CAPITAL UNIVERSITY OF SCIENCE AND TECHNOLOGY, ISLAMABAD

Voltage Control Design for an Inverter Using MPC and SMC

by

Muhammad Ali

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

in the

Faculty of Engineering

Department of Electrical Engineering

2022

This thesis is dedicated to my family, friends and those who have supported and encouraged me with their endless love.

CERTIFICATE OF APPROVAL

Voltage Control Design for an Inverter Using MPC and SMC

by

Muhammad Ali

MEE201003

THESIS EXAMINING COMMITTEE

S. No.	Examiner	Name	Organization
(a)	External Examiner	Dr. Qudrat Khan	COMSATS, Islamabad
(b)	Internal Examiner	Dr. Aamer Iqbal Bhatti	CUST, Islamabad
(c)	Supervisor	Dr. Fazal-ur-Rehman	CUST, Islamabad

Dr. Fazal-ur-Rehman
Thesis Supervisor
August, 2022

Dr. Noor Muhammad Khan
Head
Dept. of Electrical Engineering
August, 2022

Dr. Imtiaz Ahmad Taj
Dean
Faculty of Engineering
August, 2022

Author's Declaration

I, **Muhammad Ali** hereby state that my MS thesis titled "**Voltage Control Design for an Inverter Using MPC and SMC**" is my own work and has not been submitted previously by me for taking any degree from Capital University of Science and Technology, Islamabad or anywhere else in the country/abroad.

At any time if my statement is found to be incorrect even after my graduation, the University has the right to withdraw my MS Degree.

Muhammad Ali

Registration No: MEE201003

Plagiarism Undertaking

I solemnly declare that research work presented in this thesis titled "**Voltage Control Design for an Inverter Using MPC and SMC**" is solely my research work with no significant contribution from any other person. Small contribution/help wherever taken has been duly acknowledged and that complete thesis has been written by me.

I understand the zero tolerance policy of the HEC and Capital University of Science and Technology towards plagiarism. Therefore, I as an author of the above titled thesis declare that no portion of my thesis has been plagiarized and any material used as reference is properly referred/cited.

I undertake that if I am found guilty of any formal plagiarism in the above titled thesis even after award of MS Degree, the University reserves the right to withdraw/revoke my MS degree and that HEC and the University have the right to publish my name on the HEC/University website on which names of students are placed who submitted plagiarized work.

Muhammad Ali

Registration No: MEE201003

Acknowledgement

First of all, I am grateful to the creator of the world Allah almighty, who gave me the courage to continue my study with research work. The courage and support granted by Allah almighty helped me to tolerate the hard time during research work. At this time, I cannot forget prophet Muhammad (Peace Be Upon Him) who is the ideal man of the world the most respectable personality for whom the world is created, he guided us in every field of life. I would like to thank Dr. Fazal-Ur-Rehman the supervisor of my thesis, it has been an honor to me that i have worked with him. He supported, guided and encourage me all the time. I have learnt not only about thesis work but also about the way how to progress in every field of life. I am highly grateful to my family specially my parents who have supported me in every aspect. We cannot do anything without the support of family. Finally, I would like to extend my heartiest thanks to Faheem Manzoor who also guided me in my thesis.

Muhammad Ali

Abstract

This thesis presents a comparison between model predictive controller and sliding mode controller on the basis of overall performance. This comparison is done by controlling the output voltage in case of varying load at output terminals of three phase voltage source PWM inverter. The non-linear state space model in dq reference frame is linearized through input output linearization. In first case model predictive controller is designed in which output voltage is controlled through prediction. MPC design needs to minimize the cost function. The cost function is designed with the help of data and tuning matrices. Minimization of cost function means inverter operates at optimal switching states to get desired output. The second approach is sliding mode controller design for the system. In SMC, sliding surface and control law are designed in a such way that the derivative of Lyapunov function is strictly less than zero. The states converged from initial state to zero confirming the stability criteria of the system. An error is defined which also converges to zero in such a way that the require output gets the reference value. Both strategies give the control inputs in dq frame of reference as constant values. These values are converted back into three phases for PWM switching. The switching technique used in this work is sinusoidal PWM which is considered to be an effective technique for reducing total harmonic distortion. In both strategies the controller is designed for linear model then developed it for original model. Comparison shows MPC has good performance having good transient response, chattering free design , easy to design and handling of constraints than sliding mode controller. Therefore MPC is better than SMC.

Contents

Author's Declaration iv

Plagiarism Undertaking v

Acknowledgement vi

Abstract vii

List of Figures xi

Abbreviations xii

Symbols xiv

1 INTRODUCTION 1
- 1.1 Introduction . . . 1
  - 1.1.1 Grid Connected Inverter . . . 5
  - 1.1.2 Stand-alone Inverter . . . 6
  - 1.1.3 Bimodal Inverter . . . 7
- 1.2 Pulse Width Modulation Techniques . . . 8
  - 1.2.1 Sinusoidal Pulse Width Modulation . . . 8
  - 1.2.2 PWM Switching Technique . . . 9
    - 1.2.2.1 Duty Cycle . . . 10
  - 1.2.3 Third Harmonic Injection . . . 10
  - 1.2.4 Space Vector Modulation . . . 11
- 1.3 Transformation . . . 11
  - 1.3.1 Clark's Transformation . . . 11
  - 1.3.2 Park's Transformation . . . 12
- 1.4 Overview . . . 13
- 1.5 Motivation . . . 13
- 1.6 Application of Research . . . 14
- 1.7 Structure of The Thesis . . . 14
- 1.8 Summary . . . 16

2 Literature Review 17
- 2.1 Introduction . . . 17

2.2 Gap Analysis . . . 23
2.3 Problem Statement . . . 24
2.4 Research Methodology . . . 24
2.4.1 Model Predictive Controller . . . 24
2.4.2 Sliding Mode Controller . . . 25
2.5 Software Tools . . . 25
2.6 Vectors . . . 25
2.7 Vector Field . . . 25
2.8 Lie Algebra . . . 26
2.8.1 Mathematical Representation . . . 26
2.9 Runge-Kutta . . . 27
2.10 Summary . . . 27

3 Model Predictive Controller Design for an Inverter Dynamic Model 28
3.1 Three Phase Voltage Source PWM Inverter . . . 29
3.2 Dynamic Model of Three Phase Voltage Source PWM Inverter . . . 29
3.2.1 On Off Scheme of The Switching Phase . . . 31
3.2.2 State Space Model of Three Phase VSI . . . 33
3.3 Input Output Linearization . . . 35
3.4 Model Predictive Controller Design . . . 37
3.4.1 MPC Offers a Number of Advantages [12] Which are: . . . 37
3.5 Methodology . . . 38
3.5.1 Prediction Horizon . . . 39
3.5.2 Control Horizon . . . 40
3.6 General Algorithm for MPC . . . 40
3.6.1 Single Input Single Output System . . . 40
3.6.2 Prediction of States and Output Variables . . . 42
3.6.3 Optimization . . . 45
3.7 Overall Control Implementation Architecture . . . 47
3.8 Methodology in Mathematical Form for Three Phase Voltage Source PWM Inverter . . . 48
3.9 Receding Horizon Control . . . 52
3.10 Summary . . . 52

4 Sliding Mode Controller Design for an Inverter Dynamic Model 53
4.1 Sliding Mode Control . . . 53
4.1.1 Methodology . . . 54
4.2 Advantages of SMC . . . 54
4.3 Disadvantages of SMC . . . 54
4.4 Sliding Surface Design . . . 55
4.5 Signum Function . . . 55
4.6 Methodology in Mathematical Form . . . 57
4.7 Parameters Value . . . 60
4.7.1 Parameters Values for Star Connection . . . 60

4.7.2 Relations Among RMS Value, Peak Value,Peak to Peak and Average Values 61
4.8 Summary 62

5 Results and Assessments **63**
5.1 Model Predictive Control 63
5.1.1 Required Linear Controllers 64
5.2 Required Non-linear Controllers 64
5.2.1 Desired Outputs Values in dq Reference Frame 64
5.3 Sliding Mode Control 65
5.3.1 Required Linear Controllers 65
5.3.2 Required Non-linear Controllers 65
5.3.3 Behaviour of State Variables 66
5.3.4 Desired Outputs Values in dq Reference Frame 66
5.4 abc to dq and dq to abc Voltages Transformations 67
5.4.1 Three Phase Voltages abc 67
5.4.2 dq Values From abc Voltages 68
5.4.3 abc Voltages From dq Values 68
5.5 Comparison Between MPC and SMC on The Basis of Above Results 69

6 Conclusion and Future Work **71**

Bibliography **73**

List of Figures

1.1 Basic power processing block of switching converter. 3
1.2 Basic implementation scheme for the control of the inverter. 5
1.3 Grid tied inverter. 6
1.4 Stand-alone inverter. 7
1.5 Bimodal inverter. 8
1.6 Gate signal generation by comparing sine and triangular wave. . . . 9
1.7 PWM switching technique. 10
1.8 Clark's transformation. 12
1.9 Park's transformation. 12

3.1 Dynamic model of three phase voltage source inverter. 29
3.2 Switching sequence and output waveform of an inverter. 32
3.3 Overall control flow of an algorithm. 48

4.1 Sliding surface in SMC. 55
4.2 Graph of continuous time signum function. 56
4.3 Graph of discrete time signum function. 56

5.1 Linear controllers. 64
5.2 Non-linear controllers. 64
5.3 Desired output values. 65
5.4 Linear controllers. 65
5.5 Non-linear controllers. 66
5.6 Errors converged to zero. 66
5.7 Desired output values. 67
5.8 Three phase voltages abc. 68
5.9 dq reference voltage values. 68
5.10 dq to abc voltage values. 69

Abbreviations

AC	Alternating current
BS	Back stepping
DC	Direct current
DSP	Digital signal processing
DSVPWM	Digital space vector modulation
DTC	Direct torque control
EMI	Electromagnetic interference
FB	Feed back
FCS-MPC	Finite control set model predictive control
FPGA	Field programmable gate array
IEE	Institute of electrical and electronic engineers
LQR	Linear quadratic regulator
MATLAB	MATrix LABoratory
MG	Micro grid
MIMO	Multiple input multiple output
MPC	Model predictive controller
MV's	Manipulated variables
PI-PBC	Proportional integral passive based controller
PLL	Phase locked loop
PWM	Pulse width modulation
RP	Reaching phase
SISO	Single input single output
SM	Sliding mode
SMC	Sliding mode controller

SPWM	Sinusoidal pulse width modulation
SS	Sliding surface
SVM	Space vector modulation
THI	Third harmonic injection
VSC	Variable structure control
VSI	Voltage source inverter

Symbols

u	Control input
N_p, N_c	Prediction horizon and Control horizon
L_f	Inductor of output filter
C_f	Capacitor of output filter
p	Prediction window
ω	Angular frequency
V_{Ld}, V_{Lq}	Filter output line voltages in dq reference frame
V_{ld}, V_{lq}	Filter input line voltages in dq reference frame
i_{ld}, i_{lq}	Line currents in dq reference frame
x_{1d}	First desire output
x_{3d}	Second desire output

Chapter 1

INTRODUCTION

1.1 Introduction

Energy in the form of electricity is backbone for the development of any country. The world is depending mainly on fossil fuels. It is predicted that the world will face energy crises due to high demand of energy. Fossils fuels are considering to be a limited source of energy and highly toxic to environment therefore, the concentration of the world is attracted towards the green energy which is not only clean but also free with unlimited amount. The green energy is smooth/DC in nature so it must be converted into AC power to operate an AC devices. The concept of an inverter become possible due to the effort of researchers. Converter was introduced in 1892 with the name of rotary converter. After that the name is changed to synchronous converter till germanium diodes introduced in the literature [1]. Inverter was introduced by David Prince in his famous article the inverter [2] around 1925, it was a device like rectifier with operation in inverted mode. As in recent years, the fossil fuel price is increasing and the focus of researches is on the generation of electricity from clean energy sources [3, 4]. To solve the issue of fuel cost while confirming environment friendly effect, green energy sources are more attractive which are free and unlimited with considerably less amount of cost than the conventional sources . Maximum devices related to power, operate with AC power therefore energy from renewable sources must be converted into

AC from. For the conversion of DC power into AC form, feasible power electronic device is needed which is called an inverter. Inverters belong to a family of power electronic circuit to convert voltage, current and frequency from one level to another using semiconductor based switches. These switches are operated in such a way that these are either in completely turned ON or completely turned OFF state in linear region. The overall control scheme is based on proper switching of inverter in such a way that it gives the desire output. In an inverter model, switching is main parameter to have proper sinusoidal voltages at the output terminals. The properties of good switching include low power loss and fast switching having low distortions in generated signal. For the successful operation not only proper switching but also an output LCL and LC Filters are required to have sine wave instead of square wave. Inverters are of different types such as voltage source inverter, current source inverter, single phase and three phases inverter. Similarly, on the basis of mode of operation inverter may be 180 or 120. The main advantage of inverter is to use renewable energy sources which are not only clean but also free in nature. As the input is DC power to the inverter, after switching the output on H-bridge become a square wave therefore the output filter is required to have pure sinusoidal voltages or currents. In recent inverter devices it can be observed that the output value of inverter is pure sinusoidal with minimum total harmonic distortion. Researches have been conducted for the design of output filters, selection of switches and switching technique. The AC power received from the inverter can be used for domestic and industries. It is also possible to connect the inverter having LCL filter to the national grid. The advancement in inverter technology different countries like United states, China and Japan etc. are now trying to transform the conventional energy sources into green energy sources.

Inverter may be single phase or three phase the most important power electronic device to utilize the renewable energy sources in efficient way. The future of energy sources is purely clean energy in the form of renewable energy[5] such as solar, wind and batteries etc. According to an estimation electrical energy generation from renewable energy will increase 32 percent in 2030 while reducing the CO_2 emission[6]. The inverter can be used with proper performance or in an efficient way by the proper solution of some basic issues such as harmonic generation and power losses due to switching. Researches are being conducted to solve these issues regarding to switching. To convert DC power to AC, one of the most popular technique used is sinusoidal pulse width modulation (SPWM) for harmonic reduction. An inverter is used having sine wave displaced in 120 phase differences as reference signal for three phase voltage source inverter. An inverter is controlled by its switching signal, the switching signal is generated with the help of microprocessor, micro-controller having proper codding. The general block diagram of basic power processing is given in Fig. 1.1.

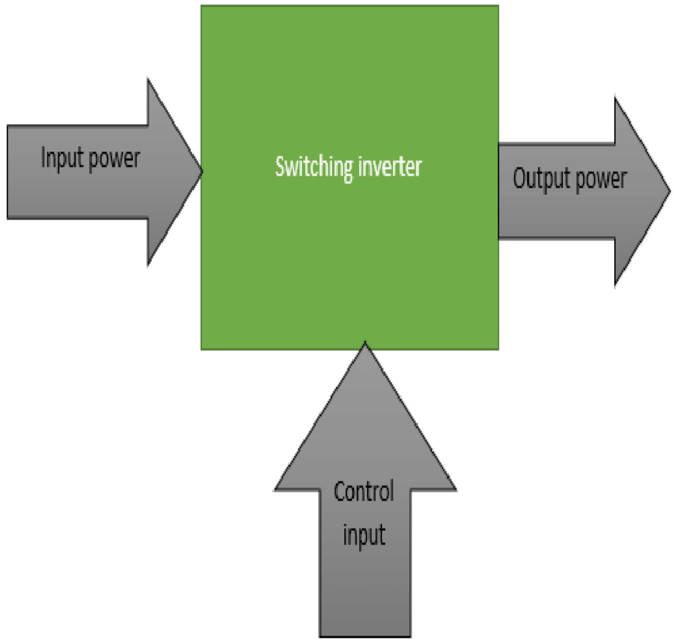

FIGURE 1.1: Basic power processing block of switching converter.

Three phase induction motor with variable load and other rotating machines, variable frequency and variable voltage supply is needed, for this purpose the voltage source inverter is used. In this research the main objective is to control the output voltage of three phase voltage source PWM inverter with the help of controllers which are required by many industrial applications [7]. In case of sudden load change, it is necessary to have desired voltage across the load for proper function therefore inverter required proper control mechanism so that it can have good performance. In this research work the non-linear mathematical model of three phase voltage source PWM inverter is given in dq reference frame [8]. The given system is linearized by input output linearization [8]. The purpose of linearization is to design the controller in easy way, while the conversion of dq reference frame gives less computation. The voltage source inverter (VSI) model having LC filter to have pure sinusoidal output waveform. There are two approaches used in this thesis to control the output voltages in which one approach is to design the model predictive controller design and the second one is sliding mode controller design. Both methods are highly efficient for voltage regulation problem. To reduce the harmonics, PWM switching technique is used[9]. The outputs of inverter are three phase sinusoidal voltages while to design the controllers three phases are converted into constant values containing real and imaginary parts. Therefore, the constant values will transform again in three phases to have proper PWM switching.

In sliding mode control design the state space model of linear system is used for designing Hurwitz sliding surface. The sliding surface must contained the parameters by defining controller law , which gives the derivative of the lyapunov function strictly less than zero to satisfy the stability conditions. To get the desire output values, errors are define which converge to zero due to the control input such that the actual output gets the desire or reference value. Sliding mode controller is an effective controller for stability of system[10] and to get desire reference value. SMC also provides better tracking control[11] in case of grid connected PV system. Model predictive controller design for desire output voltage of an inverter is also an efficient technique.

The continuous time state space model is converted into discrete time to apply discrete time model predictive controller[12]. The next step is proper selection of predictive horizon N_p and control horizon N_c such that $N_c \leqslant N_p$. For the implementation of model predictive controller this condition must be satisfied. MPC having data and identity matrices it is possible to design the require control law in such a way that the cost function is minimized at optimal level , by the result of which the desire output is achieved[12]. The overall control flow is same for both the approaches displayed in Fig. 1.2. The given flow chart explains the complete flow of proposed work.

