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COMPARATIVE ANALYSIS BETWEEN MODEL PREDICTIVE CONTROL AND SPACE VECTOR MODULATION ON NEUTRAL POINT CLAMPED INVERTER

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Declaration

This thesis is a representation of our original research work and experiments. Contributions of other researchers are involved. Although every effort has been made to justify it with due respect, providing reference to the literature, and acknowledgement of collaborative research and experiments.
This work was done under the supervision of Dr. Roky Baidya, Assistant Professor of Electrical and Electronic Engineering department at Chittagong

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ABSTRACT

The objective of our thesis is to apply different parameters of load and control techniques (MPC, SVM) on Neutral Point Clamped Inverter for induction motor and observed the response of the inverter for each of them. In case of MPC, an arbitrarily chosen constant will be selected for the optimization of cost function instead of going through any algorithmic approach. On the other hand, a simplified algorithm will be followed for allocating reference vector in different region of different vectors for SVM to minimize calculation complexities

Contents

Chapter 1

INTRODUCTION

1.1 LITERATURE REVIEW

The ever increasing usage of power inverters is growing rapidly with the evolution of industrial civilization [1]. The smooth function necessity of these power electronic instruments comes with the discussion as well. Power electronics is basically based on the study of control and conversion of electrical power. And power inverter makes it one of the kind to define the conversion of Direct Current to Alternating Current [2]. Use of power converters covers manufacturing and mining applications such as conveyors, pumps, speed drives, electric vehicles, renewable energy conversion systems etc [3].

Multilevel inverters are much more attractive for the application of high power and high voltage applications [4]. Neutral-point-clamped (NPC) inverters are the most commonly employed topology of high-power multilevel inverters which can be extended to several megawatts. The control operation of this kind of inverter describes the basic process and the most common modulation and control techniques introduced to date in a very simple way [5]. The loss distribution in semiconductors is given special consideration and an active NPC inverter is introduced to resolvethe problem [6].

The best of way of getting the desired output waveform in the most expected way is to follow better control procedure [7]. Model Predictive Control (MPC) is one of the top contenders to top the list of the procedures out there. It is an automated process control system bound for the improvement of the automation technology [8]. MPC's main advantage is that it enables utilization of the present timeslot while maintaining future timeslots in mind. This is accomplished by maximizing a finite time frame, but only by applying the current time period and then constantly modifying it [9]. MPC predicts the system response for every possible switching states based on the present outcomes and the lowest cost function is applied during the next sampling interval. [10]

Similarly, Space Vector Modulation (SVM) is also a control procedure for multilevel inverters. It uses the algorithm for the control of pulse width modulation for the creation of alternating current [6]. Advantages like good utilization of dc bus voltage reduced switching frequency and low current ripple also makes it an interesting control procedure to follow.

1.2 MOTIVATION

Producing delicate result is the main inspiration that drives any kind of research work [11]. As MPC & SVM both have the compatibility to generate a better control technique, they can be applied on NPC for a better outcome of current and voltage tracking and creation of alternating current waveform [12]. These things have led us to be inspired on the continuation of research on this and produce a solid ground to build a comparison between the above mentioned techniques.

1.3 OBJECTIVES

The goal of our work is to precisely control the output of NPC. As MPC & SVM are both chosen to apply on the inverter, it's become the first and foremost duty to thoroughly gather knowledge about the algorithms [13]. This whole process is the summation of various correlated works which are processed in a sequential way.

The main objectives are listed as follows:

1. Control the three phase AC current and voltage of neutral point clamped inverter by developing a system model through model predictive control (MPC) algorithm [14]. The most suitable switching states will be produced for each phase.

2. Track the output current and voltage with respect to reference and generate AC voltage as smooth as possible. MATLAB will be used for the model simulation procedure.

3. Control the three phase AC current and voltage of neutral point clamped inverter by building a system model through space vector modulation (SVM) algorithm and track the output current and voltage with respect to reference as delicately as possible.

4. Calculation of switching frequency and observation of the effect of high/low switching frequency on high power uses and the amount of total harmonic distortion (THD).

