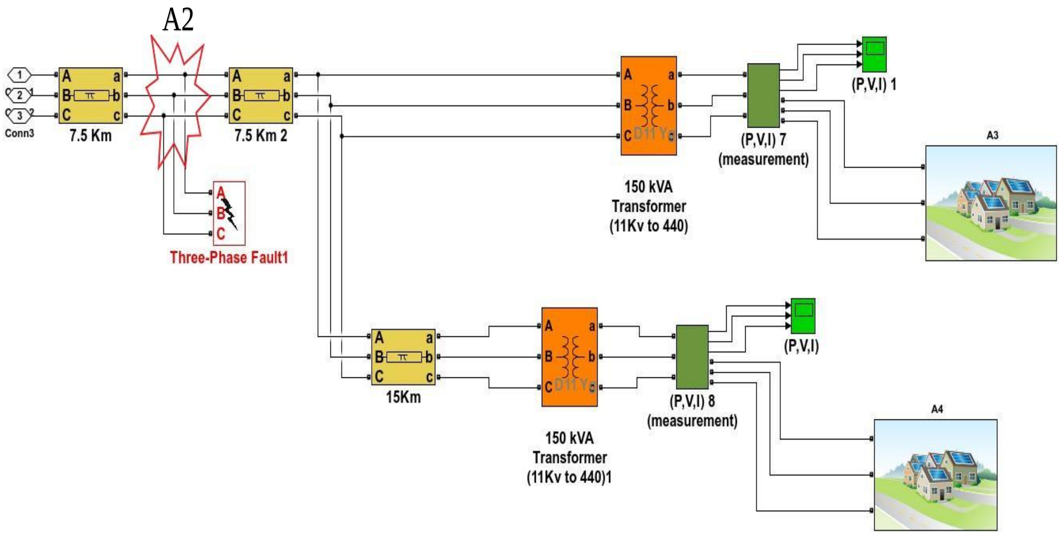

Figure 3.5: Internal Model of Feeder-2 with Three-phase (LLLG) Fault, PMT and Load

3.4 Conventional Distribution System with PV

Single line diagram of conventional distribution system with PV where three-phase (LLLG) fault is generated at 11 kV bus shown in Figure 3.6. It is composed of 132 kV three-phase source, transmission lines, substation step-down transformer, three-phase fault, feeders, distribution lines, distribution transformers and multiple loads. The single line diagram of proposed system is shown in Figure 3.6, three-phase source (S2) generating 132 kV which is transmitted by transmission lines of 10 km, after that 132 kV is step-down in 11 kV by substation step-down transformer (T2) after that (PV-system 1) is coupled on 11 kV bus (B2), where on 11 kV bus (B2) three-phase (LLLG) fault is generated, further 11 kV bus is divided in to three feeders (F1, F2, F3). (PV-system 2) is coupled after distribution transformer in feeder-1 F1, on each of the feeder there are two distribution transformers which step-down 11 KV to 440 V and load is connected to each distribution transformer. Single line diagram of conventional distribution system

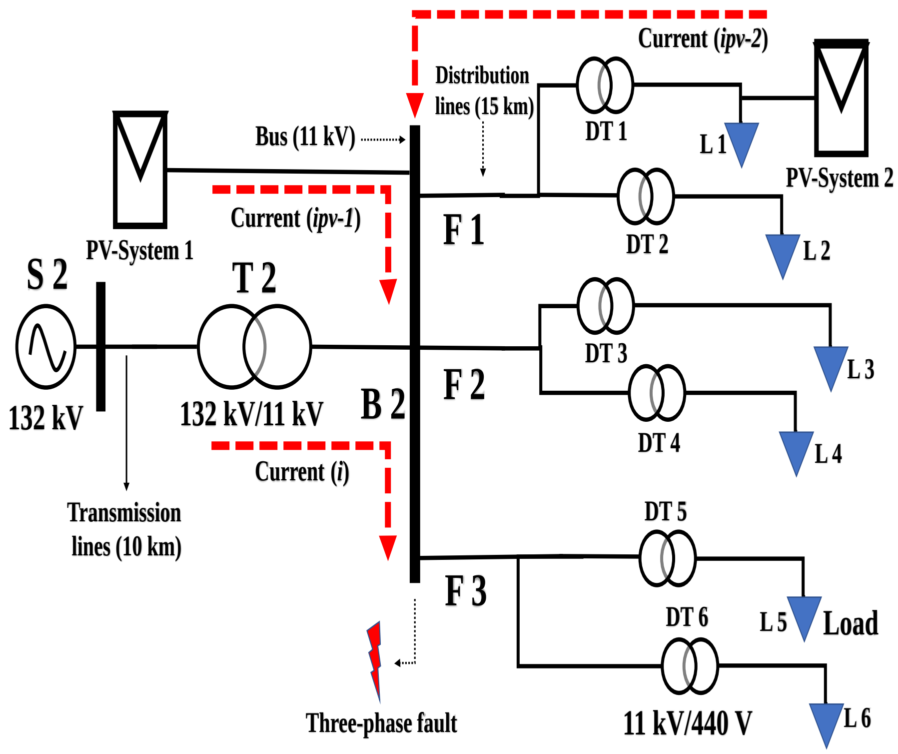

FIGURE 3.6: Single Line Diagram of Conventional Distribution System with PV System (Three-Phase (LLLG) Fault at 11kV Bus)

with PV where three-phase (LLLG) fault is generated at feeder-2 as shown in Figure 3.7. It is composed of 132 kV three-phase source, transmission lines, substation step-down transformer, three-phase (LLLG) fault, feeders, distribution lines, distribution transformers and multiple loads. The single line diagram of proposed system is shown in Figure 3.7, three-phase source (S2) generating 132 kV which is transmitted by transmission lines of 10 km, after that 132 kV is step-down in 11 kV by substation step-down transformer (T2). After that (PV-system 1) is coupled on 11 kV bus (B2) and further 11 kV bus is divided in to three feeders (F1, F2, F3), on each of feeder there are two distribution transformers which step-down 11 KV to 440 V and load connected, where on feeder-2 (F2) three-phase (LLLG) fault is generated.

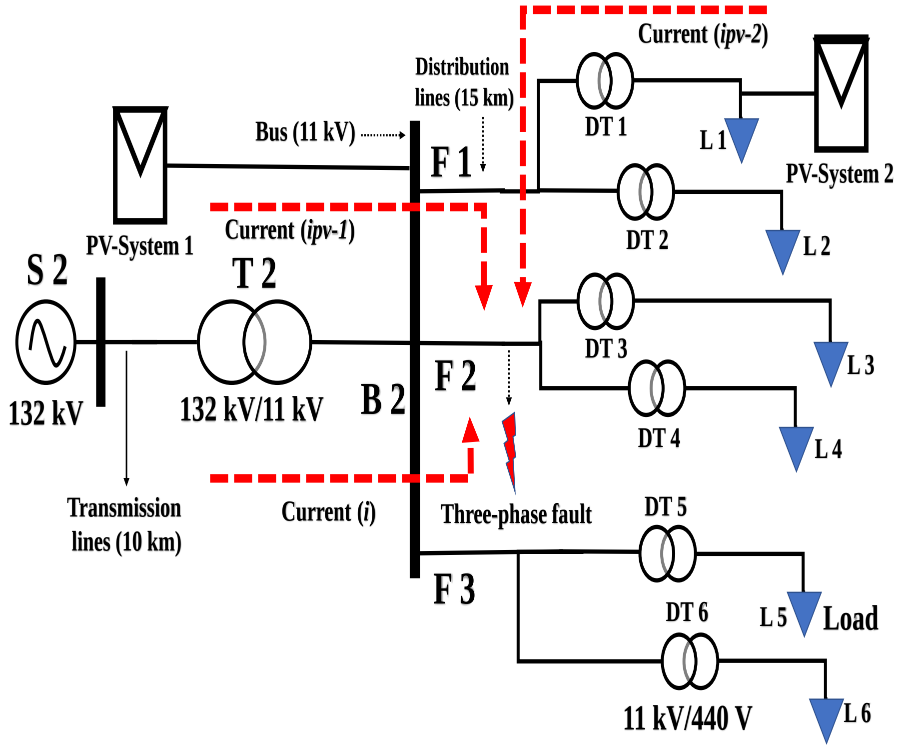

FIGURE 3.7: Single Line Diagram of Conventional Distribution System with PV System (Three-Phase (LLLG) Fault at Feeder-2)

3.5 MATLAB Model of System with PV

Conventional distribution system model with PV system in MATLAB is shown in Figure 3.8. It is composed of three-phase 132 kV generation after which 132 kV is step-down in 11 kV by using a step-down transformer. The three-phase (LLLG) fault is generated on 11 kV bus at location (A1). One of the PV system is integrated on the 11 kV bus on location (P1), 11 kV bus is further divided in to three feeders. Each feeder has two distribution transformers which step-down 11 kV to 440 V. Second PV system is integrated on feeder-1 after distribution transformer at location (P2) as shown in Figure 3.9, after that load is connected in next of each distribution transformer. An internal model of feeder-1 with PV system, where PV system is integrated on location (P2) is shown in Figure 3.9, load is attached to each distribution transformer. In Figure 3.10 PV system coupled to the 11kV bus is shown.

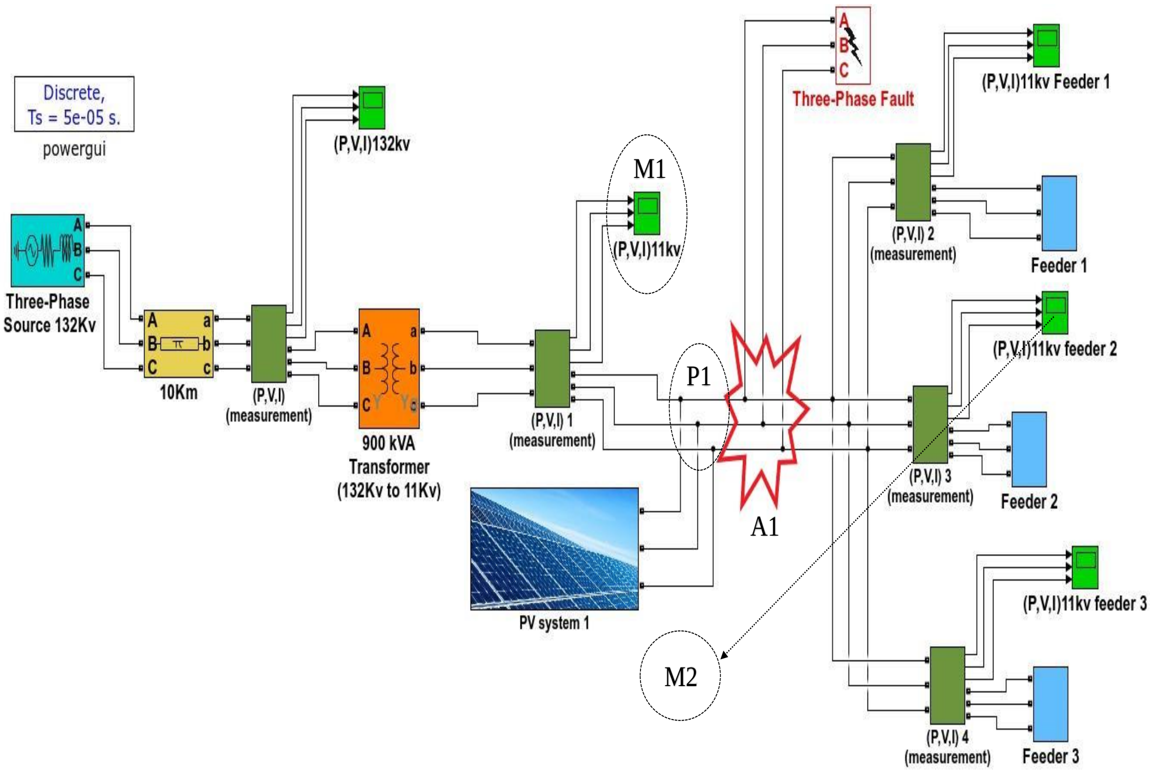

FIGURE 3.8: MATLAB Model Grid with PV System Integration where PV System is Connected at Point P1 and Three Phase (LLLG) Fault is Generated on Point A1