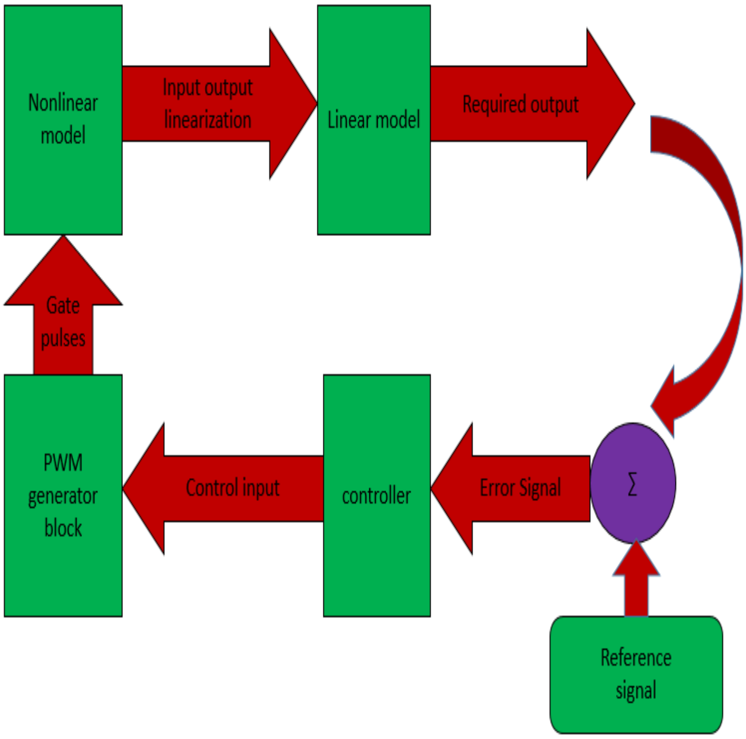

FIGURE 1.2: Basic implementation scheme for the control of the inverter.

According to mode of operation inverters can be classified into three types as given bellow:

1.1.1 Grid Connected Inverter

This is a type of an inverter which is connected with the grid having same grid frequency, phase and voltage without storage batteries as shown in Fig. 1.3. For the synchronization of inverter phase with the grid phase, PLL is used [13]. The grid connected inverter provides power to the national grid to add an extra power to the grid which enhances the flexibility of power system. The conversion of conventional power sources into clean energy, the above concept is used. Power can be provided for both AC load and grid at a time, this is an efficient operational mode in the advanced power systems. The inverter converts DC into an AC at day time in case of PV system and in case of wind power system the conversion may be at any time. Wind and solar sources are added in national grid while converting DC into AC, This conversion is only possible through inverter in grid connected mode. Energy sources use for this mode may be wind or PV, with constant voltage.

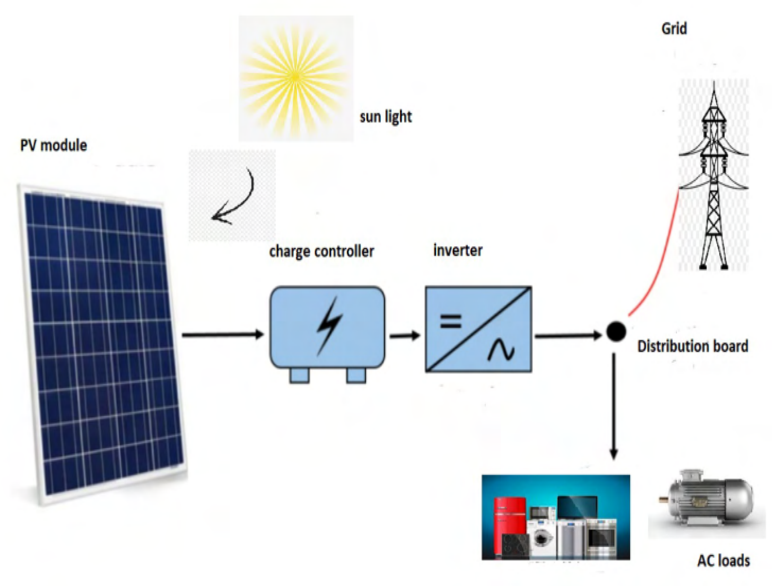

FIGURE 1.3: Grid tied inverter.

1.1.2 Stand-alone Inverter

Inverter which is not connected to the grid and works alone is called stand-alone inverter. The inverter generates fix AC output voltage and frequency for AC load. The extra power is stored in batteries for the use at the time when the power is needed [14] as shown in Fig. 1.4. In this case power can be used to run the DC appliances, AC loads or store for later uses. The component battery is key component for this type of mode because the stored power is utilized at night time when the source is absent or no sun time. Stand-alone inverter is used in case of independent power generations. Independent power plants are used for industrial,commercial and household purposes. This type of inverter can also be used when their is no power from national grid. It is observed that stand-alone inverter is mainly used in those areas where there is no centralized energy network. Demand of such inverter is high in developing countries.

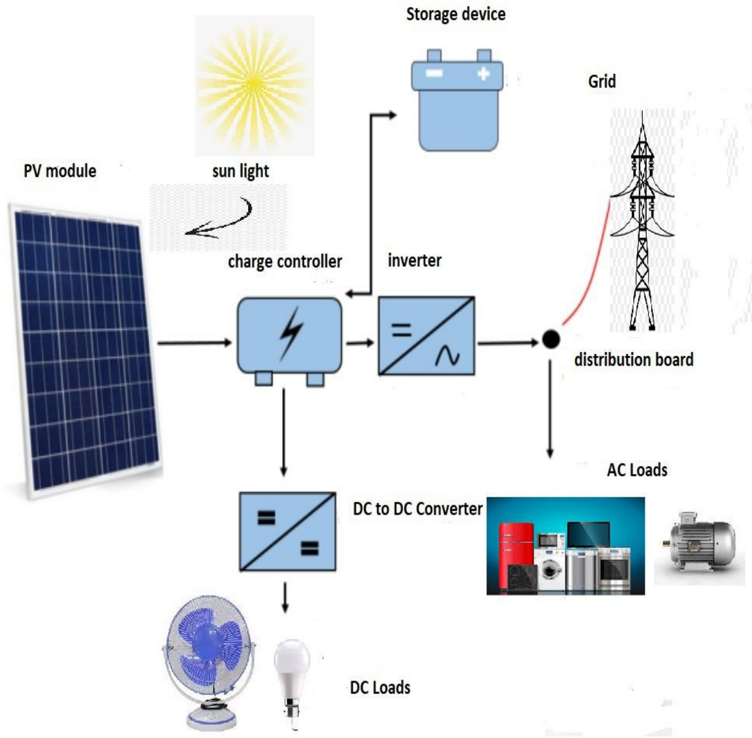

FIGURE 1.4: Stand-alone inverter.

1.1.3 Bimodal Inverter

This is the mode in which the inverter acts as both standalone and grid connected as shown in fig. 1.5. Battery bank is used to store power for temporary purpose to supply the power to the grid at peak load duration[15]. Bimodal inverter concept is used in smart grid for net metering. In this case when the power is needed to the consumer then power is extracted from national grid and when the users have extra power at peak time then power is injected to national grid to get compensation in electricity bills.

Smart grid is the latest concept in energy management, mainly used in developed countries. Bimodal inverter gives decentralized energy system against conventional one. In this system consumers also participate in generation and distribution. This inverter is the future of energy system in which smart energy management is possible. Bimodal inverter gives energy trade between consumers and government or power generation companies. The concept of smart grid will change the world because the upcoming energy crises will be minimized through energy management.

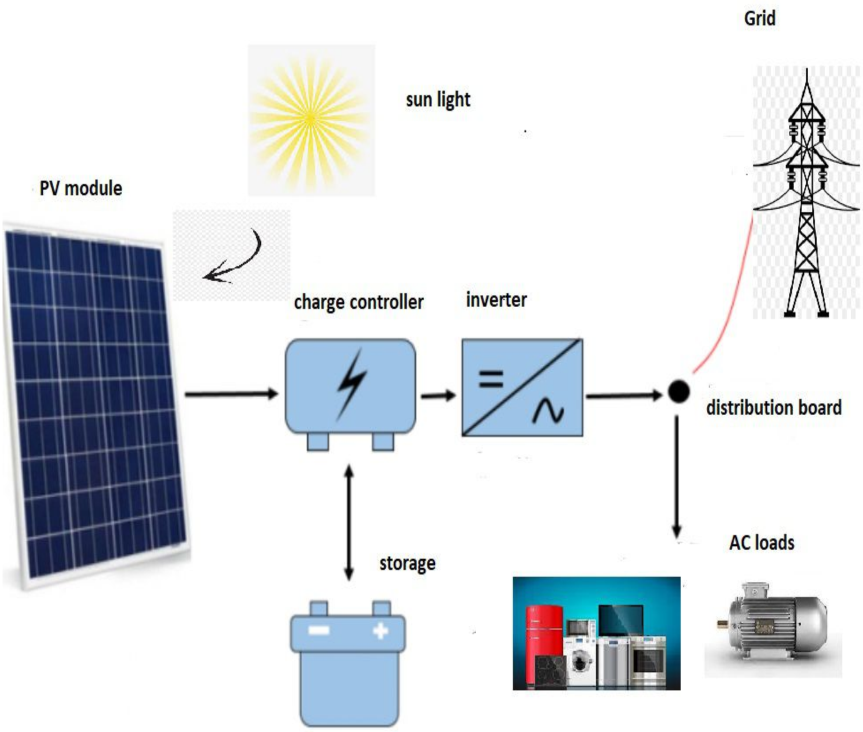

FIGURE 1.5: Bimodal inverter.

1.2 Pulse Width Modulation Techniques

Transition of power electronic switches from on state to off state and off state to on state to have an AC output, different techniques are used. The three basic techniques are given blow in which sinusoidal PWM is considered in the research work.

1.2.1 Sinusoidal Pulse Width Modulation

In SPWM triangular carrier wave is compared with simple sine wave to get the gating signals. The ratio of amplitude of reference sine wave to the amplitude of carrier wave is termed as modulation index. When the instantaneous value of reference signal sine wave is higher than the carrier then the gate pulse is high and gate pulse will be low at reverse process[16] as shown Fig. 1.6. Gate pulses are obtained from the comparison between sine waive and triangular wave. Gating pulses have two states according to their duty cycle. When the gate pulse is at high then the switch of an inverter is in on state and when the gate pulse is at low then the switch is in off state. Duty cycle is managed while changing the shape of reference signal, its mean the on and off time of the switch is adjusted according to the desired value at output terminals.

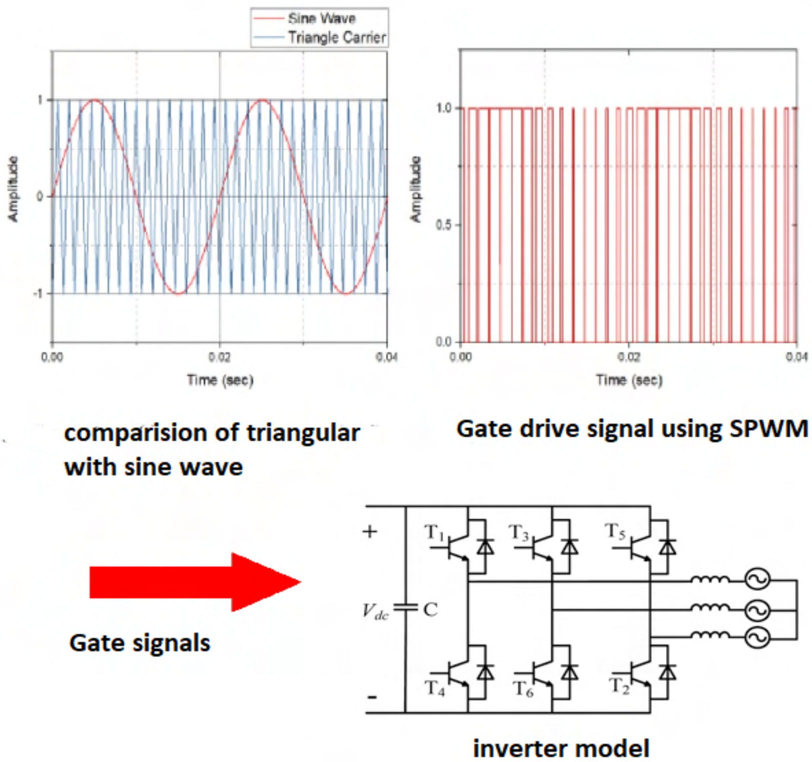

FIGURE 1.6: Gate signal generation by comparing sine and triangular wave.

This figure provides the summary of PWM switching technique which is used in most of the power electronic devices.

1.2.2 PWM Switching Technique

In this technique, a fixed DC input voltage is given to the inverter model and a controlled AC output voltage is obtained. This task is done by adjusting the on and off periods/time of the inverter components. There are two important terms, used in PWM technique which are frequency modulation index and amplitude modulation index. Overall concepts are given in fig 1.7. Pulses with wider width have more on time wile narrow pulses have minimum on time.

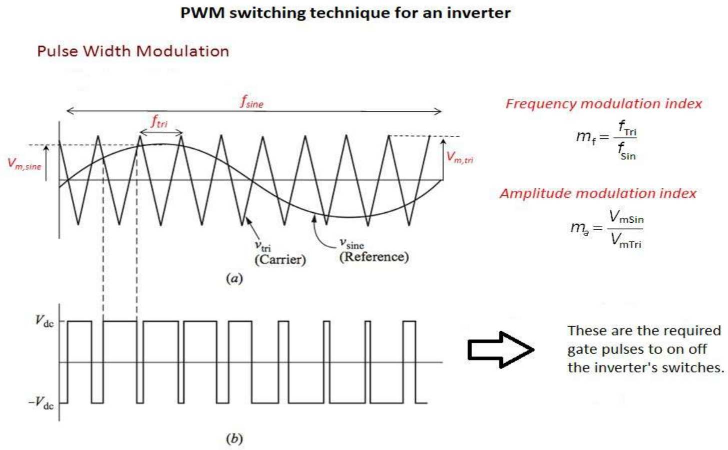

FIGURE 1.7: PWM switching technique.

1.2.2.1 Duty Cycle

Duty cycle is the ratio of ON time to the total time period of the pulse. Low duty cycle means, low power loss due to negligible current flow in the switching device and negligible voltage drop, in its off state. Duty cycle may be 0%, 25%, 50%, 75%, 100% or any other value. 50% duty cycle means, 50% of total time the switch is in On state and for 50% of total time the switch is in Off state.

1.2.3 Third Harmonic Injection

THI gives the addition of third harmonic to reference voltage to generate the modulating signal and compare this signal to triangular signal for modulation purpose. This technique is not so popular in literature as compare to other.

1.2.4 Space Vector Modulation

In this technique SVM takes switching states and generate a reference vector and the vector rotates in hexagon to produce sinusoidal output voltage giving low THD. Total harmonic distortion tells about the distortion of a current/voltage due to harmonics in the signal. Harmonics are all those frequencies which are integral multiples of fundamental frequency. Power electronic devices having low THD is preferred in real time applications. According to Institute of Electric and Electronic Engineers, the standard value of total harmonic distortion must be $\leq$ 5%.

1.3 Transformation

Controller is designed in dq reference frame for simplicity and to reduce the calculations. Three phases are converted from A, B and C into α and β with the help of Clark's transformation. The α and β are transformed into dq reference frame through Park's transformation. Inverse transformations give again three phases A, B and C respectively. These transformations involve mathematical matrices operations. Controllers work efficiently with constants values , which is also one of the main reason to use dq/ constants values. Two types of transformation are used such as:

1. Clark's Transformation.
2. Park's Transformation.

1.3.1 Clark's Transformation

In electrical engineering Clark's transformation is a mathematical transformation used to simplify the analysis of three phase electrical/electronic circuits. Through this transformation $\alpha\beta$ values are obtained. $\alpha\beta$ are the intermediate terms which are not constants. Transformation result is shown in Fig. 1.8.

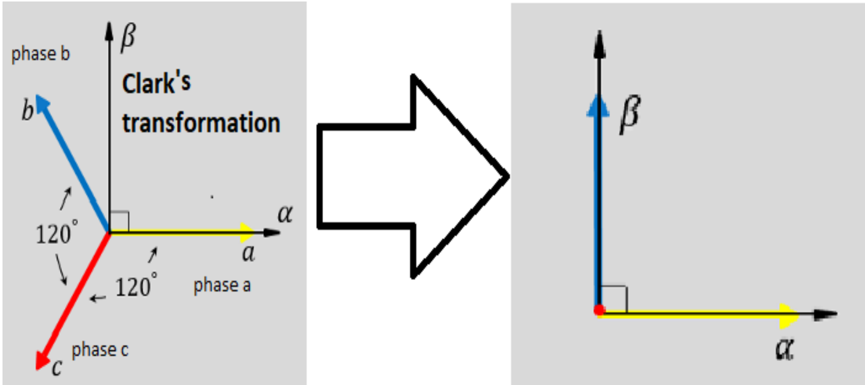

FIGURE 1.8: Clark's transformation.

The next step is to have dq values from $\alpha\beta$.

1.3.2 Park's Transformation

This transformation is also known as direct-quadrature transformation which performs the $\alpha\beta$ to dq conversion. The transformation rotates the two stationary axes $\alpha\beta$ obtained from Clark's transformation, synchronously with a reference frequency ω. The reference frequency ω is passed through the phase input ωt, which is shown in Fig. 1.9.