1.4 THESIS OVERVIEW

The best of method for getting the ideal output waveform in the most expected manner is to follow a better control strategy. Model Predictive Control (MPC) is one of the top contenders to top the rundown of the methodology out there [15]. It is a computerized procedure control framework destined for the improvement of the computerization innovation. MPC's principle advantage is that it empowers the use of the present timeslot while keeping up future timeslots as a primary concern. This is practiced by expanding a limited time span, however just by applying the present timespan and afterward continually adjusting it. MPC predicts the framework reaction for each conceivable exchanging states dependent on the present results and the most minimal cost work is applied during the following examining interim [16].

Thus, Space Vector Modulation (SVM) is additionally a control technique for staggered inverters. It utilizes the calculation for the control of the pulse width balance for the production of rotating current [17]. Points of interest like great usage of dc transport voltage, diminished exchanging recurrence and low current wave additionally make it an intriguing control technique to follow [].

Chapter 2

INVERTERS

An inverter is an electronic device which basically converts direct current/voltage to alternating voltage/current. Power inverters are primarily used in electrical power applications where high currents and voltages are present circuits that perform the same function for electronic signals, which usually have very low currents and voltages, are called oscillators. Circuits that perform the opposite function, converting AC to DC, are called rectifiers. There are different types of inverters based on the shape of the switchingwaveform. These have varying circuit configurations, efficiency, advantages and disadvantages. An inverter provides an ac voltage from dc power sources and is useful in power electronics and electrical equipment rated at the ac mains voltage. In addition, they are widely used in the switched mode power supplies inverting stages. The circuits are classified according to the switching technology and switch type, the waveform, the frequency and output waveform.

2.1 CLASSIFICATION OF INVERTERS

Though there are various types of inverters, basically all can be dividedinto two major types, especially the self-commutated ones. These two typesare known as voltage source inverters and current source inverters. The different kinds of inverters create a variation in the field of power electronics. With the help of these different kinds of inverters, a better control technique is on the rise every day and more to follow. A short description is given below:

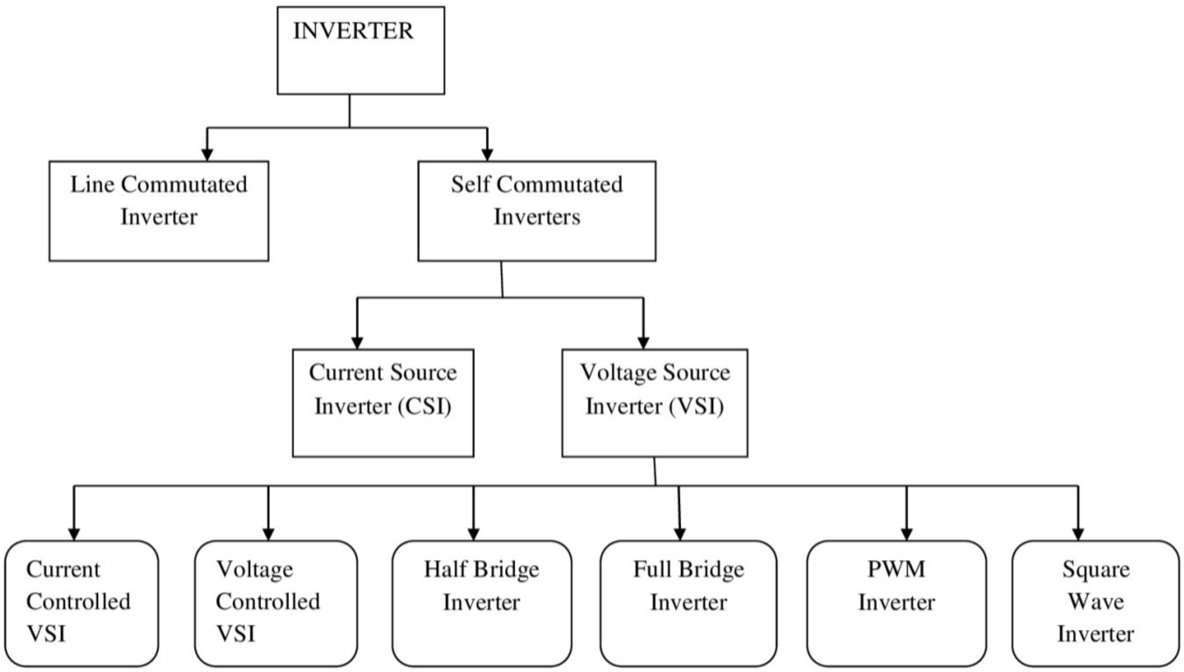

Figure 2.1: Classification of Inverters

2.2 SELF COMMUTATED INVERTER

Self commutated inverter is the very type of inverter in which the ways of commutation is

included within the inverter itself. Such as, either voltagesource inverter or current source inverter, both includes two types of selfcommutated inverter. A brief discussion is given below-

2.2.1 VOLTAGE SOURCE INVERTER(VSI)

The characteristics of this types are easily measurable from the name, a voltage
source is started as input and capacitors are used to give an output ascapacitor restores charges and releases when necessary. VSI is used commonlyas a short form. VSI can also be grouped into two level and multilevelinverter.