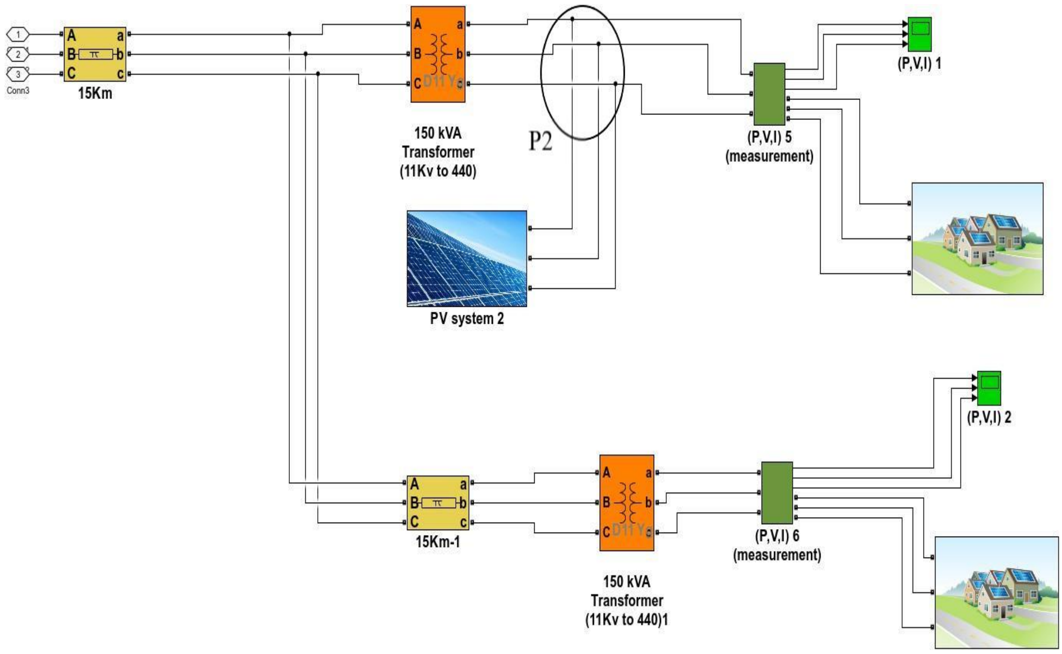

FIGURE 3.9: Internal Model of Feeder-1 with PV System where PV System is Connected at Point P2

3.6 MATLAB Model of PV System

Model of PV system is composed of four PV arrays, DC to DC converters, VSC converter and controller, the step-up transformer. The constant value of irradiance is set to 1000 watt per meter square and temperature is set 25 degrees Celsius. As irradiance and temperature applied on input of PV arrays, DC power is generated by PV arrays. For getting maximum efficiency of PV arrays maximum power point tracking technique (Perturb and Observe) is used. After getting DC power from PV arrays, DC to DC converter (with boost converter and MPPT) is used which boost output DC of PV to 500 V DC, after that VSC converter and controller is used to convert 500 volts DC link voltage to AV 354 volts, AC voltage which is further step-up by transformer from 354 V to 11 kV as shown in Figure 3.10. Which is further penetrated to grid as shown in Figure 3.8 at 11 kV bus location (P1).

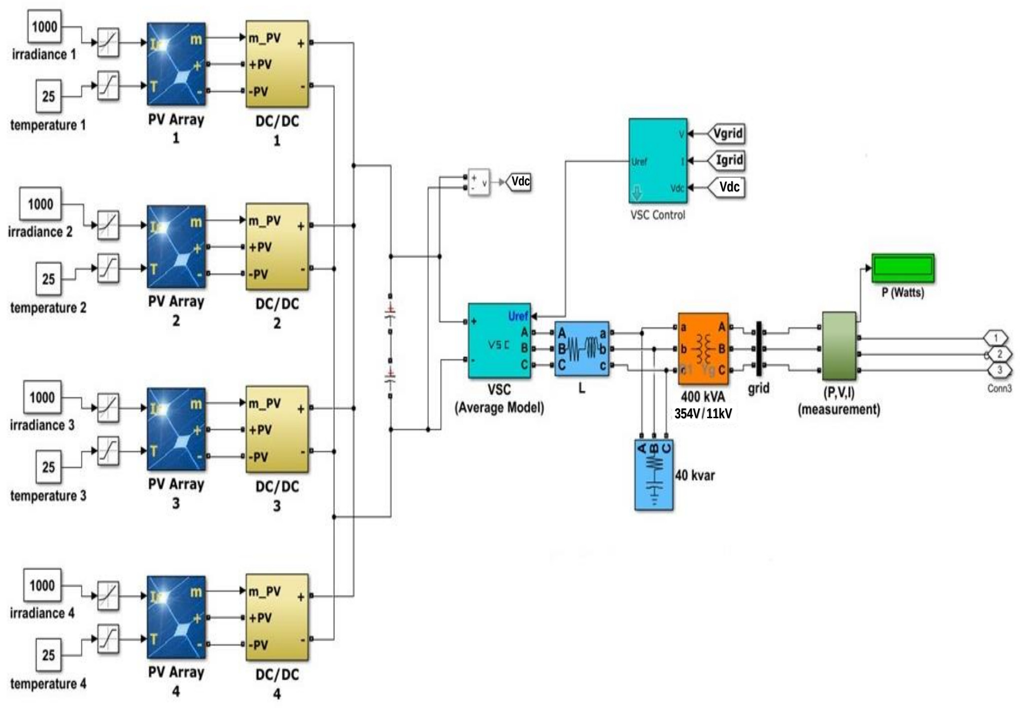

FIGURE 3.10: Model of PV System Connected with 11 kV Bus at Point P1 which is shown in Figure 3.8

3.6.1 PV Array Block Parameters and Plot

For different level of penetrations, PV models with different combinations are used in proposed research. There are two PV systems are used one is connected to 11 kV bus at location (P1) as shown in Figure 3.8 and second one is connected on feeder-1 at location (P2) as shown in Figure 3.9. One of the PV model's internal specifications are shown in Figure 3.10. There are four PV arrays in PV model, one of the PV array's and single module data block parameters (maximum power, open circuit voltage, short circuit current, voltage and current at maximum power point, irradiance, and temperature) are shown in Figure 3.11, Figure 3.12. Characteristic curve of (IV and PV) of PV Array 1 (6.3 kW) shown in Figure 3.13 where PV Array 1 is shown in Figure 3.10. Four PV arrays are connected parallel as shown in Figure 3.10. Combination of modules of PV system 1 are shown in Figure 3.11 for 10% penetration (25kW) in case of 500 kVA system, 4 parallel strings are selected and 5 series connected modules per string.

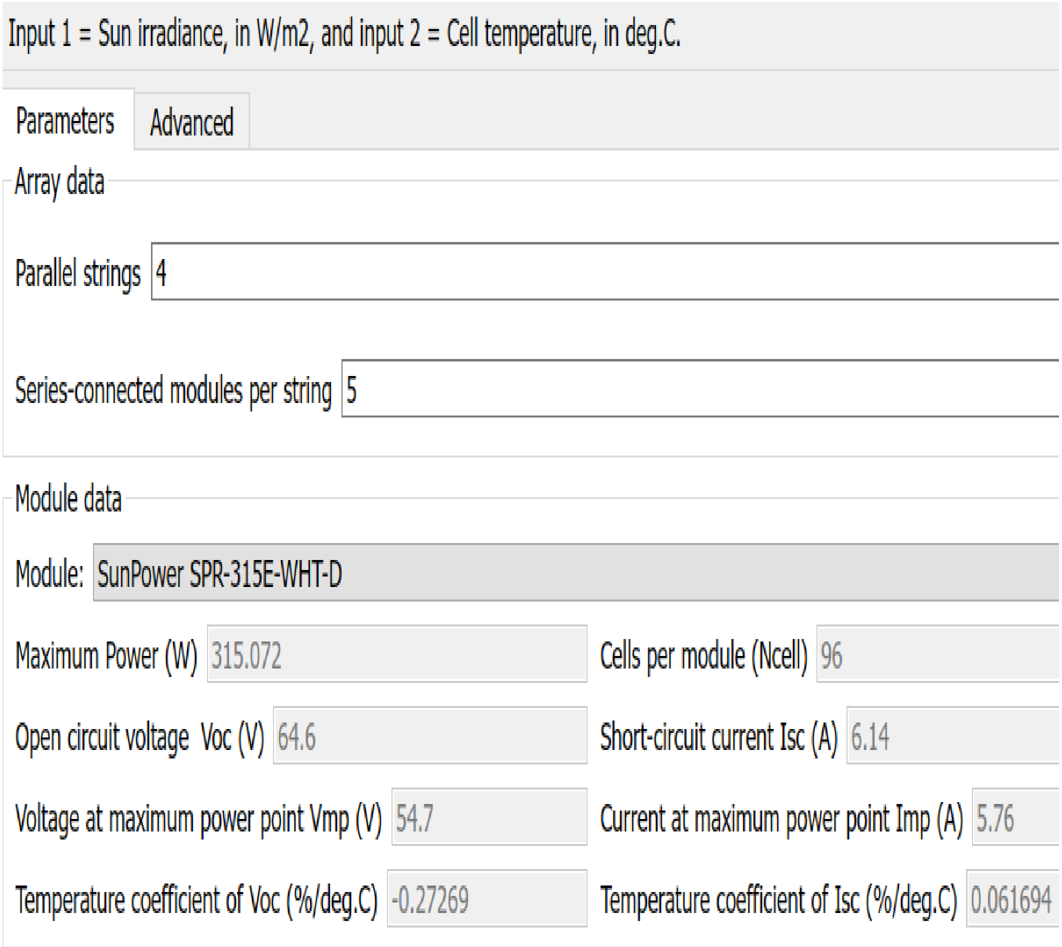

FIGURE 3.11: Block Parameters for PV Array 1 (6.3kW) and Single Module Data, which is shown in Figure 3.10

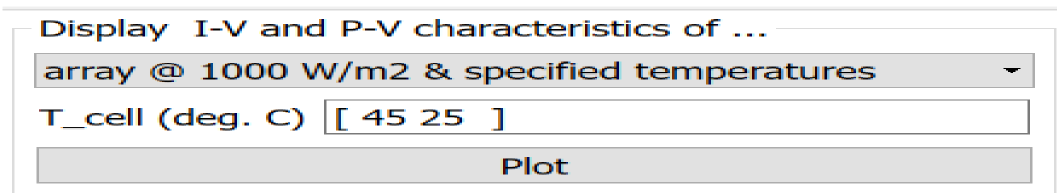

FIGURE 3.12: Block Parameters for PV Array 1 (6.3kW) and Single Module Data, which is shown in Figure 3.10

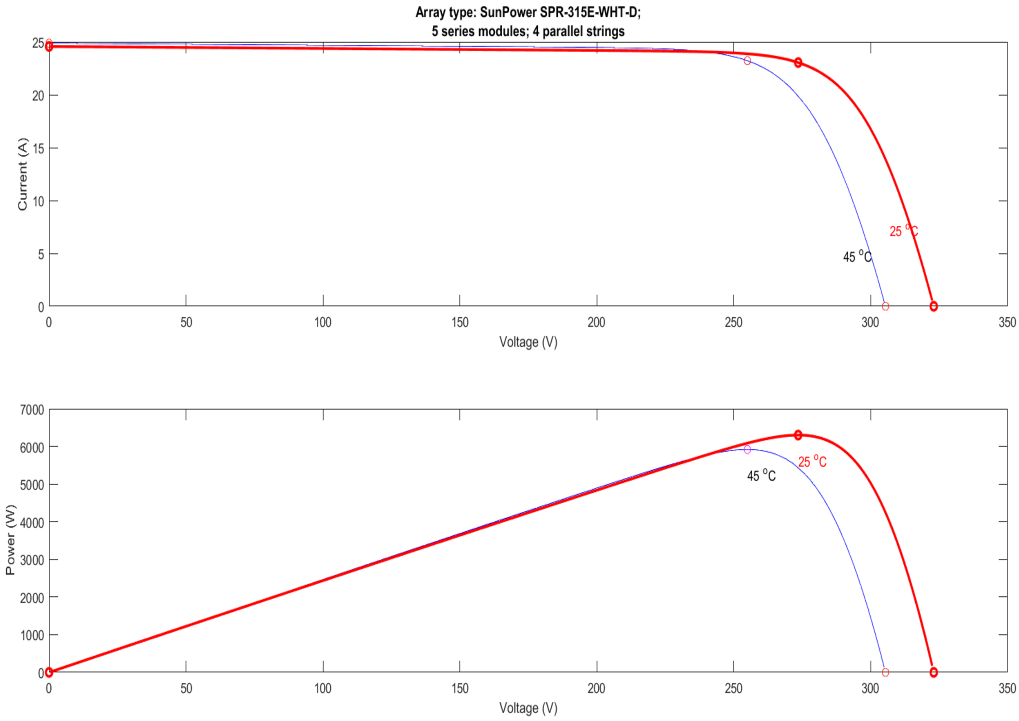

FIGURE 3.13: Characteristic Curve of (IV and PV) for PV Array 1 (6.3kW), which is shown in Figure 3.10

3.6.2 MPPT Technique and DC/DC Converter

For operating PV to gain maximum power, maximum power point tracking (MPPT) is used. There are many techniques for maximum power point tracking, but in proposed model perturb and observe technique is used. Maximal power point (MPP) does not lie at a specific point but it changes around P-V curve depends on light intensity and temperature. Perturb and observe is widely known algorithm and flow chart of this algorithm is shown in Figure 3.14. This technique's key point is to comparing recent power with the previous power of PV where power is measured using voltage and current. By comparing both powers and taking difference if it is not zero, perturb and observe algorithm will try to find optimal point in the left or right side of recent position. Maximum power point is obtained when difference between recent and previous power is zero. This technique is implemented on buck boost by adjusting PWM's duty cycle. To get maximal power point duty cycle of PWM is changed. Internal model of (DC/DC 1) block from Figure 3.10 is shown in figure Figure 3.15 where MPPT technique and built in model for boost converter is implemented in this block.