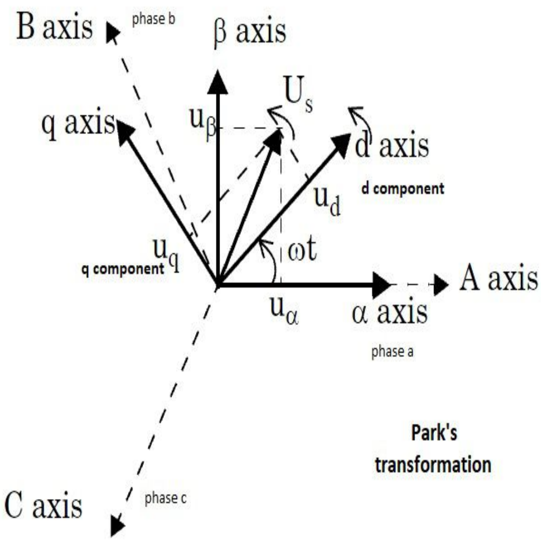

FIGURE 1.9: Park's transformation.

This transformation gives the final value in dq reference frame.

1.4 Overview

Output voltage control of three phase voltages source PWM inverter is rudimentary determination of this research work. The output voltage is controlled by two famous controllers which are model predictive controller(MPC) and sliding mode controller(SMC). The non-linear mathematical model of three phase voltage source inverter in direct-quadrature (dq) reference frame is given, linearized the model through input output linearization so that the controller design strategy become easy. The controllers are design for linear system of VSI after that it is modified to apply on non-linear system. The results are verified through simulation studies using MATLAB.

1.5 Motivation

Energy from fossils fuel and nuclear power plants is not suitable for the future because these sources of energy is not only depleting but also unhealthy to an environment. The cost of these fossil fuels increases day by day, to have a strong economy and development for any country it is highly recommended to use clean sources of energy. It is observed that all developed countries like China, United states and Europe[17] have participated to transform the conventional power system to green energy. The main focus of both the developing and developed countries on the development of renewable technology so the energy crises can easily be handled. The recent developments show how the green energy is used in vehicles[18] to have a clean transport system. Concept of clean energy is considered the key factor to reduce the main source of contamination of environment. Energy from renewable sources like solar cell become price effective[19], which is free source of energy and the advancement in wind energy technology[20] and the invention of(PWM) inverter, researchers are highly motivated towards green energy. Converter is considered hot topic in power electronics, in recent years the world is attracted towards green or renewable energy due increase the cost of fossils fuel and bad impact on environment. The efficient way to use the renewable energy in domestic or in industries, it is highly recommended to have an inverter with highly good performance. Inverters having low harmonic distortion and low switching losses are considered to be good performer in power electronics. One of the effort that is needed to control the output wave form in case of load changes or varying load. This research is one of the effort in which two different controllers are designed to control the output voltages of three phase voltage source inverter.

1.6 Application of Research

This work deals with the inverter model. There are many examples of such system in daily life. The proposed controllers which are also applicable for similar power electronic devices. This work has a brief control theory related to inverter, in similar way it can apply for converter which converts AC to DC at desired level. This research is a practical example of voltage regulation and can be extended in all those systems having regulation problem. The proposed algorithm can be extended in electrical and control systems having tracking problem. This work can also be extended for linear system, non-linear system and power electronic devices etc.

1.7 Structure of The Thesis

Chapter 2: Literature Review

Literature published about voltage controller design for an inverter is discussed in this chapter. On the basis of literature reviews a controller is designed to control the output voltage of an inverter. In this chapter the details of work related to this thesis are discussed so the problem statement can easily be understood. This chapter gives brief discussions on the flow of work to enhance the idea regarding inverter control to have a good performance. This chapter has detail informations about the flow of proposed work and different articles are critically discussed in detail. After the detail critical discussions, the research gaps are analysed.

Chapter 3: Model Predictive Controller Design for an Inverter Dynamic Model

A brief discussion on MPC algorithm is given in this chapter. Model predictive controller design for power electronic circuit is a hot research topic in recent years. In this chapter a design of MPC to voltage regulation is discussed briefly in efficient way. The controller is designed with proper selection of predictive horizon, control horizon, data matrix and weighing matrix. The given cost or energy function is minimized to have an optimal switching states of inverter to get the required voltage level.

Chapter 4: Sliding Mode Controller Design for an Inverter Dynamic Model

A brief discussion on SMC algorithm is given in this chapter. The sliding surface is designed by choosing control input U in such a way that the derivative of lyapanov/energy function become strictly less than zero. The sliding surface converges to zero means the states of given model also converge to zero showing that the system is asymptotically stable. In given model, errors are defined such that the output acquires the reference value when errors approach to zero.

Chapter 5: Results and Assessments

This chapter gives brief discussion on results of both control methods and their effectiveness on control strategies. It also gives the comparison between MPC and SMC. In both controller design strategies the output attained the reference value which is the desired one, the actual value meets the desired value as a constant term because both the linear and non-linear model are in dq reference frame. Once the control law is achieved then the dq value containing real and imaginary part is converted into three phases to get the proper switching gate pulses through PWM modulation block. The gating pulses operate the switching sequence in such a way that the inverter operates to generate the required three phase sinusoidal voltages which are maintained there in case of varying load demand. The behaviour of both controllers is briefly discussed with advantages and disadvantages so their feasibility on power electronic devices can easily be analysed for future work.

Chapter 6: Conclusion and Future Work.

This chapter gives a brief conclusion and future work regarding to proposed controllers. Moreover, future research proposals are suggested for those researchers who are interested in controller design for power electronic converters. Same controller design strategies can be extended to control the output current to achieve the reference value with minimum harmonic distortion. This chapter also gives the comparison between two approaches on the basis of performance. Chattering is an undesired property of sliding mode controller while the drawback of model predictive controller is its big computation, both issues are discussed with their proper solutions.

1.8 Summary

In this chapter the history, importance, evolution ,types and applications of inverter are discussed in detail. Basic power processing block of switching converter and basic implementation scheme for the control of the inverter are also discussed according to design strategies. Basic knowledges about PWM switching techniques, transformations from three phases to dq and dq to three phase, overview, motivation, applications of proposed research and structure of thesis are discussed to understand the proposed work.

Chapter 2

Literature Review

2.1 Introduction

In this chapter literatures related to controller design for voltage source inverter are discussed which help to design the control strategy for voltage control in an inverters. This section gives brief discussions related to the evolution of controller design for an inverter and different strategies to control the output voltage with better performance etc. After the brief discussions on literatures related to VSI controllers the research gap is obtained then this gap is filled with the help of two proposed control strategies which are model predictive controller and sliding mode controller design.

The authors in[21, 22] mention that the SVPWM for three phase two level inverter generates pulses depending on the switching of eight possible voltage vectors. The eight different vectors form six sectors hexagon. These vectors rotate in hexagon to give sinusoidal wave form as an output. The reference vector located is found while calculating the duty cycle for the pulse which is used to provide gate pulses for the switches. The author in [23] discusses the robust control strategy to improve the output power quality of three phase VSI. The control scheme having inner loop current and outer loop voltage, controllers in both cases are designed by H-infinity control technique having low harmonic power distortion and good output power quality for both linear and nonlinear loads. In this strategy the secectionof suitable weighting function and weighting parameters are considered as key factors. The H-infinity theory guarantees the performance of the inverter in worst case disturbances while having clean energy and balance output voltage in case of both linear and nonlinear loads. Linear quadratic regulator and H-infinity controller for VSI[24] present a voltage controller design to control the VSI while using LQR and H-infinity controllers. The proposed strategy has an active damping consisting an LQR voltage feedback current of filter(LC) in α, β reference frame. The proposed LQR allows the increment in bandwidth to reject the high value frequency disturbances of the system. The voltage regulation in three phase is achieved while using H-infinity control method. In this strategy a sensitivity function of four order is achieved with very low tracking error with the property of harmonic rejection generated by the non-linear load condition. A mathematical model of a voltage source inverter in α, β frame of reference and LQR theory based active damping function is implemented. For the regulation of voltage H-infinity control with new weight function to synthesize the optimal control is obtained. These strategies give the concept of an effective implementation of controller to control the voltage source inverter. This controller strategy gives better result as compare to resonant proportional controller in case of non-linear load.

Spaced vector pulse width modulation switching technique is used effectively in specific controller design problems[21, 22, 25], one of the modified digital SVPWM on low cost FPGA having an optimization for three phase VSI[25] in which the digital control circuit strategies are used with the help of this strategy the analog strategies are overcome by providing good flexibility with simple equipments. This strategy gives high frequency switching as well. In this control strategy an area optimized, modified DSVPWM is designed on low cost field programmable gate array(FPGA). The modified DSVPWM uses phase PLL to generated clocks using clock manager, called digital clock manager. These digital clock managers are used in an effective digital space pulse width modulation for the synchronization of sub modules. Digital control scheme gives many advantages over the non-digital or analog scheme. In modern control systems it is observed that the modern control systems mainly focused on digital control strategies because of their effective behavior like circuit modification, vast function to update and easy implementation. Digital signal processing is also upcoming an effective strategy to control different devices in power electronics. Digital signal processing(DSP) has many attractive behaviors including low cost and highl efficiency. In recent control schemes the hardware implementation of an AC devices like motors etc. control with new digital methods can be observed widely. By applying the digital control both cost and software can be reduced simultaneously. Field programmable gate based on very large scale integrated circuit provides an attractive solution such as configurability features and high density programmable features etc. SVPWM techniques are used in lot of converters specially in multiphases converters[26, 27] which indicates the field programmable gating array(FPGA) with SVPWM, gives enormous benefits over other hardware.

In[28] the author discuses a non-linear control scheme for three phase DC to AC in a system having more than one type of sources known as Hybrid systems with the help of proportional integral passive based controller (PI-PBC) method. The proposed method is to regulate the frequency of three phase output voltage of DC-AC inverter having inductor and capacitance as a components of filter. The inverter supplies energy to an AC loads in a system having renewable energy. In this work the proposed strategy uses well known controller, which is proportional integral (PI) having stability guarantee by mean of Lyapunov theory. The lyapunov stability theory says the system is stable if the derivative of energy function is strictly less the zero. The proposed controller provides simplicity and robustness of proportional integral controller due to the Hamiltonian based representation of considered system. With this strategy the stability and performance is improved and the output is controlled according to the required value. The strategy is effective for micro grid based hybrid renewable system with storage devices[29–32]. The system having storage devices like batteries connected with charge controller for safe charging to increase the battery life and the sources are solar and wind known as hybrid sources. The main theme of this work is that the PI controller gives the simplicity and robustness while PBC gives the stability and performance characteristics. Therefore the combination of PI and PBC give powerful tool for the design of converter in power system having more than one sources. The combination of controllers always play an important role in control system.

In[33] the author discusses the Regulation of voltage and frequency of an islanded mode MG inverter by non-linear integral back stepping controller(NLIBC). The proposed controller is built using dynamics of inverter base distributed generation and lyapunov theory. The controller eliminates the voltage and frequency deviation under uncertainties. The stability is insured by lyapunov function. The control can realize stable buss voltage and robustly restore the voltages and frequency of micro grid to the reference value in case of the existence of fluctuation in PV sources, parameter uncertainty, load variation and unknown parameter. From the results, comparison with back stepping controller the proposed strategy gives better result as it does not require communication link while giving system stability, affordability, simplicity and reliability. In case of source vitiation, parameter uncertainties and load variation the reference value is tracked by the non-linear integrated back stepping controller in minimum settling time as compared to back stepping control. The voltage and frequency regulation insured the power matching between generated to the demand load with better power quality[34]. In island mode of operation there is low inertia of renewable energy sources and there exist a variation in load demand with uncertainty. The desire output voltage and frequency control are considered highly challenging in case of micro grid. Comparison between simple back stepping and integrated back stepping in[33], the settling time is minimum in integrated back stepping, which shows that the addition of integral factor enhances the performance of system. The minimization of settling time means the robustness in response therefore non-linear integrated back stepping controller (NLIBC) is also considered as robust.

In literature the torque control in induction motor is also focus in term of controller design for regulation of voltage. Direct torque control of induction machine, the torque is controlled by PID controller[35], this is a common controller found excessively in power electronic literatures to control different parameters. In this article direct torque control (DTC) which consists of table to select the voltage vector, two estimators and two comparators. Direct torque controller controls both torque and flux by using VSI, stator flux orientation, space vector and indirect speed. By this strategy, direct torque control (DTC) with PID controller improves the starting and dynamic performance of motor. It also gives better speed control and torque with minimum ripple in load changing scenario, which is better than the results obtained from classical controls.

Modern digital control technique for voltage source inverter in green energy sources is one of the most important control scheme to regulate the output[36]. In modern era green energy for distributed generation is more common in power literature. To have optimal tracking ability with minimum error, optimal performance and abrupt response, the proposed controller gives an effective strategy for voltage source inverter. PWM generates switching frequency, is introduced for multilevel inverter. This strategy gives low computations and enhances the performance of inverter. Different possible models are analysed and the state space model is transformed into dq frame of reference to minimize the calculations. From the analyses, this scheme gives better result because of digital nature of controller while analogue controller design is considered to have long computations.

In[37] the author discusses the speed controller design for three phase induction motor while using PID controller and universal bridge, this controller is required for the adjustable speed drive system. In this case the system required variable frequency and speed control case of VSI. In this proposed method proportional integral derivative controller is designed to control the speed of induction motor fed by three phase VSI using pulse width modulation and universal bridge. The results show the successful control strategy having better performance. The performance is enhanced due to proportional integral derivative and universal bridge as compare to universal bridge without PID. The control technique is made more attractive by PWM switching technique for controlling the high complexity such as the three phase induction motor etc. This strategy also helps for the improvement of output signal having low harmonic and ripples while reducing the size of design. Overall controller strategy of controller design for inverter is to control the switches by PWM, SVPWM[25, 26, 28, 36] and switching state selector. The output voltage waveform, harmonic, power losses, amplitude of wave form and frequency depend on switching state and the method which is chosen for switching. In controller design both the controller and switching methods are considered for the effective results. From the results of literature it is noted that the output converges to desired value only when both the controller and switching methods are feasible to each other and also for the system.

A control scheme for multilevel voltage source inverter topologies is discussed in[38]. According to this article multilevel inverter is highly feasible for low power dissipation on power switching, low electromagnetic interference output (EMI) and low harmonic content. In this research the selected switching technique is also effective for harmonic elimination while generating pure sinusoidal voltages that is space vector and sigma delta PWM method. To achieve this strategy of control, hybrid modulation technique is proposed which provides low power cells switches at higher frequencies and higher power cells switches at low frequencies. In similar way a grid connected three phase voltage source inverter for industrial application, the output voltage is controlled to get pure sinusoidal voltage containing required value of load[39]. In this control technique space vector pulse width modulation (SVPWM) technique is used for voltage source inverter in case of grid connected system. Voltages and currents are transformed into α, β reference frame while the controller is proportional controller. From the result the output of three phase voltage source inverter can control with PI controller is considered as an effective method. From the results, total harmonic distortion is reduced having value less than 5 percent which is the standard value of institute of electrical and engineers (IEEE). This value of total harmonic distortion can be reduced for further improvement.

The authors in[40, 41] model predictive controller design on the basis of Neural-Network and sliding mode cooperative control for robust finite time frequency and voltage restoration gives a modern and new research ideas to control the output voltage and frequency at desired level. Both methods give new control strategies to control the power electronic circuits. Prediction based input is designed in model predictive control with the help of data and tuning matrices while converting continuous time state space model into discrete time model. In sliding mode, the control input is designed on the bases of laypunov function. From the results both controllers are robust and acquired the desire output value having considerable low total harmonic distortion and pure sinusoidal waveform. The advancement of microprocessors gives high computations in feasible time so model predictive controller is attracted towards the power electronic devices. Sliding mode controller design is also robust control for the systems and used to stabilize all those systems which can be represented in state space form.

2.2 Gap Analysis

There are some important literature gaps that must be filled. The research gaps from above literature reviews are given below. In this research works these gaps will be considered to improve the overall performance of an inverter.

1. Proportional integral derivative have very low transient response while other like DSVPWM on FPGA has a challenge in an optimization of chip area because of its complex architecture.

2. The addition of constraints in many controllers causes complexity in design procedure while proportional controller with big gain has noise/harmonics.

3. In case of multilevel inverter SVPWM technique, it give more switching states then PWM technique therefore the system becomes complex.

4. In controller design the cost of controller should be minimum thats why many proposed control strategies are effective but those are not feasible due to high cost.

5. In many control strategies the desire output value is not pure sinusoidal, the value of amplitude varies with time.

6. The output frequency also changes in some control strategies due to low performance of switching states run by the controller. This gap is one of the most important one in an inverter.

7. Without α, β and dq transformations of state space model, controllers have much more calculations. Variable values in a,b and c form are not feasible for an effective controller design.

In this work the claim is to design controller strategies having low cost, low switching losses, robust, minimum settling time and highly effective in achieving the desire output values while considering above gaps.

2.3 Problem Statement

Considering the gaps in controller design for an inverter, the purpose of this study is to control the output voltage of three phase voltage source PWM inverter. The output voltage of three phase inverter gets the reference/desired value in case of voltage drop or load change conditions. PWM switching technique is used to reduce the harmonics for three phase voltage source inverter. Finally compare model predictive controller and sliding mode controller on the basis of settling time , robustness, chattering, accuracy while getting desired values ,practical application, cost, design and constraints

2.4 Research Methodology

The research work has two controller strategies which are given below.

1. MPC.
2. SMC.

Model predictive control and sliding mode control are used in this research work to control the output voltage of an inverter. Results of both controllers are compared to each other and also compared with other controllers as well.

2.4.1 Model Predictive Controller

In model predictive controller design, an error function is minimized to get the desired control law. Initially linear controller is designed for linear system then the controller is modified for original system or non-linear system.

2.4.2 Sliding Mode Controller

In sliding mode controller design, errors are defined in term of state variables, these variables are converged to zero while satisfying the laypunov stability theory.

2.5 Software Tools

The software used to do the research work of controller design for voltage source inverter is MATLAB. For figures and block diagram both WORLD and LATEX are used.