1) Two Level VSI : Two voltage levels are present in this type of inverter.

2) Multilevel VSI : More than two voltage levels are present. These are

more precise and complicated.

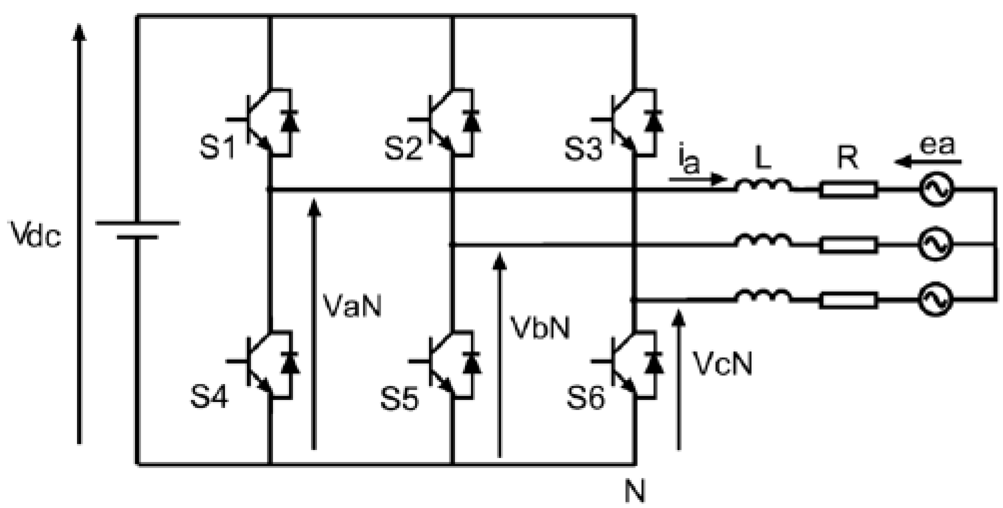

Figure2.2: A Voltage Source Inverter Circuit Diagram

2.2.2 CURRENT SOURCE INVERTER (CSI)

Current source inverters, also known as CSI uses a current source as an input.VSI uses capacitors for steady output, CSI uses inductive energy for the restoring. That is, they use inductors in their DC link to store DC energy and regulate current ripple between the converter and the inverter. Moreover, VSI uses capacitive storage, with capacitors in their DC link, which both stores and smooths the DC link voltage of the inverter.

As a matter of fact, both types of inverters are used, VSI is chosen due to its more efficiency, reliability and less complication. For controlling the motor drives, VSI is the first choice. CSI is also used but less good in the comparison.

2.3 LINE COMMUTATED INVERTER

Substitution can be defined as the turning of a thyristor switch either normally or by compelling (physically), different kinds of switches may likewise incorporate. As it were, we can accept normal recompense as line compensation. An inverter that is attached to a force matrix or line and in which the recompense of intensity (transformation from DC to AC) is constrained by the electrical cable, is known as line commutated or normal commutated inverter. Not at all like self commutated inverter, the methods for replacement is excluded inside the inverter itself. It exclusively relies upon the electrical cable.

2.4 APPLICATION OF INVERTERS

Inverters are used for a variety of applications that range from small motorized car adapters to household or office applications, and large grid systems.

Some are given below-

1. Uninterrupted power supplies
2. Stands as standalone inverters
3. In solar power systems
4. Building block of a switched mode power supply
5. Centrifugal pumps.
6. Mixers.
7. Conveyors.
8. Metering pumps.

2.5 KEY TERMS OF INVERTER

An inverter works by changing over force from DC to AC. To fulfill this process different kinds of switches are utilized and exchanging states are given. The entire area of exchanging will be increasingly reasonable if some key terms are talked about previously. Here, a concise outline is given on substitution exchanging recurrence, symphonious twisting and so on.