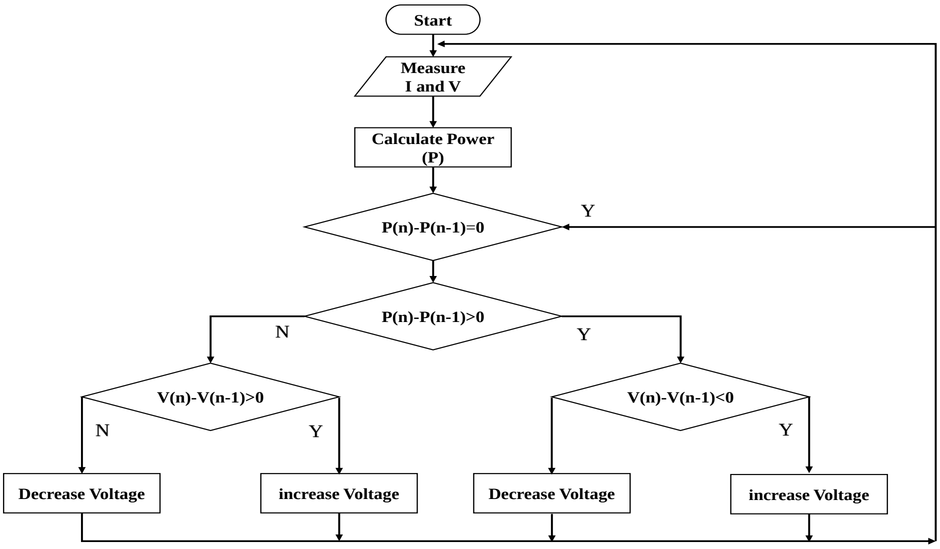

FIGURE 3.14: Flow Chart of Perturb and Observe Algorithm [52]

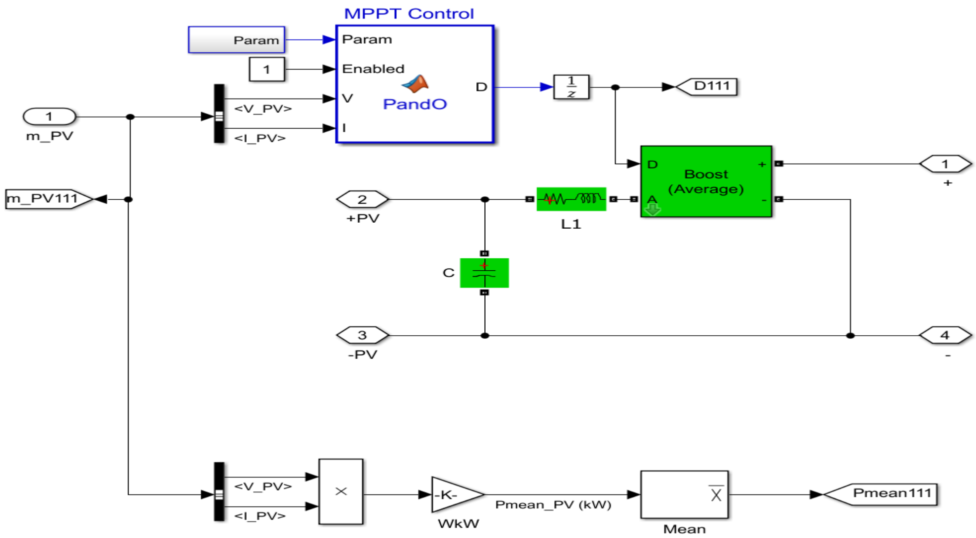

FIGURE 3.15: Internal Model of (DC/DC 1 Block), which is shown in Figure 3.10

3.6.3 VSC Converter

A three-phase Voltage Source Converter (VSC) is used in proposed research work, which converts 500 V DC to 354 V AC. Block parameters are shown in Figure 3.16 as numbers of arms set to 1 or 2 to get a single-phase converter (two or four switching devices). In proposed scenario numbers of arms are set to 3 to get a three-phase converter connected in Graetz bridge configuration as shown in Figure 3.17 (six switching devices IGBT).

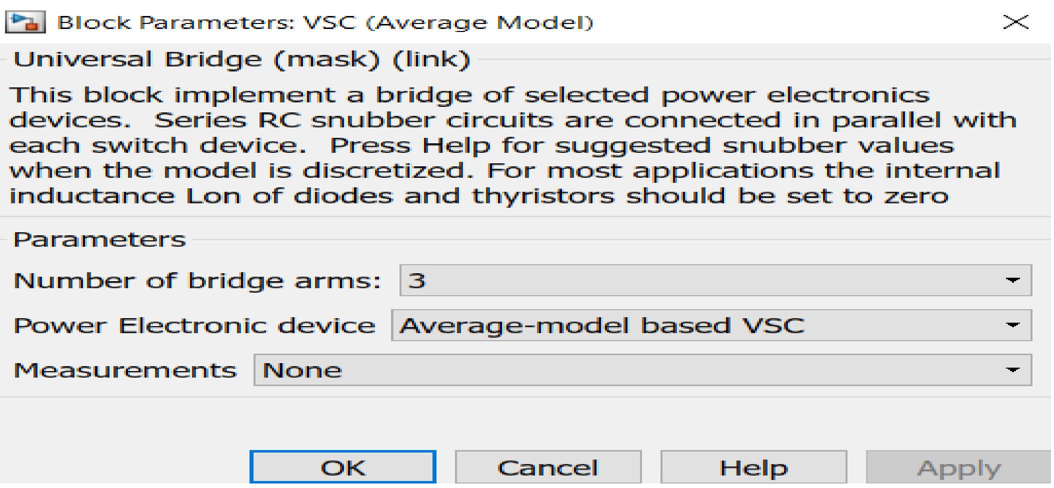

FIGURE 3.16: Block Parameter of VSC

Circuit diagram of voltage source converter (VSC) is shown in Figure 3.17

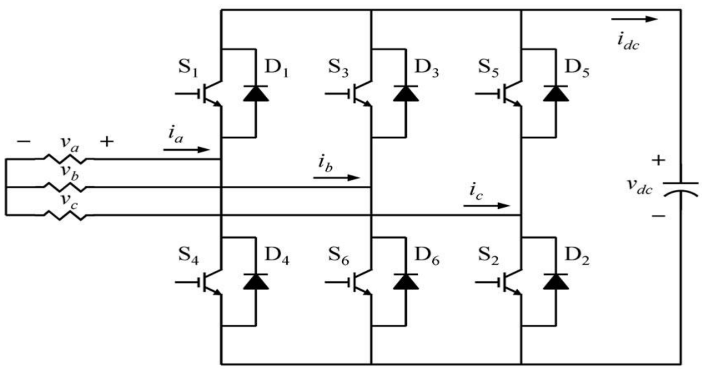

FIGURE 3.17: Circuit Diagram of VSC [53]

Chapter 4

Results and Simulations

In this chapter results of the system model are discussed briefly, the comparison between fault current levels for both (500 kVA and 1 MVA) systems, without PV and with PV done respectively. Where three-phase (LLLG) fault is generated on 11 kV bus and feeder-2 independently.

4.1 Results for 500 kVA Model

In this section results of 500 kVA distribution system without and with PV are discussed. Results for fault current (FC) on 11 kV bus without photovoltaic system (PVS) , FC on 11 kV bus with PVS, comparison between FC on 11 kV bus for grid without and with PVS with different PL.

Total power of system without and with PVS with different penetration level (PL), FC on Feeder-2 without PVS, FC on feeder-2 with PVS (55% penetration), comparison between FC on feeder-2 without and with PVS with different PL are shown respectively.

4.1.1 FC on 11 kV Bus without PVS

Three-phase (LLLG) fault is generated on 11 kV bus to investigate the behavior of the system. Fault current graph and the peak value is (714.8 A) as shown in Figure 4.1 for 500 kVA system without PVS.

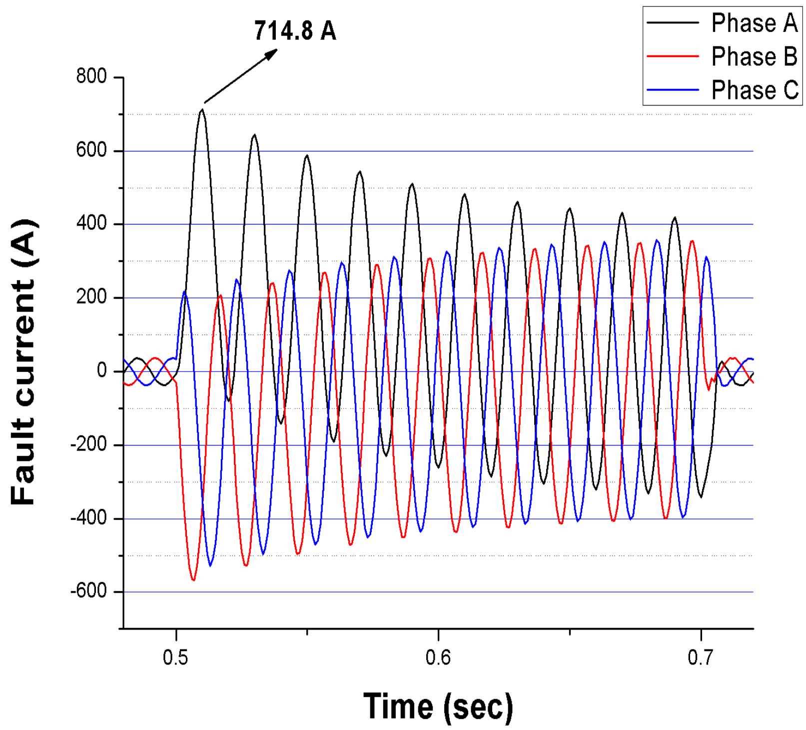

FIGURE 4.1: Fault Current without PV for 500kVA System (Fault at 11 kV bus)

4.1.2 FC on 11 kV Bus with PVS (55% Penetration)

As from results of fault current graph and peak value of fault current is (717.8 A) as shown in Figure 4.2, there is minor change in fault current after integration of PVS with grid. Insignificant change in magnitude of fault current for different level of penetrations (5%, 10%, 15%, 20%, 25%, 30%, 35%, 40%, 45%, 50%, 55%) briefly mentioned in Table 4.1 for all penetration levels of PV.

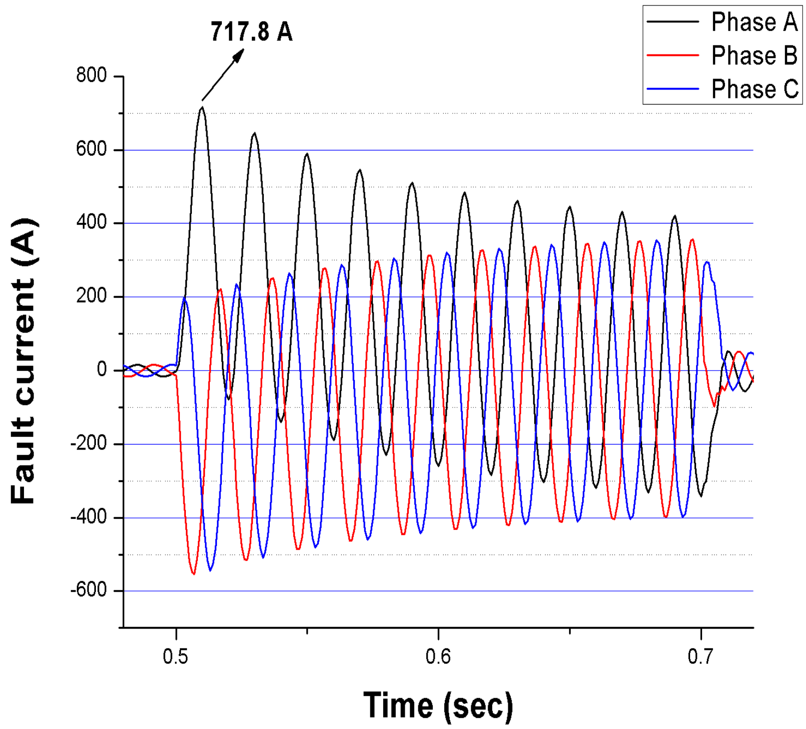

FIGURE 4.2: Fault Current on 11 kV Bus with PV System of 500 kVA Grid (55% Penetration Level)

4.1.3 Comparison between FC on 11 kV Bus Grid with and without PVS with Different PL

For comparison between fault current levels for the system without PV and with different penetration levels of PV are shown in Figure 4.3. Results of simulation shows that there is an insignificant change in fault current levels for the system without and with PV in case of 500 kVA system, as shown in Figure 4.3 all values are nearly equal for different level of penetration. Peak value of fault current without PVS is (714.8 A) as shown in Figure 4.1 and peak value of fault current with PVS is (717.8 A) as shown in Figure 4.2. To make results clear another graph is shown in Figure 4.4, for comparison between fault current of the grid without PVS and with 25% and 50% penetration level of PV. Results of simulation shows that an insignificant change in fault current for system without and with PV in case of 500 kVA system. As in Figure 4.4 it is noticed that three of fault values overlap each other this shows that an insignificant change in fault current without