2.6 Vectors

In physics and mathematics,vector is a term that refers to some quantities having both magnitude and direction. Vector is a term which is also used, for tuples. Tuples are the finite sequence of numbers having fixed length. General form of vector, for two dimensional system is represented by:

$$\overrightarrow{A} = \begin{pmatrix} a \\ b \end{pmatrix} \tag{2.1}$$

where a and b are the constant values.

2.7 Vector Field

In vector calculus and material science, a vector field is an task of a vector to each point in a subset of space. For occurrence, a vector field within the plane can be pictured as a collection of bolts with a given size and course, each attached to a point within the plane. Vector field is represented by: $\overrightarrow{F} = x_{\overrightarrow{i}} + y_{\overrightarrow{j}}$, where $\overrightarrow{F}$ is a conservative vector field with its potential function of $f_1(x, y) = x \times y$. This is a field where vectors are drawn having both magnitude and direction.

2.8 Lie Algebra

A Lie algebra(LA) is a vector space g_1 over a vector field F with an operation $[',']$:$g_1 \times g_1 \to g_1$ which we call a Lie bracket, such that the following axioms/conditions must satisfied: It is bi-linear. It is skew symmetric (square matrix having transpose equal to its negative): $[x_1,\, x_1] = 0$ which gives $[x_1,\, y_1] = -[y_1,\, x_1]$ for all values of $x_1,\, y_1 \in g_1$.

2.8.1 Mathematical Representation

1. Bi-linearity,

$$\Big[a_1x_1 + b_1y_1, z_1\Big] = a_1\Big[x_1, z_1\Big] + b_1\Big[y_1, z_1\Big]$$
$$\Big[z_1, a_1x_1 + b_1y_1\Big] = a_1\Big[z_1, x_1\Big] + b_1\Big[z_1, y_1\Big]$$

   For all scalars a_1, b_1 in F and all elements x_1,y_1,z_1 in g_1.

2. Alternatively,

$$\Big[x_1, y_1\Big] = 0$$

3. The Jacobi identity,

$$\Big[x_1, [y_1, z_1]\Big] + \Big[y_1, [z_1, x_1]\Big] - \Big[z_1, [x_1, y_1]\Big] = 0$$

   For all x_1,y_1,z_1 in g_1. Using bi-linearity to enlarge the Lie bracket $[x_1+t, x_1+y_1]$ and using alternatively it shows that $[x_1, y_1]+[x_1, y_1] = 0$ for all elements x_1,y_1 in g_1, showing that bi-linearity and consequently together imply.

4. Anti-commutativity

$$\Big[x_1, y_1\Big] = -\Big[y_1, x_1\Big]$$

   For all elements x_1,y_1 in g_1.

2.9 Runge-Kutta

Runge-Kutta(RK) method is an effective/powerful and widely used method for solving the initial-value problems (IVP) of ordinary differential equations (ODE). RK method can be used to construct high order accurate numerical procedure by functions' self without needing the high order derivatives of mathematical functions. This method is used in sliding mode controller design of proposed work.

2.10 Summary

In this chapter literatures about inverter control are discussed critically in detail. Research gaps are found, on the basis of these gaps problem statement is made. Basic concepts about MPC and SMC are also discussed to provide knowledge about proposed work. Mathematical equations and software tools are also given in detail to understand the complete flow of proposed work.

Chapter 3

Model Predictive Controller Design for an Inverter Dynamic Model

Objective of model predictive control (MPC) or receding horizon control (RHC) is to compute a trajectory of a future manipulated variable u to optimize/minimize the future behaviour of the plant output y. The optimization/minimization is performed within a limited time window by giving plant informations at the start of the time window. Optimization is done in each time step to have the best control action. MPC chooses the control action which gives the predicted output closest to desired output. Implementation of MPC has following main steps, which are:

1. State space modelling of considered system.
2. Conversion of matrices from contiguous to discrete form.
3. Construction of augmented matrices.
4. Construction of cost function.
5. Optimization of cost function. This is the error function which contains actual and desired values across output terminals.

3.1 Three Phase Voltage Source PWM Inverter

In this work three phase voltage source inverter model is considered, the output voltage of three phase voltage source PWM inverter is controlled by proposed controller technique that is model predictive control (MPC).

3.2 Dynamic Model of Three Phase Voltage Source PWM Inverter

Three phase voltage source PWM inverter in dq reference frame[8] is given in Fig. 3.1.

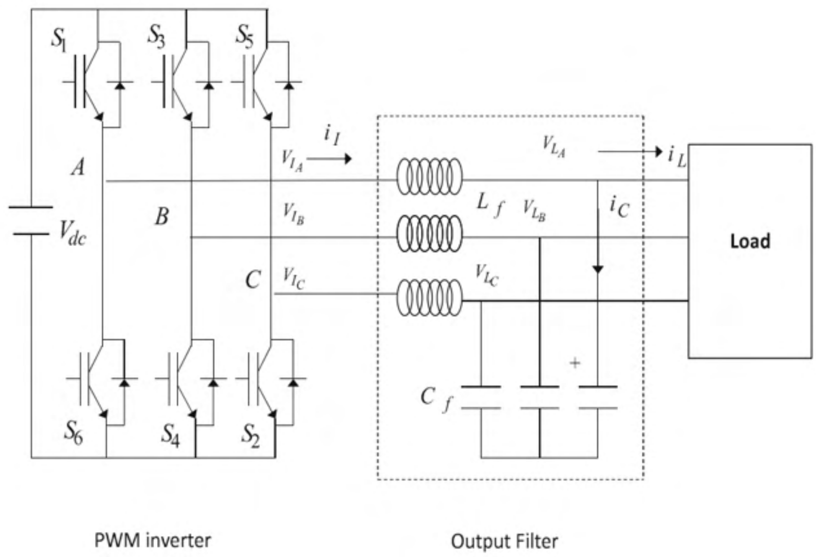

FIGURE 3.1: Dynamic model of three phase voltage source inverter.

Three phases A,B and C are converted into two components α and β in an orthogonal stationary frame by Clark's transformation[42] then the α and β are transformed into orthogonal rotating reference frame dq by Park's transformation[43]. The inverter takes the DC input from sources like storage batteries and PV panels then this input voltage is converted into an AC output for AC operated electronic devices. This conversion is done with the help of proper switching techniques. The non-sinusoidal voltage wave form is then converted into sinusoidal by the output

LC filter. Switching state is selected by proposed controller and gate pulse is generated by the PWM block generator which is considered to be an effective method having low power losses.

Parameters are defined as:

V_{dc} is the voltage source in DC form. S_1 ,S_2,S_3,S_4,S_5 and S_6 are the switches of an inverter.

VI_A ,VI_B and VI_C represent the phase voltages of phase A,B and C respectively.

The other four parameters of inverter model are:

i_L is H-bridge output/filter input current.

I_L is filter output/load current.

L_f is inductance value of output filter.

C_f is capacitance of output filter.

From the given model, three phase voltages and currents are transformed into α, β then α, β are transformed into dq reference frame to reduce the calculations and these values are feasible for controller design. After the implementation of controller, the desire output value is achieved as a constant value which is converted back into A, B and C phases. In dq reference frame the value is in form of real and imaginary components in which the d component is real while q component is an imaginary. By proper selection of above parameters/values the voltage across load is controlled with the help of controller. For this purpose, the desired/reference value is selected which is compared with the actual output voltage, from the difference of actual and desired values a signal is achieved, which is known as an error. This error is provided to the controller as an input, which gives input control values/law. The control law generated by the controller is given to PWM generator to generate gate pulses. These pulses are required to have a desired value at output terminals. For more voltage values, the switching time is more, similarly for small value of voltages the switching time is also small. Output value is controlled by the pulses generated by the PWM generator.

3.2.1 On Off Scheme of The Switching Phase

The pulses obtained from PWM generator are given to six switches of an inverter. On and Off time of these switches depends upon the duty cycle of the gate pulses. Switches are operated in a specific sequences to have proper output. S_1, S_2, S_3, S_4, S_5 and S_6 are the switches of three phase inverter. These are the power electronic switches having negligible power loss.

Switching scheme for 120 mode of operation is given as:

1. From 0 to 60: S_1 and S_4 are On/closed while remaining switches are Off/opened.
2. From 60 to 120: S_1 and S_6 are On/closed while remaining switches are Off/opened.
3. From 120 to 180: S_3 and S_6 is On/closed while remaining switches are Off/opened.
4. From 180 to 240: S_2 and S_3 are On/closed while remaining switches are Off/opened.
5. From 240 to 300: S_2 and S_5 are On/closed while remaining switches are Off/opened.
6. From 300 to 360: S_4 and S_5 are On/closed while remaining switches are Off/opened.

From these switching sequences line voltages and phase voltages are obtained. Final output waveform is not pure sinusoidal at the output terminals of three phase inverter, therefore an effective output filer is used to have pure sinusoidal output waveform. The switching sequences and output waveform of three phase inverter are shown in Fig. 3.2. V_{ao}, V_{bo} and V_{co} are the voltages of three phases with respect to neutral while V_{ab}, V_{bc} and V_{ca} are the line voltages between ab, bc and ca respectively. LC filter, at the output of an inverter has three terminals to connect three phase loads.

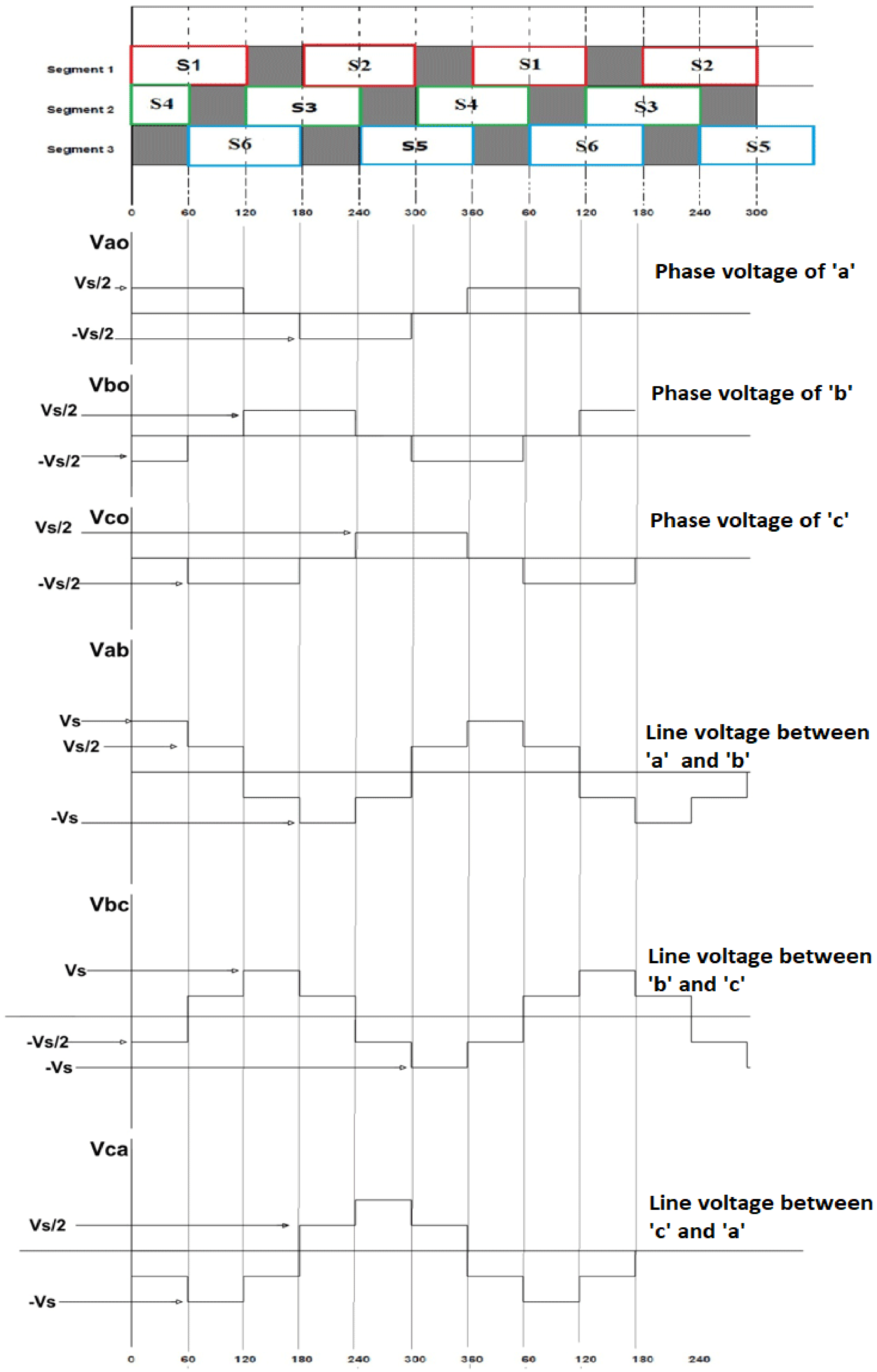

FIGURE 3.2: Switching sequence and output waveform of an inverter.

3.2.2 State Space Model of Three Phase VSI

One of the key concept of system theory is state space modeling. State space representation gives easy way of understanding or manipulating the properties of a system. The proposed control theory is possible due to state space representation. The proposed work uses state space model of three phase voltage source PWM inverter in-term of input voltages, output voltages, input currents, output currents, frequency, inductor value and capacitor value. Given state space equation is obtained from original model by applying Kurchoif's law. In this work, controller is designed for state space model of an inverter. The given equation has four state variables which are V_{Ld}, V_{Lq}, i_{ld} and i_{lq}. V_{Ld} and V_{Lq} are desires outputs of VSI. The state space model of the inverter can be represented as[8]:

$$\frac{d}{dt}\begin{pmatrix} V_{Ld} \\ V_{Lq} \\ i_{ld} \\ i_{lq} \end{pmatrix} = \begin{pmatrix} \omega V_{Lq} + \frac{1}{C_f} i_{ld} + \frac{1}{C_f} \frac{p_F V_{Ld+q_f V_{Ld}}}{V_{Ld}^2+V_{Lq}^2} + \omega C_f V_{Lq} - \frac{\omega L_f V_{Lq}(i_{ld}^2+i_{lq}^2)}{V_{Ld}^2+V_{Lq}^2} \\ -\omega V_{Lq} + \frac{1}{C_f} ilq - \frac{1}{C_f} \frac{p_F V_{Ld-q_f V_{Ld}}}{V_{Ld}^2+V_{Lq}^2} - \omega C_f V_{Lq} + \frac{\omega L_f V_{Lq}(i_{ld}^2+i_{lq}^2)}{V_{Ld}^2+V_{Lq}^2} \\ \omega i_{lq} - \frac{1}{L_f} V_{Ld} \\ -\omega i_{ld} - \frac{1}{L_f} V_{Lq} \end{pmatrix} + \begin{pmatrix} 0 & 0 \\ 0 & 0 \\ \frac{1}{L_f} & 0 \\ 0 & \frac{1}{L_f} \end{pmatrix} \begin{pmatrix} V_{ld} \\ V_{lq} \end{pmatrix} \tag{3.1}$$

where the parameters used in equation (3.1) are defined as:

1. V_{Ld} and V_{Lq} are the desired output voltages.
2. i_{Ld} and i_{Lq} are the H-bridge input currents.
3. V_{ld} and V_{lq} are the control inputs.
4. p_f and q_f are the active and reactive powers respectively.
5. C_f and L_f are capacitor and inductor values of the output filter.
6. $\omega = 2\pi f$ where f is the standard frequency used. Frequency value is different for different countries. Frequency may be 50/60 Hz.

The output vector is defined as:

$$\begin{pmatrix} y_1 \\ y_2 \end{pmatrix} = \begin{pmatrix} V_{Ld} \\ V_{Lq} \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \end{pmatrix} \begin{pmatrix} V_{Ld} \\ V_{Lq} \\ i_{ld} \\ i_{lq} \end{pmatrix} \tag{3.2}$$

The system state vector is taken to be $\bar{X} = [V_{Ld}, V_{Lq}, i_{ld}, i_{lq}]^T$ and the control input vector is to be taken as $\bar{U} = [V_{ld}, V_{lq}]^T$. While using the state variable as $x_{11} = V_{Ld}, x_{22} = V_{Lq}, x_{33} = i_{Ld}$ and $x_{44} = i_{Lq}$, the system in (3.1) can be expressed:

$$\frac{d}{dt}\begin{pmatrix} x_{11} \\ x_{22} \\ x_{33} \\ x_{44} \end{pmatrix} = \begin{pmatrix} \omega x_{22} + \frac{1}{C_f}x_{33} - \frac{1}{C_f}\frac{p_f x_{11} + q_f x_{22}}{x_{11}^2 + x_{22}^2} + \omega C_f x_{22} - \frac{\omega L_f x_{22}(x_{33}^2 + x_{44}^2)}{x_{11}^2 + x_{22}^2} \\ -\omega x_{22} + \frac{1}{C_f}x_{33} - \frac{1}{C_f}\frac{p_f x_{22} - q_f x_{11}}{x_{11}^2 + x_{22}^2} - \omega C_f x_{11} + \frac{\omega L_f x_{11}(x_{33}^2 + x_{44}^2)}{x_{11}^2 + x_{22}^2} \\ \omega x_{44} - \frac{1}{L_f}x_{11} \\ -\omega x_{33} - \frac{1}{L_f}x_{22} \end{pmatrix} + \begin{pmatrix} 0 & 0 \\ 0 & 0 \\ \frac{1}{L_f} & 0 \\ 0 & \frac{1}{L_f} \end{pmatrix} \begin{pmatrix} u_1 \\ u_2 \end{pmatrix} \tag{3.3}$$

The output vector, according to the new notations, will be:

$$\begin{pmatrix} y_1 \\ y_2 \end{pmatrix} = \begin{pmatrix} V_{Ld} \\ V_{Lq} \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \end{pmatrix} \begin{pmatrix} x_{11} \\ x_{22} \\ x_{33} \\ x_{44} \end{pmatrix} \tag{3.4}$$

System (3.3) and (3.4), in more general form can be expressed as:

$$\dot{x} = f(x) + G(x)u$$

and

$$y = h(x)$$

where $f(x)\epsilon R^{4\times 1}$; $G(x)\epsilon R^{4\times 1}$ and $h(x)\epsilon R.^{2\times 4}$.