2.5.0.1 SWITCHING FREQUENCY

The exchanging recurrence in an inverter or in a converter is the rate at which the exchanging gadget like thyristor/IGBT is turned on and off. Common place frequencies may run from a couple of KHz to a couple of megahertz (20 KHertz-2 MHeartz). Related parts as model, inductors, transformers, resistors, capacitors and so on mass part's size can be limited by expanding exchanging recurrence. Additionally the improvement can be utilized so as to diminish space necessities on the board and housings.

2.5.0.2 EFFECTS OF SWITCHING FREQUENCY

In spite of the fact that high exchanging recurrence diminishes gadget size, it prompts high distortion in the outcome. The exchanging recurrence legitimately affects the force scattering in exchanging components, for example, the diode, transistors and thyristor, the capacitive and inductive parasitic components. Additionally the electromagnetic obstruction (EMI) can likewise take place[18]. This is a significant issue to manage. As interest for higher force densities has expanded, the frequencies have likewise expanded, yet so do the related misfortunes, for example, the exchanging misfortunes that happen each time the gadget turns on. These misfortunes in this way put a limit on the commonsense most extreme exchanging recurrence. So as to get wanted smooth yield a medium degree of exchanging recurrence is recommended. More or less, we can say that exchanging recurrence of a force electronic converter is the rate at which the exchanging gadget (commonly IGBTs, MOS-FETs) is turned on and of. A wide scope of exchanging frequencies is utilized in converter circuits.

2.5.1 SWITCHING LOSS

The higher the exchanging recurrence, the more noteworthy the occasions the switch changes state every second. This causes power misfortune each time state is changed.It happens at the hour of both turn-on and turn-off condition of thyristors or then again some other switches. The lesser the state change of switches, in another word number of recompense, the lesser the exchanging misfortunes. At the point when a SCR turned on, an entryway heartbeat ought to be given over the holding current to turn it on, to turn it of, again the beat is decreased under the holding value[19]. Subsequently each procedure devours power. Additional turning on-off implies more force utilization. This loss of intensity from the source is a matter of thought. Since it diminishes the general efficiency. At long last we can say that to increase a higher efficiency, low exchanging misfortune is required.

2.5.2 COMMUTATION

Replacement can be defined as turning of a switch (essentially thyristor) with manual or characteristic methods. It draws certain measure of intensity on each exchanging state changing procedure and if the quantity of switches or states are high, the misfortune can be significant. A concise classification of recompense is given beneath

2.5.2.1 NATURAL COMMUTATION

Normal compensation implies a switch, for the most part, thyristor can be closed down normally. Right now, thyristor is turned off because of regular current getting zero and voltage inversion after each half cycle.

2.5.2.2 FORCED COMMUTATION

Constrained compensation is something contrary to normal substitution. This strategy is applied to the thyristor to close it down physically. The current gave is decreased to zero, subsequently turning switch. Outside circuits can be given known as commutating parts.

2.5.3 TOTAL HARMONIC DISTORTION

All out symphonious contortion, normally known as THD, is the apportion between the summation of all recurrence part to the key recurrence part of intensity. THD essentially announces how a lot of symphonious contortion is available in the output. The more the THD, the more twisting is available what's more, non-smooth yield produces. The twisting of a waveform comparative with an unadulterated sine wave can be estimated either by utilizing a THD analyzer to break down the yield wave into its constituent sounds and taking note of the plentifulness of every comparative with the major; or by counterbalancing the central with a step later and estimating the staying signal, which will be complete total. A defining condition can be given presenting complete consonant twisting.

$$THD_f = \sqrt{\frac{V_2^2 + V_3^2 + V_4^2 + \dots}{V_1}}$$

Here V_n is the RMS voltage of the nth symphonious and n = 1 is the fundamental recurrence segment.

2.5.3.1 APPLICATION

THD is significant in a few kinds of frameworks, including power frameworks, where a low THD implies higher force factor, lower top flows, and higher efficiency, sound frameworks, where low THD implies that the sound sign is a more dedicated generation of the first chronicle. Likewise we can take communication frameworks, where low THD implies less impedance with different gadgets around it and higher transmitting of intensity for the sign of intrigue. Therefore a low THD is wanted from any framework.