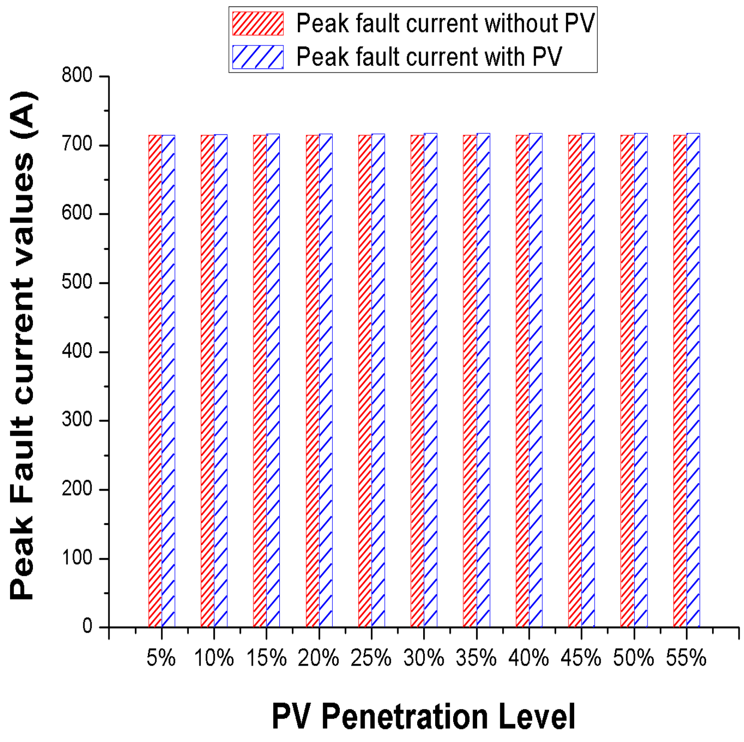

FIGURE 4.3: Comparison between Fault Current without and with PV for 500 kVA System (Fault at 11 kV Bus)

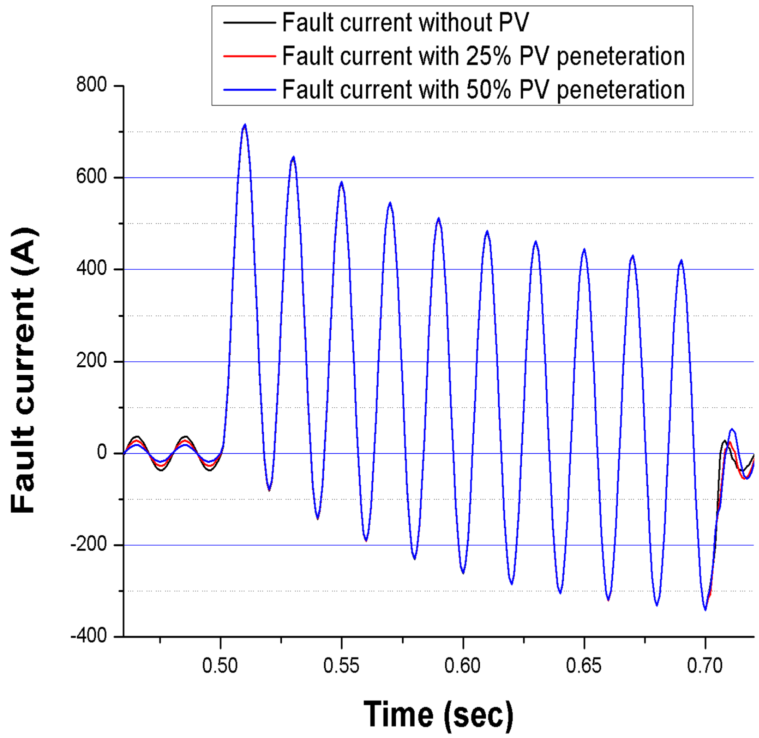

FIGURE 4.4: Comparison between Fault Current without and with PV for 500 kVA System (Fault at 11 kV Bus)

and with PVS. Hence PV integration of different penetration levels with 500 kVA grid is not problematic.

4.1.4 Total Power of System without and with PVS with Different PL

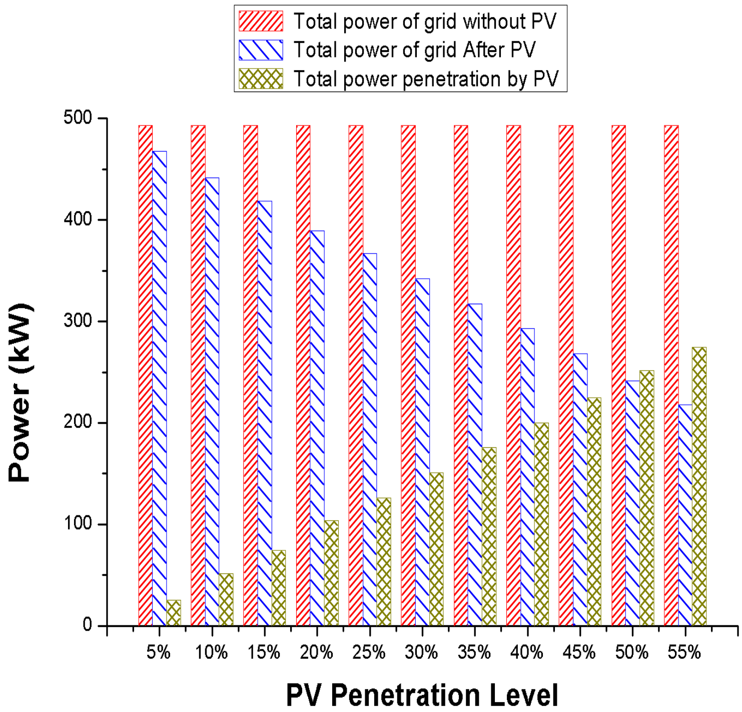

FIGURE 4.5: Power of 500 kVA System without and with PV Penetration

When PVS is integrated to a grid, power of grid become less as PVS take part of grid and supply some percentage of power by itself to the grid. Total power (TP) of grid without PVS, total power of grid after PV penetration (PVP) and total power penetrated by PVS is shown Figure 4.5. Different level of PV penetration power for 500 kVA grid is shown in Figure 4.5 clearly. All results are shown with detail in Table 4.1 for 500 kVA grid. PV penetration percentage, total power of grid, total power after PV penetration, PV penetration power, peak value of fault current without PV penetration, peak value of fault current with PV penetration, difference of fault current and percentage change in fault current where (fault is generated on 11 kV bus).

TABLE 4.1: Characteristics of Power and Fault Current for 500 kVA System (Fault at 11 kV Bus)

PVP Percentage	**PVP Power kW**	**TP of Grid kW**	**TP of Grid After PVP kW**	**Peak Value of FC without PV A**	**Peak Value of FC with PV A**	**Diff b/w FC in A**	**PC in FC**
5%	25.3	497	471.8	714.8	715	0.2	0.03%
10%	51.7	497	445.4	714.8	715.7	0.9	0.13%
15%	74.2	497	421.9	714.8	716.1	1.3	0.18%
20%	103.8	497	395.3	714.8	716.4	1.6	0.22%
25%	125.8	497	371.3	714.8	716.8	2	0.28%
30%	151	497	346.1	714.8	717.1	2.3	0.32%
35%	175.6	497	321.5	714.8	717.3	2.5	0.35%
40%	199.7	497	296.4	714.8	717.5	2.7	0.38%
45%	224.7	497	271.4	714.8	717.6	2.8	0.39%
50%	251.6	497	246.5	714.8	717.7	2.9	0.41%
55%	275	497	221.1	714.8	717.8	3	0.42%

4.1.5 FC on Feeder-2 Without PVS

Three-phase (LLLG) fault is generated on feeder-2 to investigate the behavior of the system. Fault current graph and the peak value is (653.6 A) as shown in Figure 4.6 for 500 kVA system without PV.

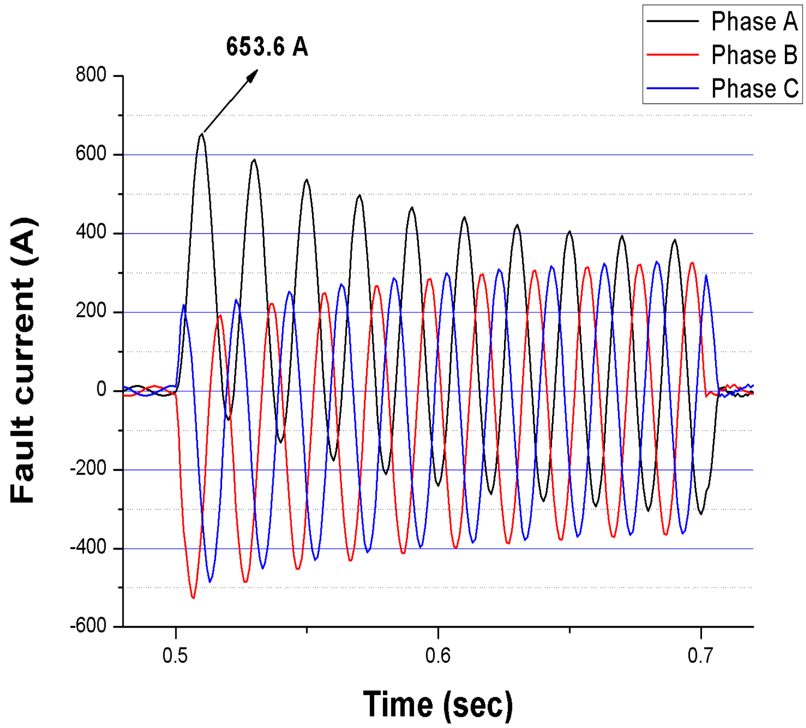

Figure 4.6: Fault Current without PV for 500 kVA System (Fault at Feeder-2)

4.1.6 FC on Feeder-2 with PVS (55% Penetration)

As from results of fault current graph and the peak value of fault current is (662.5 A) for 55% of PV penetration shown in Figure 4.7, there is an insignificant change in fault current level after integration of PVS with the grid. For all penetration levels of PV, in Table 4.2 values of fault current mentioned briefly.

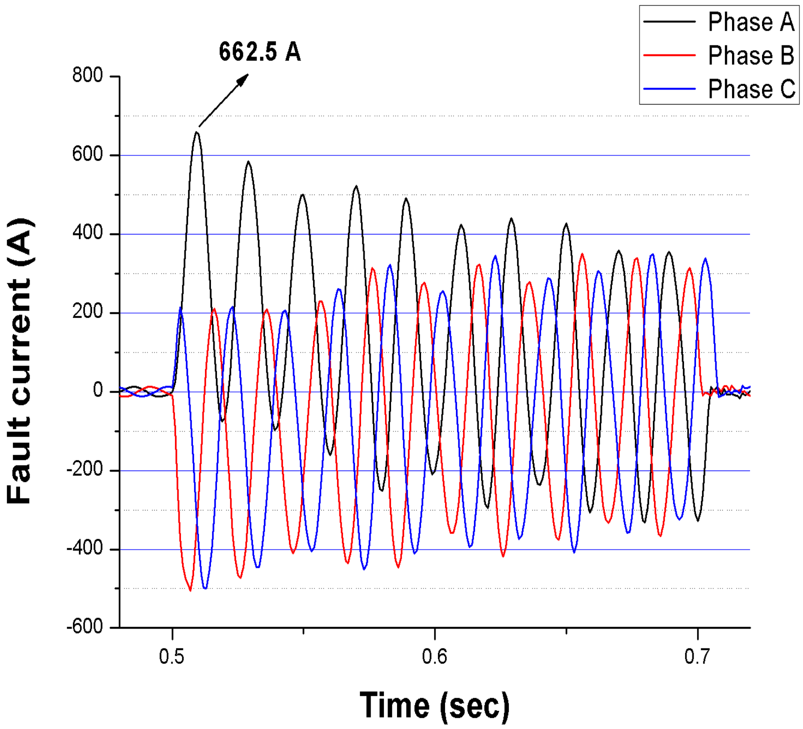

FIGURE 4.7: Fault Current on Feeder-2 with PV System of 500 kVA Grid (55% Penetration Level)

4.1.7 Comparison between FC on Feeder-2 without and with PVS with Different PL

For comparison between fault current levels of the system without PV and with the different penetration level of PV are shown in Figure 4.8. Results of simulation shows that there is an insignificant change in fault current levels for the system without and with PV in case of 500 kVA system, as shown in Figure 4.8 all values are nearly equal for different level of penetration. To make results clear another graph is shown in Figure 4.9, for comparison between fault current of the grid without PVS and with 25% and 50% penetration level of PV. Results of simulation shows that an insignificant change in fault current for system without and with PV in case of 500 kVA system. As from Figure 4.9 it is noticed that three of fault values overlap each other this shows that an insignificant change in fault current without and with PVS. Hence PV integration with different penetration levels with 500 kVA grid is not problematic. All results are shown with detail in Table 4.2 for 500