3.3 Input Output Linearization

Now we are ready to put this dynamic model into control convinient form. For this purpose feedback linearization is used. The linearization of non-linear model, reported in (3.3) and (3.4), the procedure outlined in [8] is followed here. Output vector for non-linear model is defined as:

$$\begin{aligned} V_{Ld} &= h_{11}(x) = x_{11} \\ V_{Lq} &= h_{22}(x) = x_{22} \end{aligned} \tag{3.5}$$

In case of non-linear model x_{11} and x_{22} are desired voltages at output terminals. Actually these variables are the responses of non-linear inverter model. Controller design strategy becomes easy in case of linear model therefore linearization is done through input output linearization.

The main objective of the implementation of this controller (MPC), is to fill the research gaps. Equation (3.5) holds that:

$$\begin{aligned} z_{11} &= h_{11}(x) = x_{11} \\ z_{22} &= L_f h_{11}(x) \\ \dot{z_{22}} &= L_f^2 h_{11}(x) + L_{ga} L_f h_{11}(x) u_1 + L_{gb} L_f h_{11}(x) u_2 \end{aligned} \tag{3.6}$$

Similarly,

$$\begin{aligned} z_{33} &= h_{22}(x) = x_{22} \\ z_{44} &= L_f h_{22}(x) \\ \dot{z_{44}} &= L_f^2 h_{22}(x) + L_{ga} L_f h_{22}(x) u_1 + L_{gb} L_f h_{22}(x) u_2 \end{aligned} \tag{3.7}$$

Linearization is the second important step for controller design after designing state space model of original system. When the linear model is obtained through any process then the controllability and observability are checked properly before the controller design. The initial tests are performed before designing the controller. Following are the linearization process while using Lie Algebra. Following terms are used in matrix M to design original controller.

where,

$$\begin{aligned}
L_{ga}L_f h_{11}(x) &= \frac{\partial z_{22}}{\partial x_{11}} ga_{11} + \frac{\partial z_{22}}{\partial x_{22}} ga_{22} + \frac{\partial z_{22}}{\partial x_{33}} ga_{33} + \frac{\partial z_{22}}{\partial x_{44}} ga_{44} \\
L_{gb}L_f h_{11}(x) &= \frac{\partial z_{22}}{\partial x_{11}} gb_{11} + \frac{\partial z_{22}}{\partial x_{22}} gb_{22} + \frac{\partial z_{22}}{\partial x_{33}} gb_{33} + \frac{\partial z_{22}}{\partial x_{44}} gb_{44} \\
L_{ga}L_f h_{22}(x) &= \frac{\partial z_{44}}{\partial x_{11}} ga_{11} + \frac{\partial z_{44}}{\partial x_{22}} ga_{22} + \frac{\partial z_{44}}{\partial x_{33}} ga_{33} + \frac{\partial z_{44}}{\partial x_{44}} ga_{44} \\
L_{gb}L_f h_{22}(x) &= \frac{\partial z_{44}}{\partial x_{11}} gb_{11} + \frac{\partial z_{44}}{\partial x_{22}} gb_{22} + \frac{\partial z_{44}}{\partial x_{33}} gb_{33} + \frac{\partial z_{44}}{\partial x_{44}} gb_{44} \\
L_f^2 h_{11}(x) &= \frac{\partial z_{11}}{\partial x_{11}} f_{11} + \frac{\partial z_{11}}{\partial x_{22}} f_{22} + \frac{\partial z_{11}}{\partial x_{33}} f_{33} + \frac{\partial z_{11}}{\partial x_{44}} f_{44} \\
L_f^2 h_{22}(x) &= \frac{\partial z_{44}}{\partial x_{11}} f_{11} + \frac{\partial z_{44}}{\partial x_{22}} f_{22} + \frac{\partial z_{44}}{\partial x_{33}} f_{33} + \frac{\partial z_{44}}{\partial x_{44}} f_{44}
\end{aligned} \tag{3.8}$$

After linearization, the dynamics of the inverter model are written as:

$$\begin{aligned}
\ddot{x_{11}} &= L_f^2 h_{11}(x) + L_{ga}L_f h_{11}(x) u_1 + L_{gb}L_f h_{11}(x) u_2 \\
\ddot{x_{22}} &= L_f^2 h_{22}(x) + L_{ga}L_f h_{22}(x) u_1 + L_{gb}L_f h_{22}(x) u_2
\end{aligned} \tag{3.9}$$

$$\begin{aligned}
v_1 &= L_f^2 h_{11}(x) + L_{ga}L_f h_{11}(x) u_1 + L_{gb}L_f h_{11}(x) u_2 \\
v_2 &= L_f^2 h_{22}(x) + L_{ga}L_f h_{22}(x) u_1 + L_{gb}L_f h_{22}(x) u_2
\end{aligned} \tag{3.10}$$

The final linearized model is given[12] as:

$$\begin{aligned}
\ddot{x_1} &= v_1 \\
\ddot{x_2} &= v_2
\end{aligned} \tag{3.11}$$

Defining $\dot{x_1} = x_2$, $\dot{x_2} = v_1$, $\dot{x_3} = x_4$ and $\dot{x_4} = v_2$, state space equation will be:

$$\begin{pmatrix} \dot{x_1} \\ \dot{x_2} \\ \dot{x_3} \\ \dot{x_4} \end{pmatrix} = \begin{pmatrix} 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 \end{pmatrix} \begin{pmatrix} x_1 \\ x_2 \\ x_3 \\ x_4 \end{pmatrix} + \begin{pmatrix} 0 & 0 \\ 1 & 0 \\ 0 & 0 \\ 0 & 1 \end{pmatrix} \begin{pmatrix} v_1 \\ v_2 \end{pmatrix} \tag{3.12}$$

This is the final state space form of linearized system in which v_1 and v_2 are the linear control laws. This is the initial step to design the non-linear controllers. In output vector x_1 and x_3 are the desired output.

The outputs are given by:

$$\begin{pmatrix} V_{Ld} \\ V_{Lq} \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 \end{pmatrix} \begin{pmatrix} x_1 \\ x_2 \\ x_3 \\ x_4 \end{pmatrix} \tag{3.13}$$

At this stage, a proper control convenient mode is developed, and we are ready to proceed to the control design.

3.4 Model Predictive Controller Design

Model predictive control uses a model of the plant that is needed to be controlled to make future plant output prediction. MPC solves a problem of optimization at each time step to have a control action. The control action then drives the plant output as predicted output close to the desired value. The difference between classical controller like PID, bang-bang, state controllers and model predictive controller is that the classical controllers consider only current and past system behaviour while MPC uses a system's model to predict the future behaviour while anticipating deviations from the reference input.

3.4.1 MPC Offers a Number of Advantages [12] Which are:

1. Explicitly use of a system model.
2. Explicitly handles the system constraints.
3. Straightforward formulation on the basis of well understood concepts.
4. MPC uses well understood tuning parameters.
5. It gives well understood optimization problem setup and prediction horizon.
6. It has development time which is much shorter than for completing advanced control methods.

7. MPC is easier to maintain.

8. MPC does not require complete redesign in case of changing model or specks.

Emerging Model predictive control applications are path planning and control of vehicles, spacecraft meeting with space station, underwater vehicle guidance and missile guidance. Model predictive controller is an effective controller strategy in almost every field of life. MPC is used in regulation and tracking problem more effectively like path tracking in case of unmanned or automatic aerial vehicles and missiles[44, 45]. The control action U is such that it minimizes the cost function in such a way that the predicted output of plant is closed to reference or desirer value. In recent years, model predictive controller is highly attracted in power electronics as well because the long computation is done by advanced microprocessors in minimum time. In case of model predictive controller design for power electronic circuit specially in case of converter, finite control set MPC can work efficiently without the use of modulation technique[46]. In finite control state set control model predictive control (FCS-MPC), the switching states are directly applied to the power converter without an additional modulation stage. Regulation problems can also be handled in an effective way. As frequency of an isolated electric vehicle is regulated with micro grid and electric energy storage system integration while using model predictive and adaptive controllers[47]. It regulates the frequency at high load demand in case of isolated micro grid. An advanced genetic algorithm is used to tune the model predictive controller (MPC) parameter to achieve an optimization performance. The regulation is done by solving a function called cost function, which gives an optimal control action to regulate the desire parameter/value. Model predictive controller design is a good example of optimization problem in real time applications.

3.5 Methodology

Model predictive control strategy is simple in design having tuning parameters. Following steps are followed in proposed work with $N_p = 15$ and $N_c = 8$. Efficiency of MPC depends upon the values of N_p and N_c. Main steps are given as:

1. Selection of proper state space model which is given in continuous time.
2. From the state space model, continuous time matrices are obtained.
3. Conversion of continuous time matrices into discrete time matrices with the help of proper sampling time interval Ts.
4. Conversion of discrete time matrices into augmented matrices with the help of null and identity matrices.
5. Design of state estimator matrices for cost function which has to be minimized.
6. Solution of cost function for optimal control action which gives the output closest to the desire value.
7. The control law is obtained by selecting proper prediction horizon and control horizon such that $N_p \geq N_c$.
8. For the prediction of output, the states of model also changes from current states to future states .

In proposed algorithm the control action becomes optimal because at this control law the cost function becomes minimum, which mean the actual output is closest to the desire value. The condition of having prediction horizon greater than control horizon is that design strategy does not need the controller design beyond the required limit.

3.5.1 Prediction Horizon

The model's forecasting range. The user learns how to control the system faster and achieve higher performance when the prediction horizon is adequately matched to the lag between input and output. The value of prediction horizon effects the size of state estimator matrices. Selection of prediction horizon value should relate with the control horizon value.

3.5.2 Control Horizon

The number of manipulated variable (MV) motions to be optimized at control interval k is the control horizon, m.

3.6 General Algorithm for MPC

With the help of single input single output(SISO) model predictive controller design implementation, model predictive controller design for multiple input multiple (MIMO) output is also possible with little bit change in dimensions.

3.6.1 Single Input Single Output System

MPC design for multiple-input multiple-output systems is comparatively more complex than single-input single-output systems. Following concepts are used to design MPC for single-input single-output systems then same concepts are used with some modifications for multiple-input multiple output systems. Initially single-input single-output system is considered which is described by:

$$\begin{aligned} x_m(j+1) &= A_m x_m(j) + B_m u(j) \\ y(j) &= C_m x_m(j) \end{aligned} \tag{3.14}$$

Where u is input variable, the processes output is given in the form of y and x_m which is state variable vector with dimension n_1. For general state space model formulation the input output relation will be:

$$y(j) = C_m x_m(j) + D_m u(j) \tag{3.15}$$

According to the principle of receding horizon control, for prediction and control the current information of the plant is required. It is implicitly assumed that the plant input which is defined in term of $u(j)$ can not affect the plant output $y(j)$ at same time. Therefore $D_m = 0$ in the plant model. From above two equations A is state matrix, B is input matrix, C is output matrix and D is feedback through matrix.

The difference operation on equation (3.14), following equation is obtained which provides informations about change in states. The equation is given by:

$$x_m(j+1) - x_m(j) = A_x(x_m(j) - x_m(j-1)) + B_m(u(j) - u(j-1)) \tag{3.16}$$

The difference of state variable is:

$$\triangle x_m(j+1) = x_m(j+1) - x_m(j); \triangle x_m(j) - x_m(j-1) \tag{3.17}$$

and control variable in difference form provides informations regarding change in control input from current value to past value. The equation is given as:

$$\triangle u(j) = u(j) - u(j-1) \tag{3.18}$$

The difference of state space equation is:

$$\triangle x_m(j+1) = A_m \triangle x_m(j) + B_m \triangle u(j) \tag{3.19}$$

The new state variable vector must be chosen to connect $\triangle x_m(j)$ to $y(j)$ as:

$$x(j) = [x_m(j)^T y(j)]^T \tag{3.20}$$

Note that, difference between future output value to current output value, which is given by:

$$\begin{aligned} y(j+1) - y(j) &= C_m(x_m(j+1) - x_m(j)) \\ &= C_m \triangle x_m(j+1) = C_m A_m \triangle x(j) + C_m B_m \triangle u(j) \end{aligned} \tag{3.21}$$

Above equations in state space form is given below. These equations are general for single input single output systems and same concept is implemented for multiple input multiple output system that is three phase voltage source PWM inverter. Equation (3.21) gives change in output states.

Putting (3.13) and (3.15) together to get state space model, this model is used while implementing MPC. The augmented matrices A, B and C are are used to reduce steady state errors. In multiple-input multiple-output systems the dimensions of null and identity matrices are modified. State space model having augmented matrices is give as:

$$\overbrace{\begin{bmatrix} \triangle x_m(j+1) \\ y(j+1) \end{bmatrix}}^{x(j+1)} = \overbrace{\begin{bmatrix} A_m & o_m^T \\ C_m A_m & 1 \end{bmatrix}}^{A} \overbrace{\begin{bmatrix} \triangle x_m(j) \\ y(j) \end{bmatrix}}^{x(j)} + \overbrace{\begin{bmatrix} B_m \\ C_m B_m \end{bmatrix}}^{B} \triangle u(j) \tag{3.22}$$

and

$$Y(j) = \overbrace{\begin{bmatrix} o_m & 1 \end{bmatrix}}^{C} = \begin{bmatrix} \triangle x_m(j) \\ y(j) \end{bmatrix} \tag{3.23}$$

where

$$o_m = \overbrace{\begin{bmatrix} 0 & 0 & . & . & . & 0 \end{bmatrix}}^{n_1} \tag{3.24}$$

(A,B,C) the triplet which is called augmented model that is required to design the model predictive controller.

3.6.2 Prediction of States and Output Variables

At the sampling instant $j_i > 0$, state vector $x(j_i)$ is assumed to be available through measurement. The control trajectory of future is denoted by:

$$\triangle u(j_i), \triangle u(j_i+1), ..., \triangle u(j_i+N_c-1) \tag{3.25}$$

where N_c is control horizon used to capture the control trajectory of future. N_p is prediction horizon which is the length of an optimization window or number of samples. Input control law has N_p and N_c values which are the design parameters. Equation (3.25) gives change in control input law.

The future state variables are denoted as:

$$x(j_i + 1/j_i), x(j_i + 2/j_i), x(j_i + 3/j_i), ..., x(j_i + m/j_i), ..., x(j_i + N_p/j_i) \quad (3.26)$$

where $x(j_i + m/j_i)$ is the state variable predicted at $j_i + m$ with current plant information $x(j_i)$. Model predictive controller predicts the future states and output variables. These predictions are done by solving the optimization problem. Subtraction of actual output value from desired value, gives an error signal. The error value is minimized through optimization, which means error tends to zero and actual output tends to desired one. This strategy is successfully implemented with the help of MPC. The main difference between model predictive control and convention control is that MPC considers the behaviours in present, past and future time while conventional control strategy only considers present and past behaviours. Future state prediction is done on the basis of following operations in which prediction is made while having informations about past and current behaviours. Matrices are used in discrete form while implementing model predictive control. Augmentation of matrices is also done to reduce the steady state errors, augmentation is similar to integrator which is used in proportional derivative integral controller. On the basis of state space model having A, B and C the sequential future state variable is computed by using the set of future control parameter are:

$$\begin{aligned} x(j_i + 1/j_i) &= A_x(j_i) + B\triangle u(j_i) \quad (3.27) \\ x(j_i + 2/j_i) &= A_x(j_i + 1/j_i) + B\triangle u(j_i + 1) \\ &= A_x^2(j_i) + ABu(j_i) + B\triangle u(j_i + 1) \\ &. \\ &. \\ &. \\ x(j_i + N_p/j_i) &= A_p^N x(j + i) + A^{N_p - 1} B\triangle u(j_i) \\ &+ A^{N_p - 2} Bu(j + 1) + ... + A^{N_p - N_c} Bu(j_i + N_c - 1) \end{aligned}$$

This is the most important step having state matrix and input matrix with proper values of N_p and N_c.

Predicted output variables are given as :

$$
\begin{aligned}
y(j_i+1/j_i) &= CAx(j_i) + CB\triangle u(j_i) \\
y(j_i+2/j_i) &= CA^2x(j_i) + CAB\triangle u(j_i) + \\
&\quad CB\triangle u(j_i+1) + CB\triangle u(j_i+1) \\
&. \\
&. \\
&. \\
y(j_i+N_p/j_i) &= CA_p^N x(j_i) + CA^{N_p-1}B\triangle u(j_i) \\
&\quad + CA^{N_p-2}B\triangle u(j_i+1) + ... + \\
&\quad CA^{N_p-N_c}B\triangle u(j_i+N_c-1)
\end{aligned}
\tag{3.28}
$$

From above equations all predicted variables simply formulated in term of both the current state information of variable $x(j_i)$ and the upcoming or future control movement given as $\triangle u(j_i+k)$, such that: $k = 0, 1, 2, ...N_c - 1$. In term of vector definition Y and $\triangle U$ are:

$$
\begin{aligned}
Y &= [y(j_i+1/j_i)y(j_i+2/j_i)y(j_i+3/j_i)y(j_i+4/j_i)...y(j_i+N_p/j_i]^T \\
\triangle U &= [\triangle u(j_i)\triangle u(j_i+1)\triangle u(j_i+2)\triangle u(j_i+3)...\triangle u(j_i+N_c-1)]^T
\end{aligned}
\tag{3.29}
$$

In case of single input single output case, output Y has dimension equal to N_p while the dimension of $\triangle U$ is equal to N_c. State estimator matrices and output equation are given as:

$$
F = \begin{bmatrix} CA \\ CA^2 \\ CA^3 \\ . \\ . \\ . \\ CA_p^N \end{bmatrix}, \phi = \begin{bmatrix} CB & 0 & 0 & ... & 0 \\ CAB & CB & 0 & ... & 0 \\ CA^2B & CAB & CB & ... & 0 \\ . & & & & \\ . & & & & \\ . & & & & \\ CA^{N_p-1}B & CA^{N_p-2}B & CA^{N_p-3}B & ... & CA^{N_p-N_c}B \end{bmatrix}
\tag{3.30}
$$

These two matrices are the estimators of states and used in cost function.

and

$$Y = Fx(j_i) + \phi \triangle U \tag{3.31}$$

MPC works on optimization of cost function. Above matrices are used in cost function, therefore the next step is the optimization/minimization of cost function. In coming sections, cost function is constructed wile discussing optimization.