CHAPTER 3

Chapter 3

NEUTRAL POINT CLAMPED INVERTER (NPC):

Three level neutral-point clamped inverter or shortly known as NPC inverter is widely used due to its high power medium voltage conversion for industrial purpose. The high power applications can be upto several megawatts. For high-power applications, the NPC topology has been adopted as it can achieve better harmonic reduction than conventional two-level source voltage inverters and the related control strategies help minimize losses of semiconductors.

3.1 WORKING PRINCIPLE:

A ready made circuit model is given below:

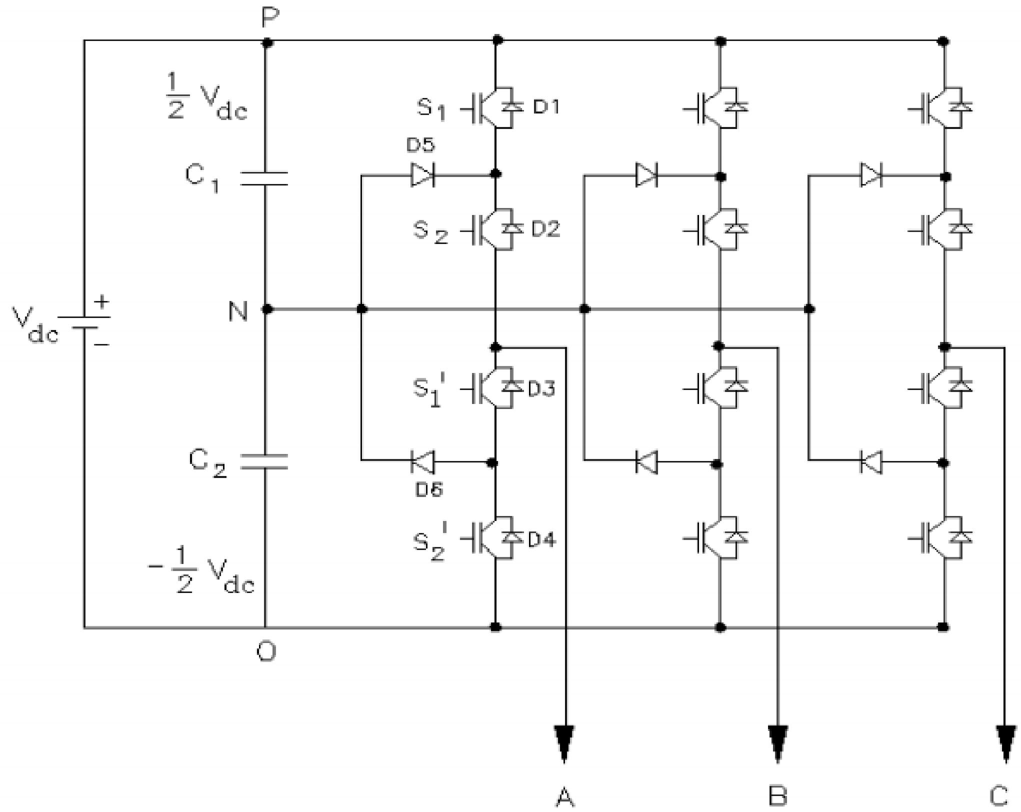

Figure 3.1: Circuit diagram of Neutral Point Clamped Inverter

NPC type Multilevel inverters play a vital role in power electronics and are commonly used in various industrial and commercial applications as they have low electromagnetic interference and significantly high performance. NPC Multilevel inverters with less noise have become more favorite over the years in high-power applications with the assurance of less disturbances and the contingency to operate at lower switching frequencies than typical two-level inverters.

Here, we can see a neutral point between two capacitor. Those are DClink capacitors with equal value and are used to divide the input voltage intoto equal sets like V_{dc} =2 at each portion. Total 12 switches are provided withfour each in a leg. The load is an R-L load and the switching states are 27 in total for three level inverter.

Switches on	Switches off	Output Voltage
$Q_{1A},\ Q_{2A}$	$Q_{3A},\ Q_{4A}$	$+V_{DC}$
$Q_{2A},\ Q_{3A}$	$Q_{1A},\ Q_{4A}$	0
$Q_{3A},\ Q_{4A}$	$Q_{1A},\ Q_{2A}$	$-V_{DC}$

The switches are switched on and off in sequential order provided by the control algorithm, producing a total of six voltage levels per 3 sets in positive and negative output direction. Thus the voltage of the DC is converted or reversed to voltage of 3 phase AC. The inverter is a voltage source inverter, since input is supplied with a voltage source.