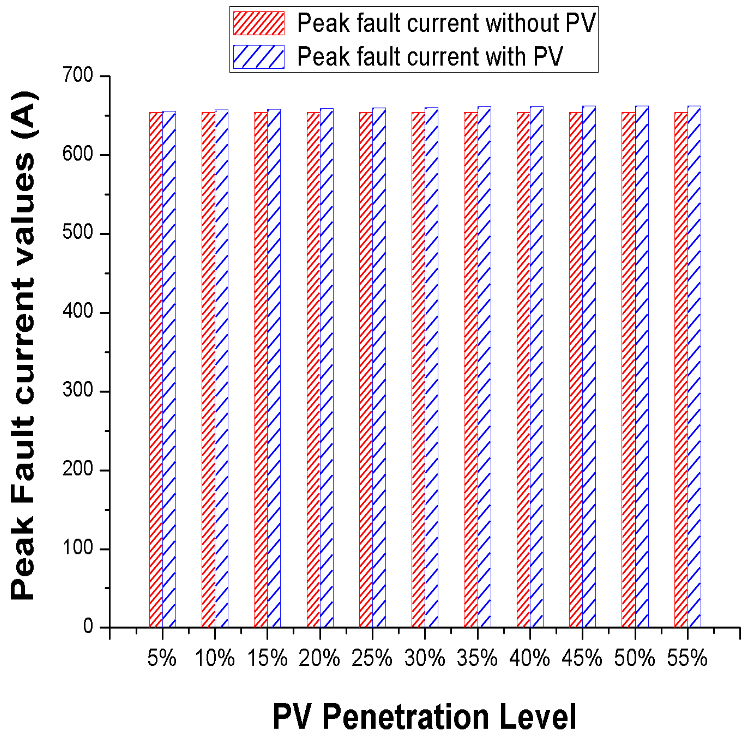

FIGURE 4.8: Comparison between Fault Current without and with PV for 500 kVA System (Fault at Feeder-2)

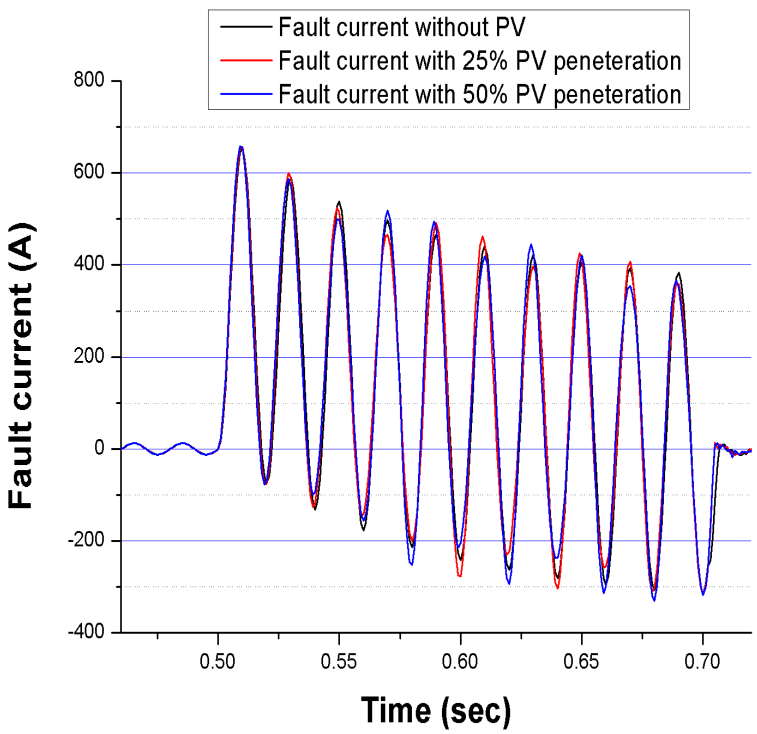

FIGURE 4.9: Comparison between Fault Current without and with PV for 500 kVA System (Fault at Feeder-2)

Table 4.2: Characteristics of Power and Fault Current for 500 kVA System (Fault at Feeder-2)

PVP Percentage	**PVP Power kW**	**TP of Grid kW**	**TP of Grid After PVP kW**	**Peak Value of FC without PV A**	**Peak Value of FC with PV A**	**Diff b/w FC in A**	**PC in FC**
5%	25.3	497	471.8	653.6	655.6	2	0.31%
10%	51.7	497	445.4	653.6	656.9	3.3	0.50%
15%	74.2	497	421.9	653.6	658.1	4.5	0.69%
20%	103.8	497	395.3	653.6	658.8	5.2	0.80%
25%	125.8	497	371.3	653.6	659.8	6.2	0.95%
30%	151	497	346.1	653.6	660.3	6.7	1.03%
35%	175.6	497	321.5	653.6	661.1	7.5	1.15%
40%	199.7	497	296.4	653.6	661.7	8.1	1.24%
45%	224.7	497	271.4	653.6	662.1	8.5	1.30%
50%	251.6	497	246.5	653.6	662.4	8.8	1.35%
55%	275	497	221.1	653.6	662.5	8.9	1.36%

kVA system. PV penetration percentage, total power of system, total power after PV penetration, PV penetration power, peak value of fault current without PV penetration, peak value of fault current with PV penetration, difference of fault current and percentage change in fault current for (fault generated on feeder-2).

4.2 Results for 1 MVA Model

In this section results of 1 MVA distribution system without and with PV are discussed. Results of FC on 11 kV bus without PVS, FC on 11 kV bus with PVS (55% penetration level), comparison between FC on 11 kV bus for grid without and with PVS with different PL, total power of system with and without PVS with different PL.

Total power of the system without and with PVS with different PL, FC on Feeder-2 without PVS, FC on feeder-2 with PVS (55% penetration), comparison between FC on feeder-2 without and with PVS with different PL are shown respectively.

4.2.1 FC on 11 kV Bus Without PVS

Three-phase (LLLG) fault is generated on 11 kV bus to investigate the behavior of the system. Fault current graph and the peak value is (1276 A) as shown in

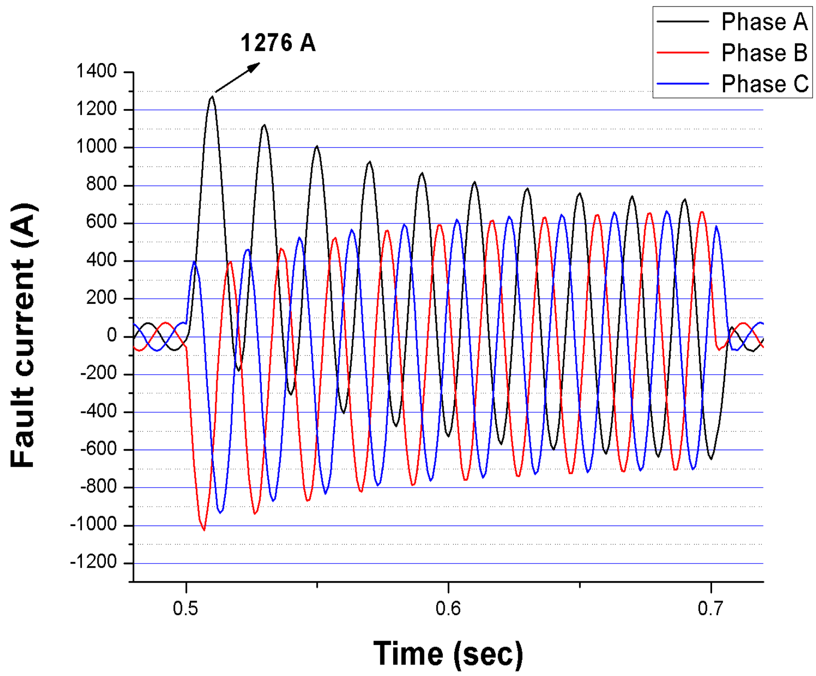

FIGURE 4.10: Fault Current without PV for 1 MVA System (Fault at 11 kV Bus)

Figure 4.10 for 1 MVA system without PV.

4.2.2 FC on 11 kV Bus With PVS (55% Penetration Level)

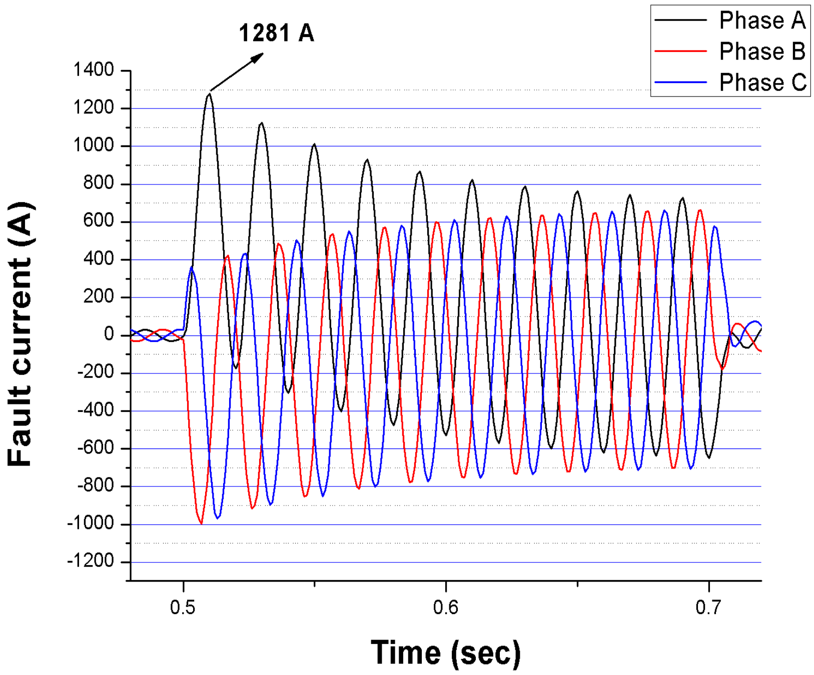

FIGURE 4.11: Fault Current on 11 kV Bus with PV System of 1 MVA Grid (55% Penetration Level)

As from results of fault current graph and peak value of fault current is (1281 A) for 55% of PV penetration shown in Figure 4.11, an insignificant change in fault current level after integration of PVS with grid. For all penetration levels of PV, in Table 4.3 values of fault current mentioned briefly.

4.2.3 Comparison between FC on 11 kV Bus with and without PVS with Different PL

For comparison between fault current levels for the system without PV and with different penetration levels of PV shown in Figure 4.12. Results of simulation shows that an insignificant change in fault current levels for the system without and with PV in case of 1 MVA system, as shown in Figure 4.12 all values are nearly equal for different level of penetration. To make results clear another graph is shown in Figure 4.13, for comparison between fault current of the grid without PVS and with 25% and 50% penetration level of PV. Results of simulation shows that an insignificant change in fault current for system without and with PVS in case of 1 MVA system. As from Figure 4.13 it is noticed that three of fault values

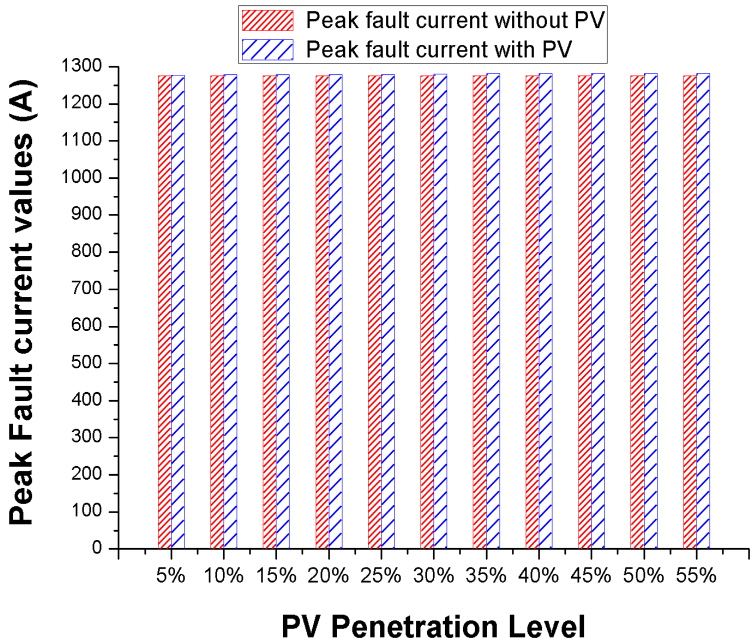

FIGURE 4.12: Comparison between Fault Current without and with PV for 1 MVA System (Fault at 11 kV Bus)

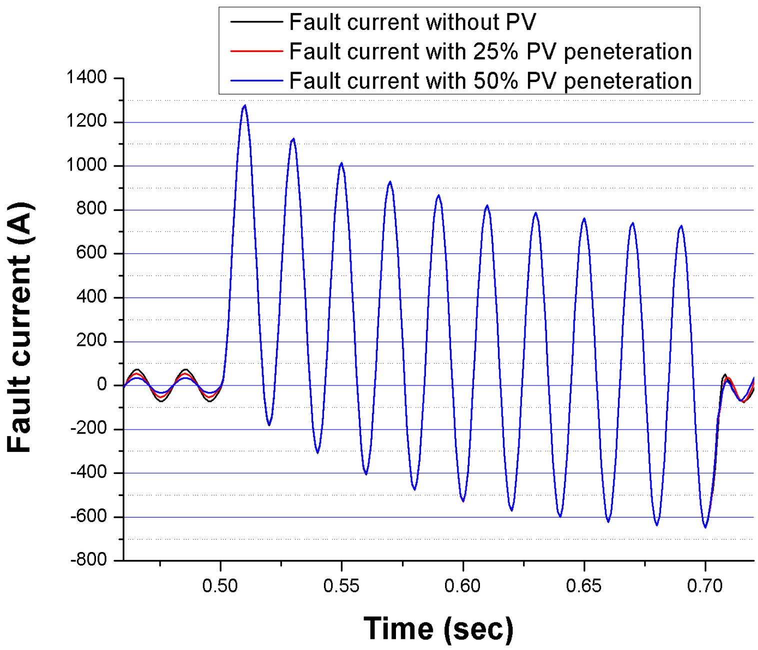

FIGURE 4.13: Comparison between Fault Current without and with PV for 1 MVA System (Fault at 11 kV Bus)

overlap each other this shows that an insignificant change in fault current without and with PV. Hence PVS integration with different penetration levels with 1 MVA grid is not problematic.