3.6.3 Optimization

The main objective of the model predictive control is to bring the output which is predicted, closed to the set point signal. It is assumed that the set point signal remain constant in overall window of optimization. For given reference/set point signal $r(j_i)$ at sample time j_i, the objective is to design the best parameter vector $\triangle U$. This parameter vector has minimum error function which minimizes the error between set point and predicted output. Minimization of an error signal is known as optimization.

R_s is the data matrix having information of set point/desired value, which is

$$R_s^T = \overbrace{[111...1]}^{N_p} r(j_i)$$

The cost function J(the main concept of MPC implementation revolves around this function) is defined, which reflects the control objective that is

$$J = (R_s - Y)^T (R_s - Y) + \triangle U^T \bar{R} \triangle U \tag{3.32}$$

In above equation the first term gives minimization of an error between the predicted output and set point while another term gives the consideration about the size of $\triangle U$. The equation has a diagonal matrix $\bar{R}$, is defined by $\bar{R} = r_\omega I_{N_c \times N_c}(r_{\omega \geq 0})$. The tuning factor (r_ω) is used as desired closed loop performance parameter. In case of $r_\omega = 0$ it means the control strategy does not pay any attention about the size of $\triangle U$ to reduce the error $(R_s - Y)^T (R_s - Y)$ while in case of large value of tuning parameter r_ω the control strategy will consider carefully how large $\triangle U$ is required to reduce the error $(R_s - Y)^T(R_s - Y)$.

Now the optimal $\triangle U$ that minimizes the cost function J by using equation (3.24) is expressed as:

$$J = (R_s - Fx(j_i))^T(R_s - Fx(j_i)) - 2\triangle U^T\phi(R_s - Fx(j_i)) + \triangle U^T(\phi^T\phi + \bar{R})\triangle U \tag{3.33}$$

By taking the first derivative of cost function J, which means change in energy. The above equation becomes:

$$\frac{\partial J}{\partial \triangle U} = -2\phi^T(R_s - Fx(j_i)) + 2(\phi^T\phi + \bar{R})\triangle U \tag{3.34}$$

To obtain the minimum/optimized J, following condition is necessary.

$$\frac{\partial J}{\partial \triangle U} = 0$$

Considering above condition, the control signal is given as:

$$\triangle U = (\phi^T\phi + \bar{R}_s)^{-1}\phi^T(R_s - Fx(j_i))$$

Assuming the existence of $(\phi^T\phi + \bar{R})^{-1}$. This matrix is called Hessian matrix. From above equation R_s is a data vector having set point informations. R_s is expressed as:

$$R_s = \overbrace{[111...]^T}^{N_p} r(j+i) = \bar{R}_s r(j_i)$$

$$R_s = \overbrace{[111...1]^T}^{N_p}$$

The final equation gives the optimal solution of control signal which has clear linked with both the set point signal $r(j_i)$ and state variable $x(j_i)$. This is the vector having desired values in dq reference frame. The desired values used in this matrix are also used in cost function in-term of R_s.

Final equation is give as:

$$\triangle U = (\phi^T \phi + \bar{R}_s)^{-1} \phi^T (R_s - F x(j_i)) \tag{3.35}$$

This is the final equation having control inputs. Input control laws are obtained from this equation to apply the proposed model. In case of dq reference frame, two control inputs are obtained from this equation.

3.7 Overall Control Implementation Architecture

The over all control flow is given in Fig. 3.3. which has following important steps as:

1. Three phase voltage source PWM inverter is considered.
2. Linearization of the model with the help of input output linearization.
3. Transformation of reference frame from three phase to dq.
4. Defining an error signal in term of actual and desire voltages.
5. Minimization of error function in such a way that the output value tends closest to desire value.
6. In general flow the controller provide gate pulse with the help of PWM generator which operates the switching sequence in such a way that the desire value of output voltage is obtained. Errors are the inputs of proposed controller, similarly u_d and u_q are the control inputs for inverter model.
7. Control inputs obtained for linear model are modified for non-linear model.
8. Control inputs are applied for given system.

Transformation of three phase values into dq without converting into $\alpha\beta$ is also possible. The direct transformation reduces the time in real time application of proposed controller.

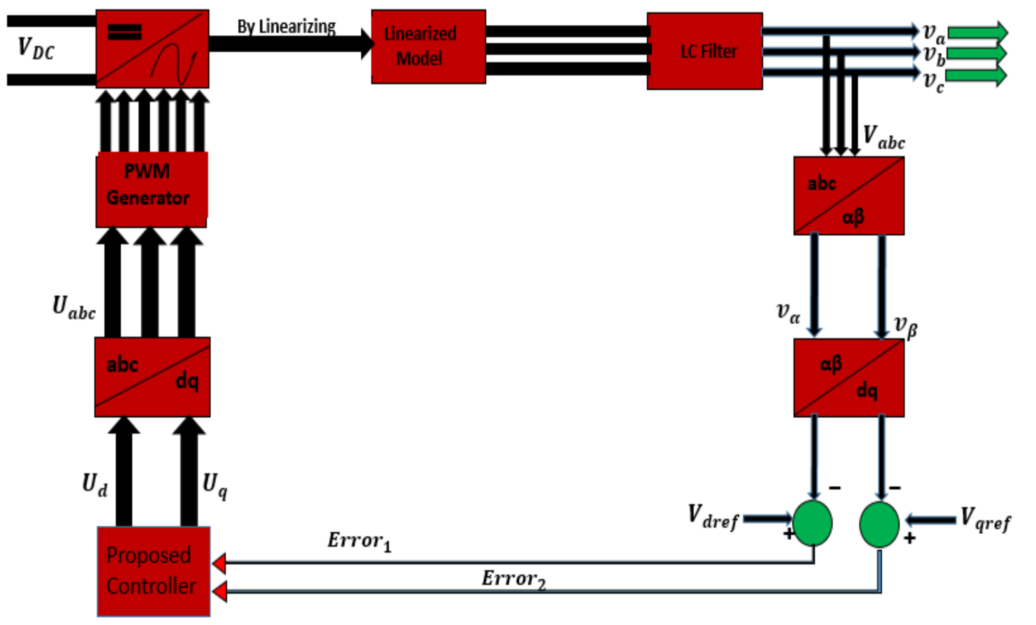

FIGURE 3.3: Overall control flow of an algorithm.

3.8 Methodology in Mathematical Form for Three Phase Voltage Source PWM Inverter

1. Continous time state space model is given [8] as:

$$\begin{pmatrix} \dot{x_1} \\ \dot{x_2} \\ \dot{x_3} \\ \dot{x_4} \end{pmatrix} = \begin{pmatrix} 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 \end{pmatrix} \begin{pmatrix} x_1 \\ x_2 \\ x_3 \\ x_4 \end{pmatrix} + \begin{pmatrix} 0 & 0 \\ 1 & 0 \\ 0 & 0 \\ 0 & 1 \end{pmatrix} \begin{pmatrix} v_1 \\ v_2 \end{pmatrix}$$

$$\begin{pmatrix} V_L d \\ V_L q \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 \end{pmatrix} \begin{pmatrix} x_1 \\ x_2 \\ x_3 \\ x_4 \end{pmatrix}$$

These matrices are used in linear controller design for both MPC and SMC. In MPC design matrices are directly used while errors are defined in SMC.

2. Continuous time matrices from of above model are given as:

$$A_c = \begin{bmatrix} 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 \end{bmatrix}, B_c = \begin{bmatrix} 0 & 0 \\ 1 & 0 \\ 0 & 0 \\ 0 & 1 \end{bmatrix}$$

and

$$C_c = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 \end{bmatrix}$$

3. conversion of A_c, B_c, C_c into discrete time matrices A_d, B_d, C_d by taking sampling time interval T_s= 0.1 second. In model predictive controller design, calculations are performed by microprocessor/micro-controller therefore matrices must be in discrete form.

   Discrete time matrices are given as:

$$A_d = \begin{bmatrix} 1 & 0.1 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0.1 \\ 0 & 0 & 0 & 1 \end{bmatrix}, B_d = \begin{bmatrix} 0.0050 & 0 \\ 0.1 & 0 \\ 0 & 0.0050 \\ 0 & 0.1 \end{bmatrix}$$

and

$$C_d = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 \end{bmatrix}$$

4. Conversion of discrete time matrices with the help of null and identity matrices into augmented matrices. These matrices help to reduce the steady state error.

   Augmented matrices perform same function as integrator performs in proportional integral derivative controller. The dimensions of null and identity matrices are changed according to the dimensions of discrete time matrices A,B and C.

Augmented matrices are given as:

$$A = \begin{bmatrix} sysd.A & om^T \\ sysd.C \times sysd.A & I \end{bmatrix}, B = \begin{bmatrix} sysd.B \\ sysd.C \times sysd.B \end{bmatrix}$$

and

$$C = \begin{bmatrix} om & I \end{bmatrix}$$

where null matrix, its transpose and identity matrix are defined as:

$$om = \begin{bmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix}, om^T = \begin{bmatrix} 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \end{bmatrix}$$

and

$$I = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}$$

The matrix D is given as a null vector of dimensions 2×2.

5. State estimator matrices for cost function with L matrix are defined as:

$$F = \begin{bmatrix} CA \\ CA^2 \\ CA^3 \\ . \\ . \\ . \\ CA^{15} \end{bmatrix}, \phi = \begin{bmatrix} CB & L & L & . \; . \; . & L \\ CAB & CB & L & . \; . \; . & L \\ CA^2B & CAB & CB & . \; . \; . & L \\ . & & & & \\ . & & & & \\ . & & & & \\ CA^{14}B & CA^{13}B & CA^{12}B & . \; . \; . & CA^6B \end{bmatrix}$$

These two matrices are the state estimators for proposed work having $N_c = 9$ and $N_p = 15$. Due to these two matrices MPC has to perform a big calculation. For the effective values of N_c and N_p ,small values are preferred and

$$L = \begin{bmatrix} 0 & 0 \\ 0 & 0 \end{bmatrix}$$

In case of multiple input multiple output, the dimension of L is 2×2 while L has 1×1 dimension in case of single input single output. The function which has to be optimized, must contains state estimator matrices, current states, identity matrix and reference matrix. Dimensions of identity matrix depends upon the value of N_c.

6. The control law has $N_c = 9, N_p = 15$ while reference output is given as:

$$Rs = \begin{bmatrix} r \\ r \\ r \\ r \end{bmatrix}$$

where r has dimension of 1×6.

7. The final cost function which gives the control law is given as:

$$\triangle U = (\phi^T \phi + I_{2N_c \times 2N_c})^{-1} (\phi^T R_s - \phi^T F x_f)$$

where x_f is current state and the controllers for linear system will be:

$$v_1 = \triangle U(1, 1)$$

$$v_2 = \triangle U(2, 1)$$

8. Final control law is obtained from $\triangle U$ while updating the states. The equation of state is given as:

$$x_f = \begin{bmatrix} xm_N - xm_{Old} \\ Y \end{bmatrix}$$

This equation gives the changed values of four states for inverter model.

9. Final control inputs for linear model are v_1 and v_2 while u_d and u_q are the controll inputs for non-linear/original model [8].

$$\begin{pmatrix} u_d \\ u_q \end{pmatrix} = M^{-1} \begin{pmatrix} v_1 - f_1 \\ v_2 - f_2 \end{pmatrix} \tag{3.36}$$

where M , f_1 and f_2 are defined as:

$$M = \begin{pmatrix} LgaL_f h_1(x) & LgbL_f h_1(x) \\ LgaL_f h_2(x) & LgbL_f h_2(x) \end{pmatrix},$$

where $f_1 = L_f^2 h_1(x)$ and $f_2 = L_f^2 h_2(x)$.

3.9 Receding Horizon Control

Receding horizon control, is a general purpose control scheme. In this controller, optimization problem has to be solved at each time step to choose the control action. Receding horizon control handles constraints, such as limits on control variables. The main disadvantage of receding horizon control is that an optimization problem has to be solved repeatedly which is feasible for systems having slow sampling.

3.10 Summary

In this chapter, non-linear model of three phase voltage source PWM inverter is considered. The model is linearized with input output linearization. MPC is designed to control the output voltage of an inverter at desired value. Controller is designed for linear model and then it is modified for non-linear/original model. The methodology of MPC for both single input single output and multiple input multiple output systems is also discussed with the explanation of different control terminologies.

Chapter 4

Sliding Mode Controller Design for an Inverter Dynamic Model

4.1 Sliding Mode Control

Sliding mode control(SMC) is a control technique which is applicable for both linear and nonlinear control systems with inherent properties of robustness beside turbulence, perturbation and parametric change etc. It is different from classical one with healthy properties. Sliding mode controller is on off sort of control system. The controller switches the control path which always depend upon the value of predefine polynomial. The controller brings the states of given system to sliding surface or states converge towards zero. This technique is considered as simple to design and execution. This controller can be used for estimation and rejection of irritation. The proposed controller technique is highly effective in stability analysis of system[48]. SMC can also be used in synchronization and regulation of system parameter[49]. In case of regulation problem, the error function is defined, the error contained desired and actual value of output. When the state of error is zero then the actual value of output gets the desire value by satisfying the condition of convergence. This research work performs the same strategy as the desire value is achieved by defining an error. From the stability analysis using sliding mode controller design, the given inverter model is also stabilized.

4.1.1 Methodology

1. Selection of proper state space model.
2. Design of sliding surface.
3. Defining an energy/laypnunov function.
4. Choosing the control input containing signum function in such a way that the time derivative of energy function strictly less than zero satisfying asymptotic stability of the system.
5. Modify the linear control law for non-linear model.

4.2 Advantages of SMC

1. Simple in design .
2. Simple in redesign.
3. Highly robust controller.
4. It can be design for both linear and non-linear system.
5. It has the ability to estimate the unknown values as well.
6. SMC has good performance in stabilization of system having state space model.

4.3 Disadvantages of SMC

Sliding mode controller is high frequency on off (has chattering problem) type of controller, in practical case the device can be damaged at high frequency switching. Chattering is the only drawback of sliding mode controller design. Researches have been conducted to reduce this problem so that the practical application of SMC become feasible. Different SMC modes are used to reduce the chattering phenomena, these are integral sliding and higher order SMC.

4.4 Sliding Surface Design

In sliding surface design, variable structure control (VSC) in a way such that it acts as a speedy swapped FB control[50, 51]. According to this rule, in every feedback the gain switches track between -1 to 1 depend on the state value at every point. The transferring reason of the control function is to trail the state onto a plane which is predefine one, in this way the system state remains on the sliding surface for consequent time. This surface is called switching surface. The states of dynamic system slide on the surface where surface is at zero. Fig. 4.1 shows sliding mode (SM), reaching phase (RP) and sliding surface (SS).

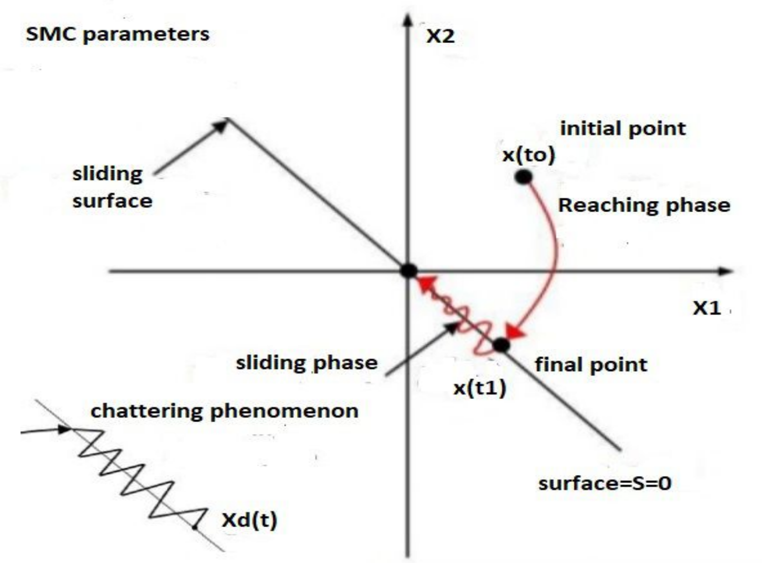

FIGURE 4.1: Sliding surface in SMC.

4.5 Signum Function

$$sgn(x) = y = \begin{cases} 1, & \text{if } x > 0 \\ 0, & \text{if } x = 0 \\ -1, & \text{if } x < 0 \end{cases}$$

This is the equation of continuous time signum function. Signum function is a piecewise function of real value x. This function gives continuous time graph on coordinate axis while satisfying three conditions. Signum function acts like a switch and it is a key component in sliding mode controller design.

The graphical representation of continuous time signum function is given in Fig 4.2.

Discrete time signum function is defined as:

$$sgn(n) = \begin{cases} 1, & \text{if } n > 0 \\ 0, & \text{if } n = 0 \\ -1, & \text{if } n < 0 \end{cases}$$

Similarly the graphical representation of discrete time signum function is given in Fig 4.3.