Chapter 4

MODEL PREDICTIVE CONTROL

Model Predictive Control (MPC) is a control philosophy that processes an ideal control activity dependent on a model of a dynamical framework and its anticipated future development while fulfilling a lot of constraints.Model Predictive Control has been being utilized in compound plants and oil refineries since the 1980s. These days it is likewise being utilized in the Power system field and Power gadgets. Prescient control strategy plays a very significant guideline in numerous applications. Different sorts of prescient controllers are appeared in a later figure.

In direction based control, the controlled variable is compelled to follow a previously defined direction. In hysteresis control, the controlled variable is kept nearby the limits of the hysteresis zone. In miscreant control,the blunder is made indistinguishable from zero in the accompanying time frame to acquire the ideal actuation. In model prescient control, a cost work is utilized to be smaller than normalized, which is more effective than the others.

Model Predictive control utilizes a model of the framework for foreseeing what's to come conduct of the controlled factors. The controller utilizes the qualities to acquire the ideal actuator esteem, where the ideal qualities were beforehand defined. Prescient control has brisk transient response.

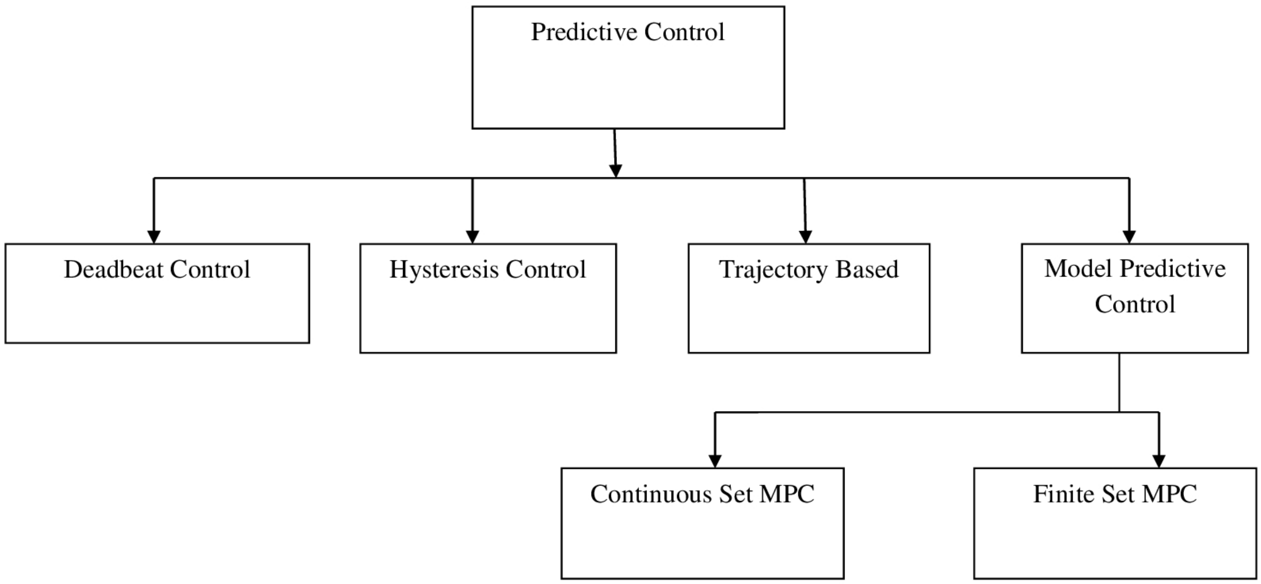

Figure 4.1: Types of predictive control methods used in power electronics

Both linear and non linear models can be controlled. One or beyond what one factors can be controlled. Limitations are forced on the factors while planning the controller. The deadbeat control and MPC with persistent control set need a modulator to create the necessary voltage. It brings about having fixed exchanging frequency. Different controllers create the exchanging signals for the converter which needn't bother with a modulator and will introduce a variable switching recurrence. MPC is more efficient and more astute than other controlling strategies on the grounds that regular controlling frameworks have some lackings like moderate reaction and no forecast capability.This paper depends on the utilization of finite set control for a Three-Phase Neutral Point-Clamped Inverter.