4.2.4 Inverter Current for 55% of PV Penetration (1 MVA System Fault at 11 kV Bus)

The industry rule of thumb for fault current contribution from PV systems considered for studies and modeling is twice the inverter rated current. This can however, vary between 1.2 -2.5 times the inverter rated current depending on different types and manufacturers of inverters for PV systems [54]. Inverter current for 55% of PV penetration (1 MVA System with fault at 11 kV Bus) is shown in Figure 4.14. As we can see nominal value of current is 917 A and fault current value is 1830 A. Limited fault contributions of the inverter as fault current increase 2 times, with comparison to nominal current. It is typically assumed that the total fault contribution for a PV inverter is less than or equal to twice the inverter's rated output current. The reason behind no effect of PV penetration on fault current levels is that grid tied inverters are capable of fast disconnection (i.e., in less than four cycles); interrupts the inverter current contribution immediately during a fault event. As response time of inverters is in milliseconds so inverter is able to instantly cease operation after a disturbance is detected. Therefore, the duration of the fault current contributions is also limited [55].

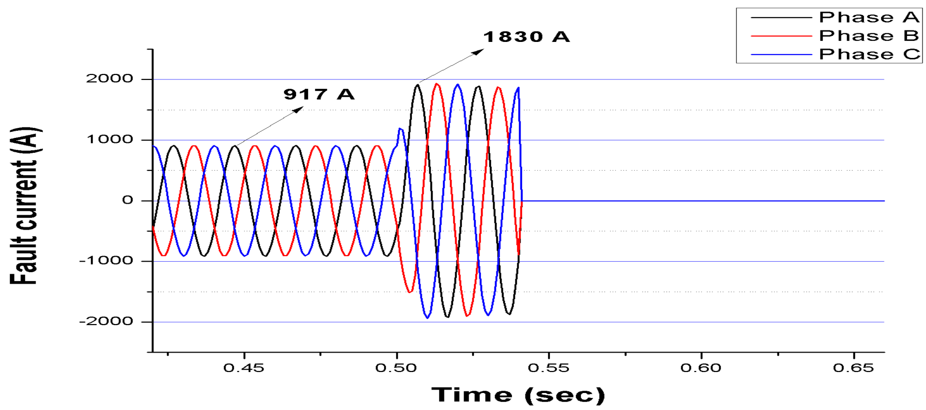

FIGURE 4.14: Inverter Current for 55% of PV Penetration (1 MVA System Fault at 11 kV Bus)

4.2.5 Total Power of System without and with PVS with Different PL

When PVS is integrated to a grid, power of the grid become less as PVS take part of grid and supply some percent of power by itself to the grid. Total power of grid without PVS, total power of grid after PV penetration and total power penetrated by PVS is shown Figure 4.15. Different level of PV penetration power for 1 MVA grid shown in Figure 4.15 clearly. All results are shown with detail in Table 4.3 for 1 MVA grid system. PV penetration percentage, total power

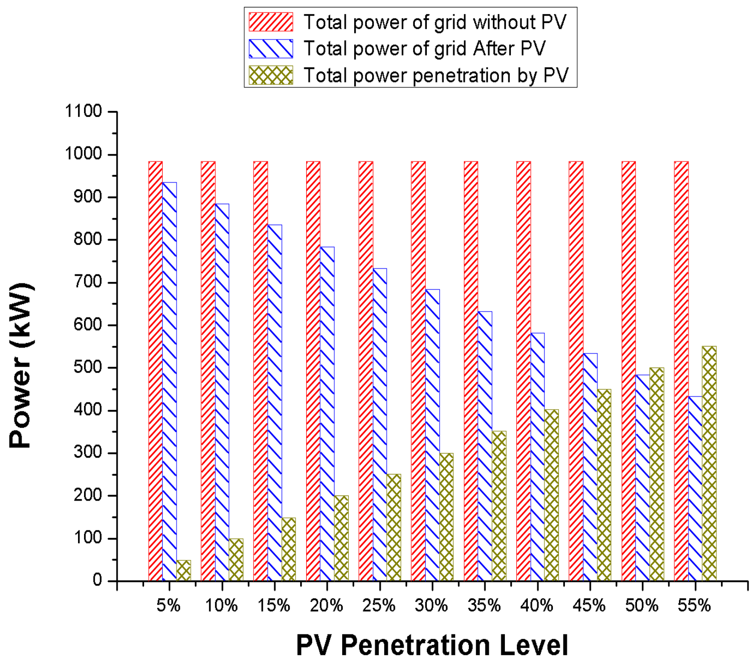

FIGURE 4.15: Power of 1 MVA System without and with PV Penetration

of system, total power after PV penetration, PV penetration power, peak value of fault current without PV penetration and peak value of fault current with PV penetration, difference of fault current and percentage change in fault current for (fault generated on 11 kV bus).

Table 4.3: Characteristics of Power and Fault Current for 1 MVA System (Fault at 11 kV Bus)

PVP Percentage	**PVP Power kW**	**TP of Grid kW**	**TP of Grid After PVP kW**	**Peak Value of FC without PV A**	**Peak Value of FC with PV A**	**Diff b/w FC in A**	**PC in FC**
5%	49.4	984	934.6	1276	1277	1	0.08%
10%	99.4	984	884.6	1276	1278	2	0.16%
15%	148.6	984	835.4	1276	1278	2	0.16%
20%	200.5	984	783.5	1276	1279	3	0.24%
25%	251.1	984	732.9	1276	1279	3	0.24%
30%	300.4	984	683.6	1276	1280	4	0.31%
35%	351	984	633	1276	1280	5	0.39%
40%	402.2	984	581.8	1276	1281	5	0.39%
45%	449.5	984	534.5	1276	1281	5	0.39%
50%	500.6	984	483.4	1276	1281	5	0.39%
55%	550.6	984	433.4	1276	1281	5	0.39%

4.2.6 FC on Feeder-2 without PVS

Three-phase (LLLG) fault is generated on feeder-2 to investigate the behavior of the system. Fault current graph and the peak value is (1093 A) as shown in Figure 4.16 for 1 MVA system without PV.

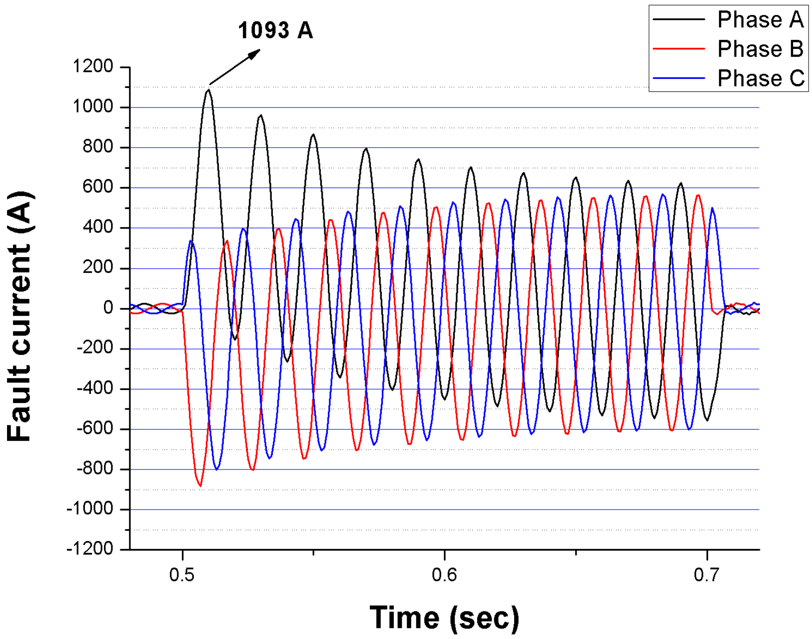

FIGURE 4.16: Fault Current without PV for 1 MVA System (Fault at Feeder-2)

4.2.7 FC on Feeder-2 with PVS (55% Penetration Level)

As from results of fault current graph and the peak value of fault current is (1109 A) for 55% of PV penetration as shown in Figure 4.17, an insignificant change in fault current level after integration of PV system to the grid. For all penetration levels of PV, in Table 4.4 values of fault current mentioned briefly.

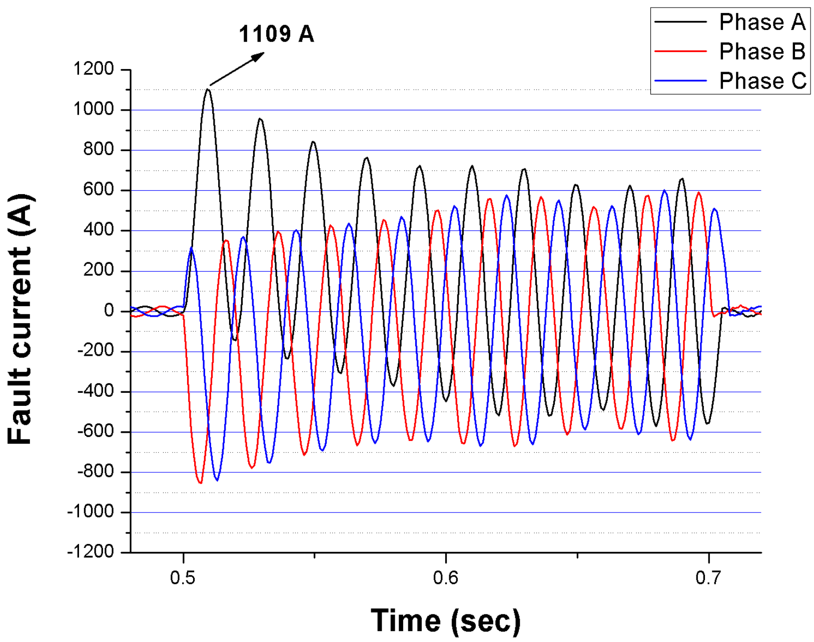

FIGURE 4.17: Fault Current on Feeder-2 with PV System of 1 MVA Grid (55% Penetration Level)

4.2.8 Comparison between FC on Feeder-2 without and with PVS with Different PL

For comparison between fault current levels of the system without PV and with the different penetration levels of PV shown in Figure 4.18. Results of simulation shows that an insignificant change in fault current levels for the system without and with PV in case of 1 MVA system, as shown in Figure 4.18 all values are nearly equal for different level of penetration. To make results clear another graph is shown in Figure 4.19, for comparison between fault current of grid without PVS and with 25% and 50% penetration level of PV. Results of simulation shows that an insignificant change in fault current for system without and with PV in case of 1 MVA system. As from Figure 4.19 it is noticed that three of fault values overlap each other this shows an insignificant change in fault current without and with PVS. Hence PV integration with different penetration levels with 1 MVA grid is not problematic. All results are shown with detail in Table 4.4 for 1 MVA system. PV penetration percentage, total power of system, total power after PV

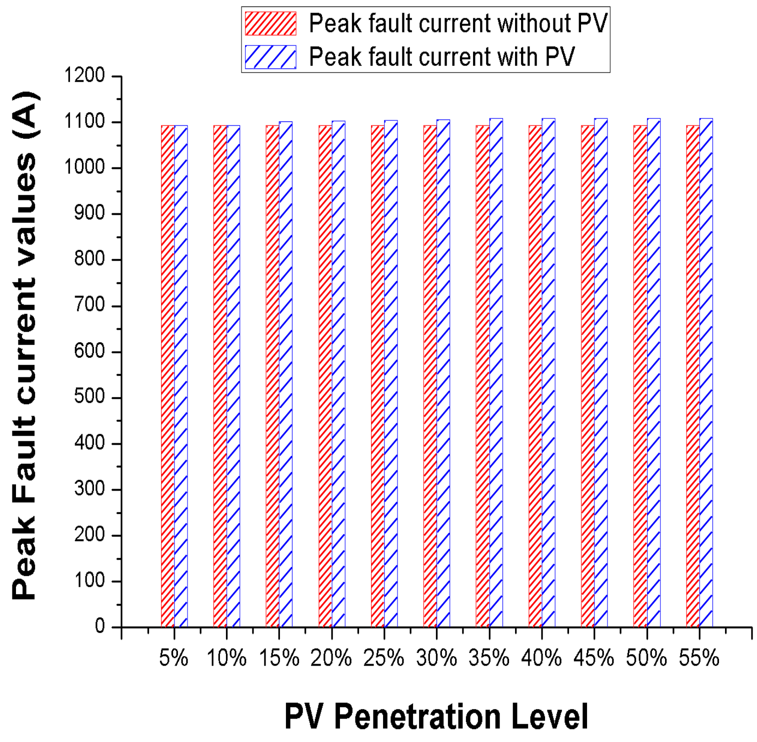

FIGURE 4.18: Comparison between Fault Current without and with PV for 1MW System (Fault at Feeder-2)