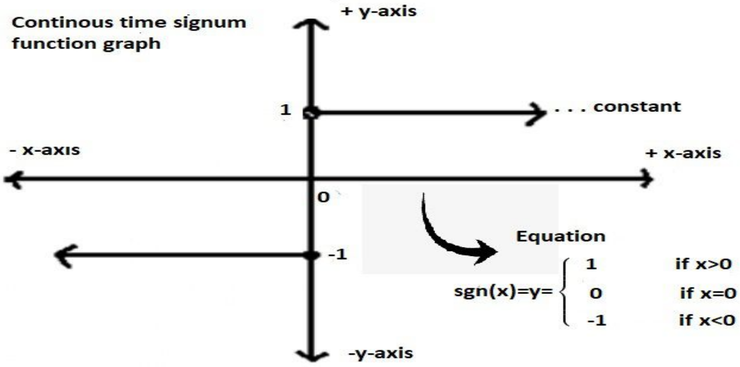

FIGURE 4.2: Graph of continuous time signum function.

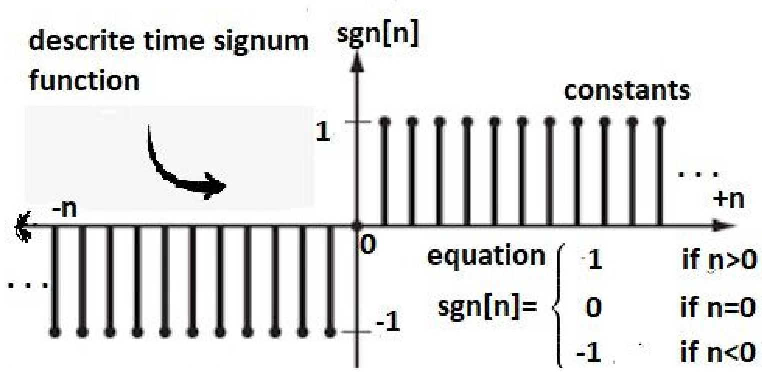

FIGURE 4.3: Graph of discrete time signum function.

Signum function satisfies three conditions which is used in design of sliding mode controller. This function performs on off mechanism in control strategy while satisfying predefine conditions. Signum function is widely used in control system while designing different controllers.

4.6 Methodology in Mathematical Form

1. Final linear model of three phase voltage source PWM inverter is given [8] by:

$$\begin{aligned} \ddot{x_1} &= v_1 \\ \ddot{x_2} &= v_2 \end{aligned} \tag{4.1}$$

2. Taking first part of equation (4.1), the state space model is given as:

$$\begin{aligned} \dot{x_1} &= x_2 \\ \dot{x_2} &= v_1 \\ y_1 &= x_1 \end{aligned} \tag{4.2}$$

3. $y_1 = x_1$ is first output of the system and the value of x_1 must tends to x_{1d} which means y_1 tends to y_{1d} which is given as:

$$\begin{aligned} y_1 &= x_1 \\ y_1 &\rightarrow y_{1d} \\ x_1 &\rightarrow x_{1d} \end{aligned} \tag{4.3}$$

4. Errors are defined for first part of equation (4.1) will be:

$$\begin{aligned} e_1 &= x_1 - x_{1d} \\ e_2 &= x_2 - x_{2d} = x_2 \end{aligned} \tag{4.4}$$

5. The time derivative of errors are:

$$\begin{aligned} \dot{e_1} &= \dot{x_1} - \dot{x_{1d}} = x_2 = e_2 \\ \dot{e_2} &= \dot{x_2} - 0 = \dot{x_2} = v_1 \end{aligned} \tag{4.5}$$

This is the standard form of state space to design the control law. When errors tend to zero then the actual value tends to desired value.

6. State equations for (4.5) case will be:

$$\begin{aligned} \dot{e_1} &= e_2 = x_2 \\ \dot{e_2} &= v_1 \end{aligned} \tag{4.6}$$

7. The sliding surface for second order system having n=2, will be:

$$\begin{aligned} s_1 &= (1+D)^{n-1}x_1 \\ s_1 &= (1+D)^{2-1}x_1 \\ s_1 &= x_1 + \dot{x_1} = x_1 + x_2 \end{aligned} \tag{4.7}$$

8. Laypanov/energy function and its derivative is given as:

$$\begin{aligned} V &= \frac{1}{2}s_1^2 \\ \dot{V} &= s_1\dot{s_1} = (x_1 + x_2)(\dot{x_1} + \dot{x_2}) \\ \dot{V} &= (x_1 + x_2)(\dot{x_1} + \dot{x_2}) = (x_1 + x_2)(x_2 + v_1) \end{aligned} \tag{4.8}$$

9. Choose the control input v_1 in such a way that defined errors converge to zero. So the final control input for first case of equation (4.1) is given by:

$$v_1 = -x_2 - ksign(s_1) \tag{4.9}$$

Similarly for control input v_2 we have:

1. Taking second part of equation (4.1), that is $\ddot{x_2} = v_2$. The state space model to design v_2 is given by:

$$\begin{aligned} \dot{x_3} &= x_4 \\ \dot{x_4} &= v_2 \\ y_2 &= x_3 \end{aligned} \tag{4.10}$$

   x_3 is desired value of output in dq reference frame. The actual value must be regulated to desired value at output terminal. In this equation v_2 is the control law to have desired output x_3.

2. $y_2 = x_3$ is second output of the inverter model, x_3 must tends to x_{3d} which means y_2 tends to y_{2d}.

$$\begin{aligned} y_2 &= x_3 \\ y_2 &\rightarrow y_{2d} \\ x_3 &\rightarrow x_{3d} \end{aligned} \tag{4.11}$$

3. Errors for the second part of equation(4.1) are defined as:

$$\begin{aligned} e_3 &= x_3 - x_{3d} \\ e_4 &= x_4 - x_{4d} \\ x_{4d} &= 0 \end{aligned} \tag{4.12}$$

4. The time derivatives will be:

$$\begin{aligned} \dot{e_3} &= \dot{x_3} - \dot{x_{3d}} = \dot{x_3} = x_4 = e_4 \\ \dot{e_4} &= \dot{x_4} = v_2 \end{aligned} \tag{4.13}$$

5. The state equations for (4.13) are:

$$\begin{aligned} \dot{e_3} &= e_4 + x_4 \\ \dot{e_4} &= v_2 \end{aligned} \tag{4.14}$$

6. Sliding surface for n=2 is:

$$\begin{aligned} s_2 &= (1 + D)^{n-1} x_3 \\ s_2 &= (1 + D)^{2-1} x_3 \\ s_2 &= x_3 + \dot{x_3} = x_3 + x_4 \end{aligned} \tag{4.15}$$

Sliding surface is used in sliding mode controller design for stability analysis of different systems. In sliding surface design, order of state space equation is considered as design parameter. This surface is used in energy function to perform Laypunov stability criteria. All states from their initial conditions, converged to the sliding surface. This surface provides path towards zero.

7. Laypunov function is given for equation (4.15) as follows:

$$
\begin{aligned}
V &= \frac{1}{2}s_2^2 \\
\dot{V} &= s_2\dot{s_2} \\
\dot{V} &= (x_3 + x_4)(\dot{x_3} + \dot{x_4}) = (x_3 + x_4)(x_4 + v_2)
\end{aligned}
\tag{4.16}
$$

Finally the second control law is obtained which is:

$$v_2 = -x_4 - ksign(s_2) \tag{4.17}$$

Final controllers for original model [8] will be:

$$\begin{pmatrix} u_d \\ u_q \end{pmatrix} = M^{-1} \begin{pmatrix} v_1 - f_1 \\ v_2 - f_2 \end{pmatrix} \tag{4.18}$$

where M , f_1 and f_2 are defined as:

$$M = \begin{pmatrix} LgaL_f h_1(x) & LgbL_f h_1(x) \\ LgaL_f h_2(x) & LgbL_f h_2(x) \end{pmatrix},$$

$f_1 = L_f^2 h_1(x)$ and $f_2 = L_f^2 h_2(x)$.

4.7 Parameters Value

The control strategy needs three phase voltages, currents and components values. Basic formulas are required for calculations, which are given below.

4.7.1 Parameters Values for Star Connection

In this work it is considered that the balanced load is star connected with 120 mode of operation. The considered load is pure resistive in nature while other types of load(capacitive/inductive) can also be considered.

1. Relation between line voltage and phase voltage is given as:

$$V_L = (1.732)V_{ph} \tag{4.19}$$

2. Relation between line current and phase current is given as:

$$I_L = I_{ph} \tag{4.20}$$

4.7.2 Relations Among RMS Value, Peak Value,Peak to Peak and Average Values

3. Relation between V_{rms} and V_p is given as:

$$V_{rms} = (0.7071)V_p \tag{4.21}$$

4. Relation between V_{rms} and V_{p-p} is given as:

$$V_{rms} = (0.3535)V_{p-p} \tag{4.22}$$

5. Relation between V_{rms} and V_{avg} is given as:

$$V_{rms} = (1.11)V_{avg} \tag{4.23}$$

6. Parameters and components values are selected properly which are given as: Capacitor value is $C_f = 22\mu F$, inductor value is $L_f = 15mH$ and load resistance is 20Ω. The desired voltage at output terminal is $220V_{rms}$ which is equal to 311 V_p. The result can be evaluated by using different values of load. Output waveform of inverter is not pure sinusoidal without the output filter. Capacitor and inductor are the main parameters used in output filter to smooth the output waveform. Power values are calculated in term of voltage and current in dq reference frame. Both active and reactive powers are considered with proper values. The parameter values can be calculated directly in dq reference frame while using some basic values of original model.

4.8 Summary

In this chapter linear model of three phase voltage source PWM inverter is considered. Desired output voltage is obtained at output terminals while designing sliding mode controller in load variations or voltage drop condition. Controller is designed for linear model and modified it for non-linear/original model. The designed SMC controlled the output value at desire level in load change/ voltage drop condition effectively.

Chapter 5

Results and Assessments

Model predictive controller is designed by optimizing the cost function while sliding mode controller is designed by using laypanov stability criteria to get the desired output voltages. In this chapter the results of both controllers strategies are given and compared to examine the feasibility for real time applications. Sliding mode controller is considered an effective strategy to control the parameters and deals the regulation problems. Model predictive controller is also an emerging controller technique in power electronic devices which is also considered robust and regulation problems controller.

The following results are given on the bases of which it will be decided which one is more effective in real time applications. The comparison is made for an inverter which is a power electronic device.

5.1 Model Predictive Control

In this section the results obtained from model predictive controller design are given. The actual output of three phase voltage source inverter is successfully regulated at desired values. The desired values are in dq reference frame. Following graphs show the desired output values and the controllers needed to have proper regulation in case of model predictive controller (MPC).

5.1.1 Required Linear Controllers

v_1 and v_2 are the linear controllers to obtain the desire outputs V_{Ld} and V_{Lq} for linear model are given in Fig 5.1.

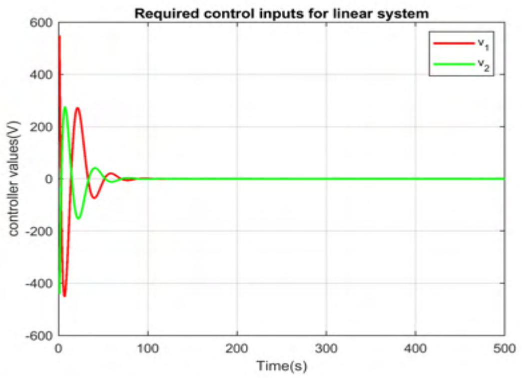

FIGURE 5.1: Linear controllers.

5.2 Required Non-linear Controllers

u_1 and u_2 are the non-linear controllers to obtain the desire outputs V_{Ld} and V_{Lq} for non-linear/original model are given in Fig 5.2.

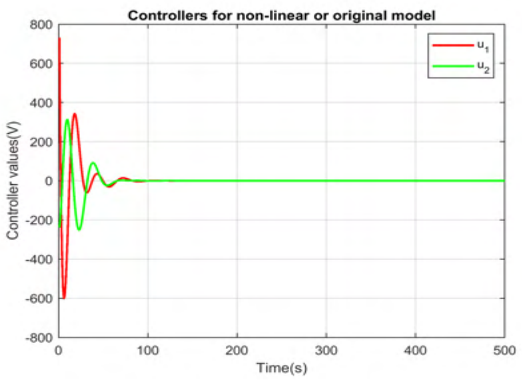

FIGURE 5.2: Non-linear controllers.

5.2.1 Desired Outputs Values in dq Reference Frame

Final outputs of original system are obtained in dq reference frame are $V_{Ld} = -333.3$ and $V_{Lq} = 190$ are given in Fig 5.3. This is the final result after the modification of linear control law.

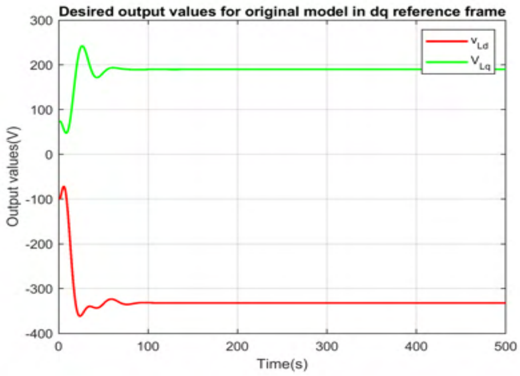

FIGURE 5.3: Desired output values.

5.3 Sliding Mode Control

In this section the results obtained from sliding mode controller design are given.

5.3.1 Required Linear Controllers

v_1 and v_2 are the linear controllers to obtain the desire outputs V_{Ld} and V_{Lq} for linear model are given in Fig 5.4.

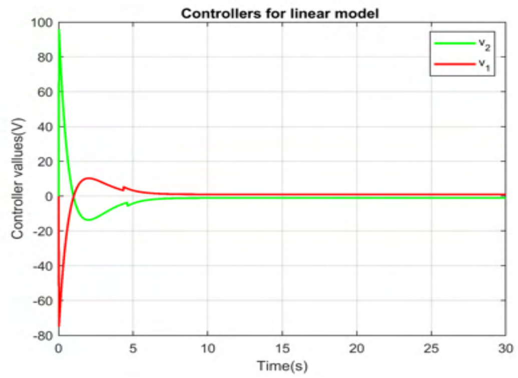

FIGURE 5.4: Linear controllers.

5.3.2 Required Non-linear Controllers

u_1 and u_2 are the non-linear controllers to obtain the desire outputs V_{Ld} and V_{Lq} for non-linear/original model are given in Fig 5.5.

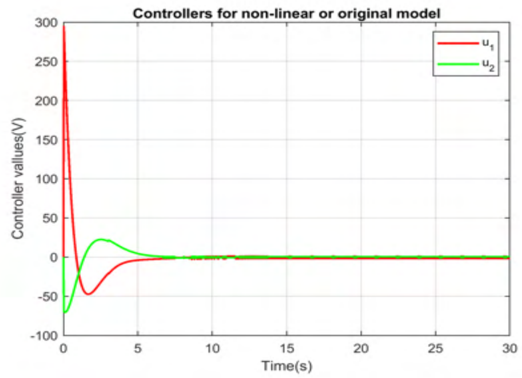

FIGURE 5.5: Non-linear controllers.

5.3.3 Behaviour of State Variables

State variables tend to zero showing the stability of system. When errors converge to zero then the actual values tend to desire values. The desire values are V_{Ld} and V_L are given in Fig 5.6.

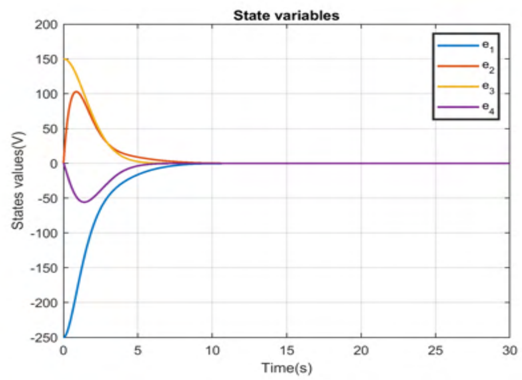

FIGURE 5.6: Errors converged to zero.

5.3.4 Desired Outputs Values in dq Reference Frame

Final outputs of original system are obtained in dq reference frame are $V_{Ld} = -333.3$ and $V_{Lq} = 190$ are given in Fig 5.7. These are the desired values in real and an imaginary form. These values are converted back into three phases to have proper switching pulses. Pulses from PWM generator are given to six switches in required sequence. The equivalent values of dq to a,b and c are the desired output values at output terminals in case of load variations.

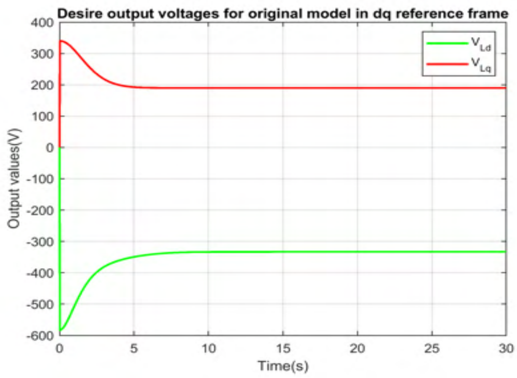

FIGURE 5.7: Desired output values.

Loads are considered to be connected in star.

5.4 abc to dq and dq to abc Voltages Transformations

Three phase alternating voltages are converted into dq reference frame to design the controllers. Controllers give better response to constant values. The dq values are converted back to abc for proper switching.

5.4.1 Three Phase Voltages abc

abc are the three phase voltages having $311V_p$. These voltages are converted into dq to design the controllers are given in Fig 5.8. $220V_{rms}$ is generally used to operate AC devices, therefore this value is considered as desired value. The given graph shows $220V_{rms}$ and 311_{p-p} values which are the equivalent values of $V_{Ld} = -333.3$ and $V_{Lq} = 190$ in dq reference frame. a,b and c values are final terminal output voltages given to AC devices in case of varying load. In this work loads are considered to be connected in star for distribution purpose. The voltages a,b and c simultaneously operate three loads connected to each terminals. In case of load variation, the controller provides fix AC voltages at terminals while controlling the switches. Three phase inverter is one of the main device used in industries to provide three phases for specific loads.