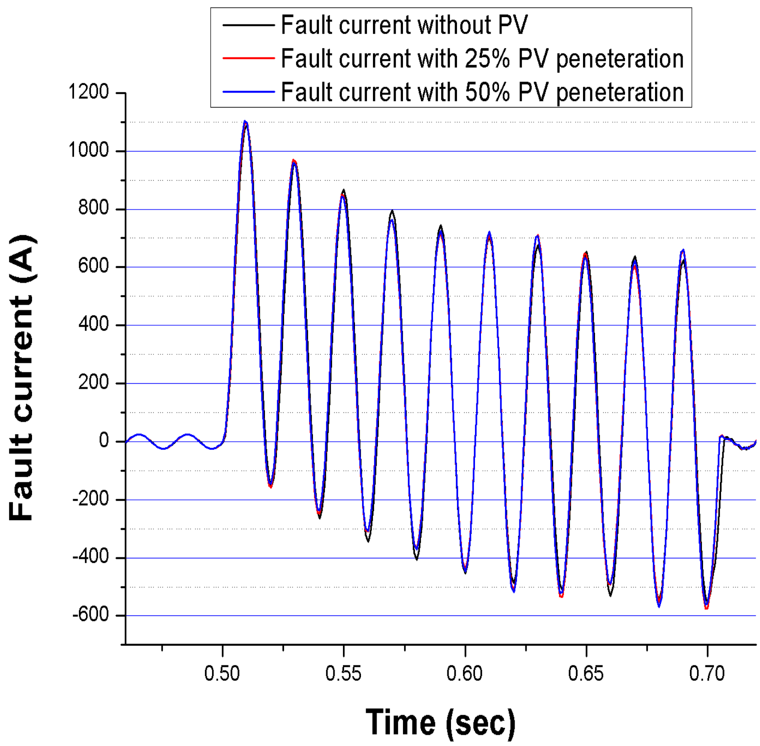

FIGURE 4.19: Comparison between Fault Current without and with PV for 1MW System (Fault at Feeder-2)

Table 4.4: Characteristics of Power and Fault Current for 1 MVA System (Fault at Feeder-2)

PVP Percentage	**PVP Power kW**	**TP of Grid kW**	**TP of Grid After PVP kW**	**Peak Value of FC without PV A**	**Peak Value of FC with PV A**	**Diff b/w FC in A**	**PC in FC**
5%	49.4	984	934.6	1093	1095	2	0.18%
10%	99.4	984	884.6	1093	1098	5	0.46%
15%	148.6	984	835.4	1093	1101	8	0.73%
20%	200.5	984	783.5	1093	1103	10	0.91%
25%	251.1	984	732.9	1093	1104	11	1.01%
30%	300.4	984	683.6	1093	1106	13	1.19%
35%	351	984	633	1093	1108	15	1.37%
40%	402.2	984	581.8	1093	1108	15	1.37%
45%	449.5	984	534.5	1093	1109	16	1.46%
50%	500.6	984	483.4	1093	1109	16	1.46%
55%	550.6	984	433.4	1093	1109	16	1.46%

penetration, PV penetration power, peak value of fault current without PV penetration and peak value of fault current with PV penetration, difference of fault current and percentage change in fault current for (fault generated on feeder-2).

4.3 Discussion

Fault current analysis is performed on two models of (500 kVA and 1 MVA) without and with PV system with different level of PV penetration. By generating two three-phase faults, at 11 kV bus and feeder-2 independently to investigate whether fault current level is been affected or not. Three-phase (LLLG) fault is generated in 500 kVA system without PV is shown in Figure 3.3 and with PV is shown in Figure 3.8 on the 11 kV bus at location (A1), where peak value of fault current level for model without PV is (714.8 A) as shown in Figure 4.1 and peak value of fault current level for model with PV is (717.8 A) as shown in Figure 4.2. For results we compared fault current level in Figure 4.3 and in Table 4.1 for all levels of PV penetration. There is an insignificant change in fault current level by integration of PV system.

Comparative analysis of fault current level performed, when three-phase fault is generated on feeder-2 at location (A2) as shown in Figure 3.5 in 500 kVA system without and with PVS. As it is noticed that peak value of fault current level for model without PV is (653.6 A) as shown in Figure 4.6 and peak value of fault current level for model with (55% PV penetration) is (662.5 A) as shown in Figure 4.7. Despite 55% PV penetration is done which makes it clear PV integration has no effect on fault current levels. For results we compared fault current level in Figure 4.8 and in Table 4.2 for all level of PV penetration. There is an insignificant change in fault current level by integration of PV system.

For 1 MVA system without and with PVS, when three-phase fault is generated on 11 kV bus. Comparative analysis for fault current level is performed where peak value of fault current level for model without PV is (1276 A) as shown in Figure 4.10 and peak value of fault current level for model with (55% PV penetration) is (1281 A) as shown in Figure 4.11. Despite 55% PV penetration is done which makes it clear PV integration has no effect on fault current levels. As from Figure 4.13, three fault current values for without PV, with 25% and 50% PV penetration level respectively overlap each other. This shows an insignificant change in fault current level by integration of PV system. For all level of penetration results are shown in Figure 4.12 and in Table 4.3. Three-phase (LLLG) fault is generated in 1 MVA system without and with PVS on feeder-2, for result we compare fault current level in Figure 4.18 and in Table 4.4, there is an insignificant change in fault current level despite 55% PV penetration is done which makes it clear PV integration has no effect on fault current levels. The reason behind no effect of PV penetration on fault current levels is that grid tied inverters are capable of fast disconnection (i.e., in less than four cycles); interrupts the inverter current contribution immediately during a fault event. As response time of inverters is in milliseconds so inverter is able to instantly cease operation after a disturbance is detected. Therefore, the duration of the fault current contributions is also limited. It is typically assumed that the total fault contribution for a PV inverter is less than twice the inverters rated output current.

Chapter 5

Conclusion and Future Work

In this chapter conclusion and future work are discussed, area of this research is so vast and there are many opportunities for new research. Future recommendations are discussed also.

5.1 Conclusion

By integrating PV system with the conventional grid, level of fault current can increase which has a severe impact on existing system, such as fault protection equipment and overall infrastructure of distribution system. There are two opinions, regarding to this effect of change in fault current levels due to PV penetration. One of the opinion states that as PV penetration increases fault current level will increase and will have negative effect on the fault protection equipment and overall infrastructure. The other opinion states that the change in fault current level will be insignificant with PV penetration. There is a contradiction between these two opinions and our objective is, to determine which opinion is correct among the above mentioned two opinions. We have proved that by integrating PV system with conventional grid there is an insignificant change in fault current level with the help of simulations and results. As in proposed research work, different level of penetration of PV system studied and results show that there is no negative impact of PV integration during the fault condition. Two models of 500 kVA and 1 MVA without and with PVS were used to perform comparative analysis. It was observed that by high penetration of PV there is an insignificant change in fault current level. The reason behind no effect of PV penetration on fault current levels is that grid tied inverters are capable of fast disconnection (i.e., in less than four cycles); interrupts the inverter current contribution immediately during a fault event. As response time of inverters is in milliseconds so inverter is able to instantly cease operation after a disturbance is detected. Therefore, the duration of the fault current contributions is also limited. It is typically assumed that the total fault contribution for a PV inverter is less than twice the inverters rated output current.

5.2 Future Work

In this research work, we used the concept of decentralized generation and that will be used on the distributed level. In future centralized PV farms will be integrated with conventional grid it is important to analyze the impact of centralized generation on the conventional grid. For the protection of grid, grid-tied inverters should be operational and intelligent. Moreover, the impact of a hybrid system including the penetration of large scale PV system will be considered for future work.

Bibliography

[1] V. Jayasankar, M. Gururaj, and U. Vinatha, "A study on hybrid renewable energy source interface to the non-ideal grid at distribution level with power quality improvements," in *Power Systems (ICPS), 2016 IEEE 6th International Conference on*. IEEE, 2016, pp. 1–5.

[2] D. Carlson, "Fossil fuels, the greenhouse effect and photovoltaics," *IEEE Aerospace and Electronic Systems Magazine*, vol. 4, no. 12, pp. 3–7, 1989.

[3] R. Burrett, C. Clini, R. Dixon, M. Eckhart, M. El-Ashry, D. Gupta, A. Haddouche, D. Hales, K. Hamilton, U. Chatham House *et al.*, "Renewable energy policy network for the 21st century," pp. 9–12, 2007.

[4] M. Thomson and D. G. Infield, "Network power-flow analysis for a high penetration of distributed generation," *IEEE Transactions on Power Systems*, vol. 22, no. 3, pp. 1157–1162, 2007.

[5] I.-T. Theologitis, E. Troester, and T. Ackermann, "Aspects of a generic photovoltaic model examined under the german grid code for medium voltage," in *1st International Workshop on Integration of Solar Power into Power Systems, Aarhus, Dänemark*, pp. 3–6, 2011.

[6] A. Jager-Waldau, "European commission joint research centre," *PV Status Report 2003: Research, Solar Cell Production and Market Implementation in Japan, USA and the European Union*, pp. 5–9, 2003.

[7] D. Gielen, "Renewable energy technologies: cost analysis series," *Sol Photovolt*, vol. 1, no. 1, pp. 55-58, 2012.

[8] Michael, M. El-Ashry, D. Gupta, A. Haddouche, D. Hales, K. Hamilton, R. Chatham House, Burrett, C. Clini, R. Dixon *et al.*, "Renewable energy policy network for the 21st century," pp. 100–105, 2016.

[9] W. A. Omran, M. Kazerani, and M. Salama, "Investigation of methods for reduction of power fluctuations generated from large grid-connected photovoltaic systems," *IEEE Transactions on Energy Conversion*, vol. 26, no. 1, pp. 318–327, 2011.

[10] A. Ihbal, R. A. Abd-Alhameed, M. Elgadal, H. Gabasa, and M. Ehbal, "Investigation of using photovoltaic system at local residential community level," in *Green Energy, 2014 International Conference on*. IEEE, 2014, pp. 1–7.

[11] A. H. Eldin, M. Refaey, and A. Farghly, "A review on photovoltaic solar energy technology and its efficiency", 17th international middle-east power system conference (mepcon'15), at mansoura university, egypt. pp.1–7, 2015."

[12] R. Mallwitz and B. Engel, "Solar power inverters," in *Integrated Power Electronics Systems (CIPS), 2010 6th International Conference on*. IEEE, 2010, pp. 1–7.

[13] T. Ehara, "Overcoming pv grid issues in urban areas," *IEA PVPS Task*, vol. 10, pp. 59–62, 2009.

[14] S. M. A. S. Bukhari, J. Maqsood, M. Q. Baig, S. Ashraf, and T. A. Khan, "Comparison of characteristics–lead acid, nickel based, lead crystal and lithium based batteries," in *Modelling and Simulation (UKSim), 2015 17th UKSim-AMSS International Conference on*. IEEE, 2015, pp. 444–450.

[15] B. Dunn, H. Kamath, and J.-M. Tarascon, "Electrical energy storage for the grid: a battery of choices," *Science*, vol. 334, no. 6058, pp. 928–935, 2011.

[16] A. Kheldoun, R. Bradai, R. Boukenoui, and A. Mellit, "A new golden section method-based maximum power point tracking algorithm for photovoltaic systems, ėlsvier journal," *Energy Conversion and Management*, vol. 111, pp. 125–136, 2016.

[17] R. Bradai, R. Boukenoui, A. Kheldoun, H. Salhi, M. Ghanes, J.-P. Barbot, and A. Mellit, "Experimental assessment of new fast mppt algorithm for pv systems under non-uniform irradiance conditions, ėlsvier journal," *Applied Energy*, vol. 199, pp. 416–429, 2017.

[18] A. K. Abdelsalam, A. M. Massoud, S. Ahmed, and P. N. Enjeti, "High-performance adaptive perturb and observe mppt technique for photovoltaic-based microgrids," *IEEE Transactions on Power Electronics*, vol. 26, no. 4, pp. 1010–1021, 2011.

[19] V. Energy, "Multiplus inverter/charger," *Data sheet*, vol. 375, no. 2, p. 2, 2000.

[20] S. Kirmani, M. Jamil, C. Kumar, and M. J. Ahmed, "Techno economic feasibility analysis of a stand-alone pv system to electrify a rural area household in india," *International Journal of Engineering Science and Technology*, vol. 2, no. 10, pp. 5231–5237, 2010.

[21] E.-S. A. Nafeh *et al.*, "Design and economic analysis of a stand-alone pv system to electrify a remote area household in egypt," *The open renewable energy journal*, vol. 2, no. 1, pp. 33–37, 2009.

[22] N. Altin and İ. Sefa, "dspace based adaptive neuro-fuzzy controller of grid interactive inverter," *Energy Conversion and Management, ĖLSVIER Journal*, vol. 56, pp. 130–139, 2012.

[23] B. Ernst and B. Engel, "Grid integration of distributed pv-generation," in *Power and Energy Society General Meeting Conference, 2012.* IEEE, 2012, pp. 1–7.

[24] B. Noone, "Pv integration on australian distribution networks," *The Australian PV Association, UNSW, Australia, Project Report*, pp. 13–18, 2013.

[25] M. A. Mahmud, M. Hossain, and H. Pota, "Worst case scenario for large distribution networks with distributed generation," in *Power and Energy Society General Meeting, 2011.* IEEE, 2011, pp. 1–7.

[26] P.-C. Chen, R. Salcedo, Q. Zhu, F. De Leon, D. Czarkowski, Z.-P. Jiang, V. Spitsa, Z. Zabar, and R. E. Uosef, "Analysis of voltage profile problems due to the penetration of distributed generation in low-voltage secondary distribution networks," *IEEE Transactions on Power Delivery*, vol. 27, no. 4, pp. 2020–2028, 2012.

[27] D. Caples, S. Boljevic, and M. F. Conlon, "Impact of distributed generation on voltage profile in 38kv distribution system," in *Energy Market (EEM), 2011 8th International Conference on the European*. IEEE, 2011, pp. 532–536.

[28] P. Mitra, G. T. Heydt, and V. Vittal, "The impact of distributed photovoltaic generation on residential distribution systems," in *North American Power Symposium (NAPS) Conference, 2012*. IEEE, 2012, pp. 1–6.

[29] A. S. Masoum, P. S. Moses, M. A. Masoum, and A. Abu-Siada, "Impact of rooftop pv generation on distribution transformer and voltage profile of residential and commercial networks," in *Innovative Smart Grid Technologies (ISGT) Conference, 2012 IEEE PES*. IEEE, 2012, pp. 1–7.

[30] P. Chiradeja, "Benefit of distributed generation: A line loss reduction analysis," in *Transmission and Distribution Conference and Exhibition: Asia and Pacific, 2005 IEEE/PES*. IEEE, 2005, pp. 1–5.

[31] A. A. Kadir, A. Mohamed, and H. Shareef, "Harmonic impact of different distributed generation units on low voltage distribution system," in *Electric Machines & Drives Conference (IEMDC), 2011 IEEE International*. IEEE, 2011, pp. 1201–1206.

[32] S. KoohiKamali, S. Yusof, J. Selvaraj, and M. N. B. Esa, "Impacts of grid-connected pv system on the steady-state operation of a malaysian grid," in *Power and Energy (PECon), 2010 IEEE International Conference on*. IEEE, 2010, pp. 858–863.

[33] A. Gabash and P. Li, "Active-reactive optimal power flow for low-voltage networks with photovoltaic distributed generation," in *Energy Conference*

and Exhibition (ENERGYCON), 2012 IEEE International. IEEE, 2012, pp. 381–386.

[34] J. Qiang, Z. Shuo, and L. Yong-li, "A study on capacity of distributed generation and its effect on short circuit current at micro-grid operation mode," in *Electric Utility Deregulation and Restructuring and Power Technologies (DRPT), 2011 4th International Conference on.* IEEE, 2011, pp. 1109–1112.

[35] C. J. Mozina, "Impact of smart grid and green power generation on distribution systems," in *Innovative Smart Grid Technologies (ISGT) Conference, 2012 IEEE PES.* IEEE, 2012, pp. 1–13.

[36] Y. Baghzouz, "Voltage regulation and overcurrent protection issues in distribution feeders with distributed generation-a case study," in *System Sciences, 2005. HICSS'05. Proceedings of the 38th Annual Hawaii International Conference on.* IEEE, 2005, pp. 1–6.

[37] M. Geidl, "Protection of power systems with distributed generation, power systems laboratory swiss federal institute of technology (eth) zurich," vol. 2, pp. 17–19, 2005.

[38] D. Turcotte and F. Katiraei, "Fault contribution of grid-connected inverters," in *Electrical Power & Energy Conference (EPEC), 2009 IEEE.* IEEE, 2009, pp. 1–5.

[39] J. de la Cruz and P. Gómez, "Real problems in utility high voltage network due to grid connected photovoltaic power generation. the experience of endesa," in *Proc. 2010 International Conference on Renewable Energies and Power Quality, Granada, Spain*, 2010, pp. 1–6.

[40] T. Ghanbari and E. Farjah, "Development of an efficient solid-state fault current limiter for microgrid," *IEEE Transactions on Power Delivery*, vol. 27, no. 4, pp. 1829–1834, 2012.

[41] A. Abramovitz, M. Smedley *et al.*, “Survey of solid-state fault current limiters,” *IEEE Transactions on power electronics*, vol. 27, no. 6, pp. 2770–2782, 2012.

[42] S. Ananwattanaporn and A. Ngaopitakkul, “Impact of multi-distributed generation on key parameter in distribution system,10th international conference on advances in power system control, operation and management,” IET, pp. 4–6, 2015.

[43] S. Phuttapatimok, A. Sangswang, M. Seapan, D. Chenvidhya, and K. Kirtikara, “Evaluation of fault contribution in the presence of pv grid-connected systems,” in *Photovoltaic Specialists Conference, 2008. PVSC’08. 33rd IEEE.* IEEE, 2008, pp. 1–5.

[44] S. Bhattacharya, T. Saha, and M. Hossain, “Fault current contribution from photovoltaic systems in residential power networks,” in *Power Engineering Conference (AUPEC), 2013 Australasian Universities.* IEEE, 2013, pp. 1–6.

[45] U. S. Khan and M. N. Arbab, “Impact of solar pv integration on short circuit current and protection of distribution system, international journal of engineering works,” vol. 5, pp. 96–102, 2018.

[46] N. Nimpitiwan, G. T. Heydt, R. Ayyanar, and S. Suryanarayanan, “Fault current contribution from synchronous machine and inverter based distributed generators,” *IEEE Transactions on power delivery*, vol. 22, no. 1, pp. 634–641, 2007.

[47] T. Sidhu and D. Bejmert, “Short-circuit current contribution from large scale pv power plant in the context of distribution power system protection performance, conference on renewable power generation,” IET, pp. 134–135, 2011.

[48] N. Mourad and B. Mohamed, “Short circuit current contribution of distributed photovoltaic integration on radial distribution networks,” in *Electrical Engineering (ICEE), 2015 4th International Conference on.* IEEE, 2015, pp. 1–4.

[49] Y.-K. Wu, Y. Guan-Ting, and M. Shaaban, "Impact analysis of large pv integration: Case studies in taiwan," in *Industrial and Commercial Power Systems Technical Conference (I&CPS), 2016 IEEE/IAS 52nd*. IEEE, 2016, pp. 1–10.

[50] S. Afifi, M. Darwish, and G. Taylor, "Impact of photovoltaic penetration on short circuit levels in distribution networks," in *International Conference on Renewable Energy and Power Quality Conference*, 2014, pp. 8–10.

[51] H. Ravindra, M. O. Faruque, P. McLaren, K. Schoder, M. Steurer, and R. Meeker, "Impact of pv on distribution protection system," in *North American Power Symposium (NAPS), 2012*. IEEE, 2012, pp. 1–6.

[52] R. I. Putri, S. Wibowo, and M. Rifai, "Maximum power point tracking for photovoltaic using incremental conductance method," *Energy Procedia, 2nd International Conference on Sustainable Energy Engineering and Application, ICSEEA 2014*, vol. 68, pp. 22–30, 2014.

[53] P. Zuniga-Haro and J. M. Ramirez, "Modeling of multi-pulse vsc based sssc and statcom," *Journal of Electromagnetic Analysis and Applications*, vol. 2, no. 03, pp. 145–146, 2010.

[54] J. Keller, B. Kroposki, R. Bravo, and S. Robles, "Fault current contribution from single-phase pv inverters," in *Photovoltaic Specialists Conference (PVSC), 2011 37th IEEE*. IEEE, 2011, pp. 001 822–001 826.

[55] F. Katiraei, J. Holbach, T. Chang, W. Johnson, D. Wills, B. Young, L. Marti, A. Yan, P. Baroutis, G. Thompson *et al.*, "Investigation of solar pv inverters current contributions during faults on distribution and transmission systems interruption capacity," in *Western Protective Relay Conference*, pp. 70–78, 2012.

[56] K. Chopra, P. Paulson, and V. Dutta, "Thin-film solar cells: an overview," *Progress in Photovoltaics: Research and Applications*, vol. 12, no. 2-3, pp. 69–92, 2004.

Appendices

Existing Technologies of PV Cells Existing technologies of PV cells are discussed one by one in detail in this section.

First Generation PV

First generation of PV is based on wafers of silicone, two main types of first

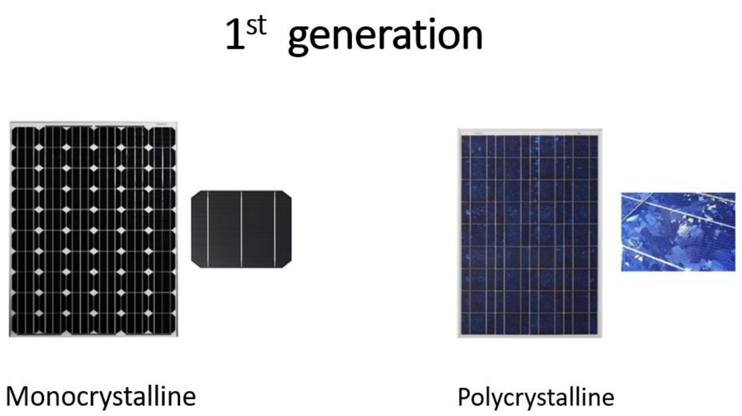

FIGURE 1: Mono Crystalline and Poly Crystalline First-Generation PV [11]

generation are mono crystalline and poly crystalline cells both of technologies are shown in Figure 1. Mono crystalline cell structure is made of single crystal of silicon. Life span of these cells is $25 - 30$ years. Poly crystalline cells structure is made of multiple smaller crystals of silicon. Poly crystalline is slightly less efficient then mono crystalline cells. Reason for being less efficient than mono crystalline is that in poly crystalline its crystal structure has different size of crystals, on different crystals defects occur on border, due to these defects poly crystalline cells are less efficient [11].

Second Generation PV

Second generation PV modules are named as thin film solar cells two major types

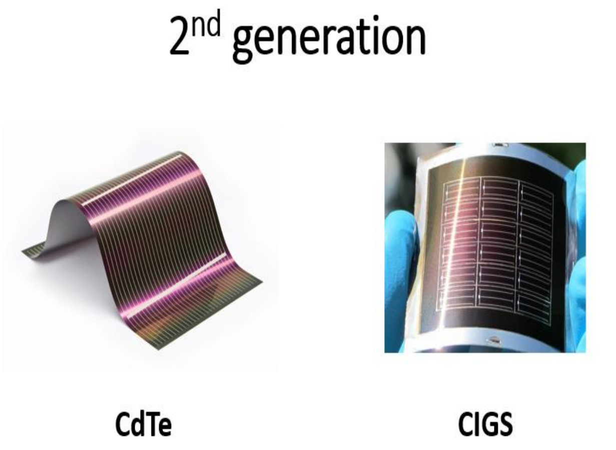

Figure 2: CdTe and CIGS Second Generation PV [11]

of thin film solar cells are CdTe and CIGS as shown in Figure 2. Thin film solar cells can generate more economical electricity as compared c-Si ingots based solar cells [56]. Thin film technology is flexible and can be used on buildings and cars easily [11].

Third Generation PV

Third generation PV cells are multi-junction cells, technology is shown in Fig-

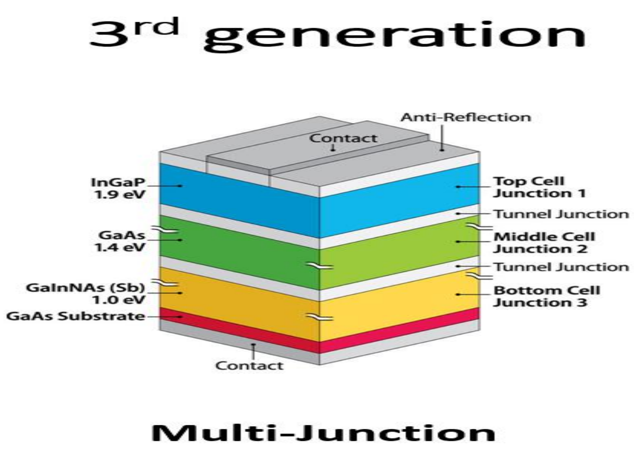

Figure 3: Multi-Junction Third Generation PV [11]

ure 3. Multiple pn-junctions absorb different wavelengths of light which are on top of each other. This technology is very efficient and used for highly sophisticated areas such as used for space projects. Record efficiency is 45% but this technology is very expensive.

Third generation technology is still not developed technology, some of these are being used commercially but comparing existing technologies in market it is still not clear yet how will this technology compete existing one [11].