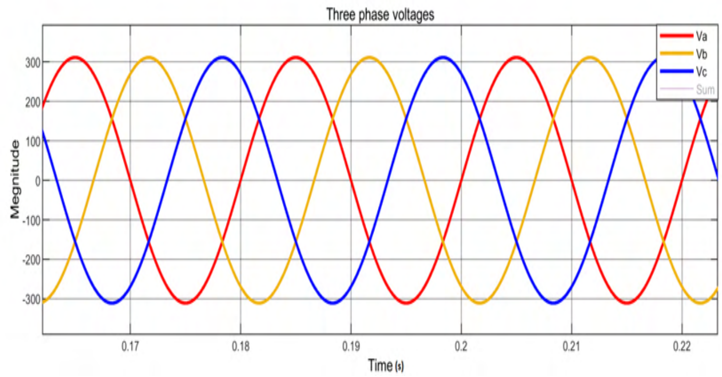

FIGURE 5.8: Three phase voltages abc.

5.4.2 dq Values From abc Voltages

Controllers show comfortability with constant values that's why the three phase voltages and currents are converted into dq constant values to design the controller are given in Fig 5.9.

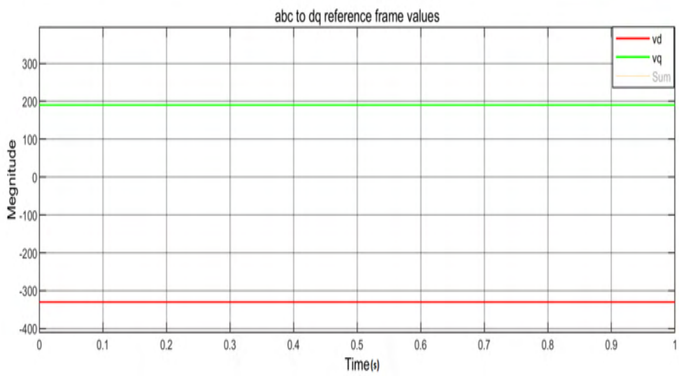

FIGURE 5.9: dq reference voltage values.

5.4.3 abc Voltages From dq Values

The dq values are converted back into abc again to operate the switches and the output three phases are utilized to run the devices and loads are given in Fig 5.10. In given graph the equivalent values of dq can be observed. These are the final output values having $220V_{rms}/311V_{p-p}$. In general calculations the root mean square value is considered for voltage and current values. Power value is calculated in term of voltage and current as $P = V \times I$.

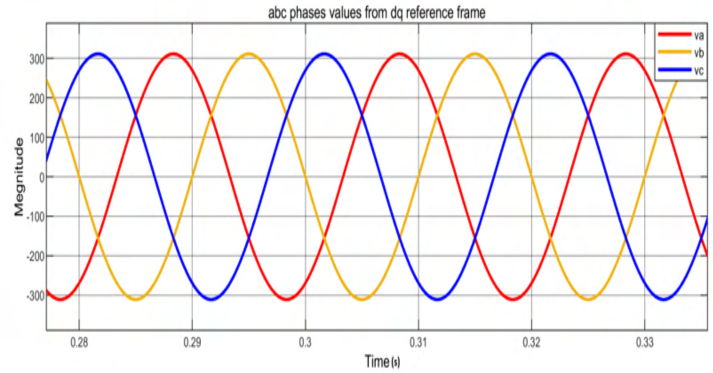

FIGURE 5.10: dq to abc voltage values.

5.5 Comparison Between MPC and SMC on The Basis of Above Results

Following are the comparisons between the two proposed strategies.

1. From the results, MPC shows good transient response than SMC as MPC takes 0.78 to 1.5 seconds to reach the steady state while SMC takes 2 to 4 seconds.
2. Sliding mode controller has chattering problem which is undesired for practical application in power electronic devices.
3. Sliding mode controller is high frequency on off type of controller, in practical case the device can be damaged at high frequency switching.
4. Sliding mode controller has more settling time than model predictive controller.
5. Both controller strategies are cost effective than some other strategies like FPGA base controller.
6. Both controllers are more efficient in case of regulation problems.
7. MPC and SMC give pure sinusoidal output with fixed output frequency as compared to some conventional controllers. In power electronic devices, pure sinusoidal waveform is used for proper working.

8. MPC has big a calculations to handle which is the only undesired in practical applications but due to advancement in digital microprocessors the problem has minimized.

9. MPC is more preferable than SMC because of having no chattering problem and good transient response with constraints.

10. MPC explicitly handles the system constraints.

11. MPC has straightforward formulation on the bases of well understood concepts.

12. MPC uses well understood tuning parameters.

13. MPC has development time which is much shorter than for completing advanced control methods.

14. MPC is easier to maintain.

15. MPC does not require complete redesign in case of changing model or specs.

The comparison shows, model predictive controller has better performance than sliding mode controller.

Chapter 6

Conclusion and Future Work

Conclusion

The error regulation between reference voltage and actual voltage is done with two controller strategies. At first, the three phase voltages are converted into dq reference frame and then error were defined. In this work the terminal voltages are regulated at desire values. Both controllers work properly in given conditions. MPC shows more attractive behaviours like good transient response, addition of constraints and chattering free design than SMC in real time applications. Sliding mode controller has a chattering problem while model predictive controller has big calculations to handle. Both problems are acceptable for real time applications. In this work the switching technique used for inverter model is PWM, which gives low harmonics.

To compare the overall performance between model predictive controller and sliding mode controller, this work presents voltage control strategies in three phase voltage source PWM inverter. Overall performance is compared between MPC and SMC. The results also compared with previous works with respect to overall performance like transient response,cost,efficiency,constraints and noise/chattering. The given results describe the performance and effectiveness of the proposed work. In next step the future work is discussed in detail for further research work. The proposed research work is highly effective for power electronic devices.

Future Work

1. Sliding mode controller has chattering phenomenon therefore an improved strategy is needed to deal with this problem. Chattering can be minimized by using integral sliding mode or other methods.

2. In model predictive controller strategy, it has a big calculation so by enhancing calculation technique the performance can be improved further.

3. The future work in MPC strategy is the addition of input, output and state constraints to remove the undesired peaks in proposed work.

4. MPC and SMC strategies used in this research work can also apply to other power electronic devices like converter, motor and generator to control/regulate the parameters.

Bibliography

[1] E. L. Owen, "History [origin of the inverter]," *IEEE Industry Applications Magazine*, vol. 2, no. 1, pp. 64–66, 1996.

[2] A. Sarkar, *Modeling and control of a three phase voltage source inverter with an LCL filter.* Arizona State University, 2015.

[3] Y. Chen and K. Smedley, "Three-phase boost-type grid-connected inverter," *IEEE Transactions on Power Electronics*, vol. 23, no. 5, pp. 2301–2309, 2008.

[4] P. Channegowda and V. John, "Filter optimization for grid interactive voltage source inverters," *IEEE Transactions on Industrial Electronics*, vol. 57, no. 12, pp. 4106–4114, 2010.

[5] V. Pires, J. Martins, D. Foito, H. Chen *et al.*, "A grid connected photovoltaic system with a multilevel inverter and a le-blanc transformer," *International Journal of Renewable Energy Research (IJRER)*, vol. 2, no. 1, pp. 84–91, 2012.

[6] D. Energy, "Eu energy trends to 2030–update 2009," *European Commission, Directorate-General for Energy: Brussels*, 2010.

[7] I. Colak and E. Kabalci, "Developing a novel sinusoidal pulse width modulation (spwm) technique to eliminate side band harmonics," *International Journal of Electrical Power & Energy Systems*, vol. 44, no. 1, pp. 861–871, 2013.

[8] G. G. Rigatos, *Nonlinear control and filtering using differential flatness approaches: applications to electromechanical systems.* Springer, 2015, vol. 25.

[9] B. Vaikundaselvan, N. Prakash, and S. Sivaraju, "Pwm strategy for three phase voltage source inverter with minimum harmonic distortion."

[10] M. S. Mahmoud, N. M. Alyazidi, and M. I. Abouheaf, "Adaptive intelligent techniques for microgrid control systems: A survey," *International Journal of Electrical Power & Energy Systems*, vol. 90, pp. 292–305, 2017.

[11] I.-S. Kim, "Robust maximum power point tracker using sliding mode controller for the three-phase grid-connected photovoltaic system," *Solar energy*, vol. 81, no. 3, pp. 405–414, 2007.

[12] L. Wang, *Model predictive control system design and implementation using MATLAB®*. Springer Science & Business Media, 2009.

[13] R. J. Devi and S. S. Kadam, "Phase locked loop for synchronization of inverter with electrical grid: A survey," *International Journal of Engineering Research & Technology (IJERT)*, vol. 4, no. 2, pp. 352–358, 2015.

[14] A. Fragaki and T. Markvart, "Stand-alone pv system design: results using a new sizing approach," *Renewable Energy*, vol. 33, no. 1, pp. 162–167, 2008.

[15] A. K. Sahu and K. Sudhakar, "Effect of uv exposure on bimodal hdpe floats for floating solar application," *Journal of materials research and technology*, vol. 8, no. 1, pp. 147–156, 2019.

[16] M. Rashid, *Power electronics handbook: devices, circuits, and applications, ser.* Academic Press. Elsevier, 2010.

[17] M. DeCastro, S. Salvador, M. Gómez-Gesteira, X. Costoya, D. Carvalho, F. Sanz-Larruga, and L. Gimeno, "Europe, china and the united states: Three different approaches to the development of offshore wind energy," *Renewable and Sustainable Energy Reviews*, vol. 109, pp. 55–70, 2019.

[18] X. Sun, Z. Li, X. Wang, and C. Li, "Technology development of electric vehicles: A review," *Energies*, vol. 13, no. 1, p. 90, 2019.

[19] A. Veldhuis and A. H. Reinders, “Reviewing the potential and cost-effectiveness of grid-connected solar pv in indonesia on a provincial level,” *Renewable and Sustainable Energy Reviews*, vol. 27, pp. 315–324, 2013.

[20] I. Marti, G. Kariniotakis, P. Pinson, I. Sanchez, T. Nielsen, H. Madsen, G. Giebel, J. Usaola, A. M. Palomares, R. Brownsword *et al.*, “Evaluation of advanced wind power forecasting models–results of the anemos project,” in *Proc. of the European Wind Energy Conference*, 2006, pp. 2–2.

[21] F. Sevilmiş and H. Karaca, “Simulation and analysis of svpwm based vsi for wind energy systems,” in *Proceedings of the 2014 6th International Conference on Electronics, Computers and Artificial Intelligence (ECAI)*. IEEE, 2014, pp. 73–78.

[22] B. Sujatha and D. S. Meghana, “Simulation and performance of induction motor drive using svpwm technique,” 2017.

[23] M. A. U. Rasool, M. M. Khan, Z. Ahmed, and M. A. Saeed, “Analysis of an h infinity robust control for a three-phase voltage source inverter,” *Inventions*, vol. 4, no. 1, p. 18, 2019.

[24] T. Jorge, J. M. R. Scarpetta, and F. Andrade, “Lqr and h-infinity control of voltage source inverters for ac microgrids,” in *2020 22nd European Conference on Power Electronics and Applications (EPE’20 ECCE Europe)*. IEEE, 2020, pp. P–1.

[25] S. Vashishtha and R. KR, “Modified digital space vector pulse width modulation realization on low-cost fpga platform with optimization for 3-phase voltage source inverter.” *International Journal of Electrical & Computer Engineering (2088-8708)*, vol. 11, no. 4, 2021.

[26] R. Foley, R. Kavanagh, W. Marnane, and M. Egan, “Multiphase digital pulsewidth modulator,” *IEEE Transactions on Power Electronics*, vol. 21, no. 3, pp. 842–846, 2006.

[27] J. Alvarez, O. Lopez, F. D. Freijedo, and J. Doval-Gandoy, “Digital parameterizable vhdl module for multilevel multiphase space vector pwm,” *IEEE Transactions on Industrial Electronics*, vol. 58, no. 9, pp. 3946–3957, 2010.

[28] F. M. Serra, L. M. Fernández, O. D. Montoya, W. Gil-González, and J. C. Hernández, “Nonlinear voltage control for three-phase dc-ac converters in hybrid systems: An application of the pi-pbc method,” *Electronics*, vol. 9, no. 5, p. 847, 2020.

[29] O. Ellabban, H. Abu-Rub, and F. Blaabjerg, “Renewable energy resources: Current status, future prospects and their enabling technology,” *Renewable and sustainable energy reviews*, vol. 39, pp. 748–764, 2014.

[30] M. Bueno-Lopez and S. G. Lemos, “Electrification in non-interconnected areas: Towards a new vision of rurality in colombia,” *IEEE Technology and Society Magazine*, vol. 36, no. 4, pp. 73–79, 2017.

[31] O. D. Montoya, A. Garcés, and F. M. Serra, “Ders integration in microgrids using vscs via proportional feedback linearization control: Supercapacitors and distributed generators,” *Journal of Energy Storage*, vol. 16, pp. 250–258, 2018.

[32] P. Zou, Q. Chen, Q. Xia, G. He, and C. Kang, “Evaluating the contribution of energy storages to support large-scale renewable generation in joint energy and ancillary service markets,” *IEEE Transactions on Sustainable Energy*, vol. 7, no. 2, pp. 808–818, 2015.

[33] A. A. Shah, X. Han, H. Armghan, and A. A. Almani, “A nonlinear integral backstepping controller to regulate the voltage and frequency of an islanded microgrid inverter,” *Electronics*, vol. 10, no. 6, p. 660, 2021.

[34] D. E. Olivares, A. Mehrizi-Sani, A. H. Etemadi, C. A. Cañizares, R. Iravani, M. Kazerani, A. H. Hajimiragha, O. Gomis-Bellmunt, M. Saeedifard, R. Palma-Behnke *et al.*, “Trends in microgrid control,” *IEEE Transactions on smart grid*, vol. 5, no. 4, pp. 1905–1919, 2014.

[35] A. N. Abdullah and M. H. Ali, "Direct torque control of im using pid controller," *International Journal of Electrical and Computer Engineering*, vol. 10, no. 1, p. 617, 2020.

[36] S. Tahir, J. Wang, M. H. Baloch, and G. S. Kaloi, "Digital control techniques based on voltage source inverters in renewable energy applications: A review," *Electronics*, vol. 7, no. 2, p. 18, 2018.

[37] H. Hartono, R. Sudjoko, and P. Iswahyudi, "Speed control of three phase induction motor using universal bridge and pid controller," in *Journal of Physics: Conference Series*, vol. 1381, no. 1. IOP Publishing, 2019, p. 012053.

[38] I. Colak, E. Kabalci, and R. Bayindir, "Review of multilevel voltage source inverter topologies and control schemes," *Energy conversion and management*, vol. 52, no. 2, pp. 1114–1128, 2011.

[39] P. N. BVR, "Three phase voltage source inverters with grid connected industrial application," *International Journal of Engineering & Technology*, vol. 7, no. 4, p. 18, 2018.

[40] I. S. Mohamed, S. Rovetta, T. D. Do, T. Dragicević, and A. A. Z. Diab, "A neural-network-based model predictive control of three-phase inverter with an output *lc* filter," *IEEE Access*, vol. 7, pp. 124 737–124 749, 2019.

[41] A. Pilloni, A. Pisano, and E. Usai, "Robust finite-time frequency and voltage restoration of inverter-based microgrids via sliding-mode cooperative control," *IEEE Transactions on Industrial Electronics*, vol. 65, no. 1, pp. 907–917, 2017.

[42] A. Houari, H. Renaudineau, J.-P. Martin, S. Pierfederici, and F. Meibody-Tabar, "Flatness-based control of three-phase inverter with output *lc* filter," *IEEE Transactions on Industrial Electronics*, vol. 59, no. 7, pp. 2890–2897, 2011.

[43] G. G. Rigatos, "Modelling and control for intelligent industrial systems," *adaptive algorithms in robotics and industrial engineering*, 2011.

[44] M. Kamel, T. Stastny, K. Alexis, and R. Siegwart, "Model predictive control for trajectory tracking of unmanned aerial vehicles using robot operating system," in *Robot operating system (ROS).* Springer, 2017, pp. 3–39.

[45] L. Singh, "Autonomous missile avoidance using nonlinear model predictive control," in *AIAA guidance, navigation, and control conference and exhibit*, 2004, p. 4910.

[46] J. Rodriguez, M. P. Kazmierkowski, J. R. Espinoza, P. Zanchetta, H. Abu-Rub, H. A. Young, and C. A. Rojas, "State of the art of finite control set model predictive control in power electronics," *IEEE Transactions on Industrial Informatics*, vol. 9, no. 2, pp. 1003–1016, 2012.

[47] M. U. Jan, A. Xin, H. U. Rehman, M. A. Abdelbaky, S. Iqbal, and M. Aurangzeb, "Frequency regulation of an isolated microgrid with electric vehicles and energy storage system integration using adaptive and model predictive controllers," *IEEE Access*, vol. 9, pp. 14 958–14 970, 2021.

[48] H. H. Choi, "Robust stabilization of uncertain fuzzy-time-delay systems using sliding-mode-control approach," *IEEE Transactions on Fuzzy Systems*, vol. 18, no. 5, pp. 979–984, 2010.

[49] A. Kumar, M. N. Anwar, and S. Kumar, "Sliding mode controller design for frequency regulation in an interconnected power system," *Protection and Control of Modern Power Systems*, vol. 6, no. 1, pp. 1–12, 2021.

[50] F. Ren, C. Lin, and X. Yin, "Design a congestion controller based on sliding mode variable structure control," *Computer communications*, vol. 28, no. 9, pp. 1050–1061, 2005.

[51] W. Perruquetti and J. P. Barbot, *Sliding mode control in engineering.* Marcel Dekker New York, 2002, vol. 11.