4.1 BASIC PRINCIPLES OF MODEL PREDICTIVE CONTROL

Among the propelled control systems, MPC is the most progressive than others like PID controllers. MPC has been effectively applied in modern applications. MPC has been effectively applied in the synthetic procedure industry since 1970s. The utilization of MPC has been begun in power gadgets for high force framework with low recurrence from 1980s.MPC controllers utilizes a numerical model of the framework to anticipate the

future conduct of the control factors until a predefined skyline in time, what's more, to choose the ideal activation by limiting a cost work.
The essential standards of MPC are as per the following:

1. To foresee the future practices of the factors for next inspecting time,a model of the framework is utilized.

2. A cost function is made which speaks to the attributes of the framework and gives a chance to improvement estimating the blunders.

3. By limiting the cost function ideal actuation is acquired.

A discrete-time model is used which is known as state space representation as follows:

$$\mathrm{x(k + 1) = Ax(k) + Bu(k)}$$
$$\mathrm{y(k) = Cx(k) + Du(k)}$$

The cost function shows the equation of the performance of the model of the system that includes references, controlled variables, switching elements etc:

$$g = fx\,(k)\,u\,(k)\ldots u\,(k+N)$$

To get the best output ,we need to minimize the cost function and this value is taken for a predefined horizon N and regarding other restrictions to the system.

$$u(k) = [10 \ldots .0]$$

4.2 ADVANTAGES AND DISADVANTAGES OF MPC

MPC is picked for some applications as opposed to different controllers. Since it has a few preferences:

1. It can anticipate future practices of the control factors. Present outcomes are seen to choose future information sources.
2. It is cost effective and vitality sparing. Force misfortune can be redressed by modification in the calculation.
3. It's idea is simple and straightforward.
4. It has improved transient reaction.
5. It is a closed loop control framework.
6. It can control multi-variables inside limitations.
7. It has a quick powerful reaction.

In spite of the fact that MPC has a few preferences ,it additionally has a few weaknesses as well.
1. Countless computations are to done than different controllers.

2. The model has direct influence on the nature of yield. To keep up the quality, a few estimations are expected to consider.

4.3 MODEL PREDICTIVE CONTROL IN POWER ELECTRONICS AND DRIVES

The utilization of MPC in power gadgets and drivers was presented in 1970s or on the other hand 80s[6]. It has been conceivable because of the improvement of the quick exchanging time of MPC and the accessibility of the quick miniaturized scale controllers from the last-decade. MPC incorporates a different controller and a few different usage have been proposed. Summed up prescient control (GPC),an alternative,provides arrangement of the streamlining issue scientifically for the straight framework with no imperatives, giving an unequivocal control law to be effectively actualized. For different sorts of intensity converters and drive applications, this control systems have been utilized. To execute MPC in a genuine framework, little league is considered for computations because of the quick inspecting time in MPC. A method called explicit MPC has been recommended which moves the advancement issue oine[23]. Explicit MPC has been utilized in different converters and inverters.

4.3.0.1 CONTROLLER DESIGN

To design a finite control set MPC for the control of a power converter, the steps below are followed:

1) To design a Model of the power converter identifying all possible switching states and its relation to the input or output voltages or currents.
2) To define a cost function that represents the desired behavior of the system.
3) To obtain discrete-time models to predict the future behavior of the control variables .

To model a converter, the basic element is the power switch, which may be an IGBT, a gate turn-off thyristor (GTO), a thyristor, or others. The simplest model is switches with two states: ON and OFF. So, the total number of the switching state elements of the converters are the different combinations of these two states for every switches.

If x is the level of voltages of converter and y is the number of converters, then the number of possible switching states N is

$$N = x^y$$

As example, for a three-phase two-level converter, possible switching states
N = $2^3 = 8$
For three-phase three level converter, possible switching states
N = $3^3 = 27$

In multilevel converter there may be very high number of switching states. There is also relationship between voltage levels and switching states. There may also produce same voltage vector for two different switching states. For example, in a three-phase two-level converter, seven different voltage vectors are generated by eight switching states with two switching states generating the zero vector.

In a three-phase three-level converter 27 switching states generate 19 different voltage vectors. In figure 4.2, the relation between switching states and voltage vectors is shown.

While developing model for the prediction, the controlled variables must be considered to get discrete-time model. It is also necessary to define the variables which are measured and which are not measured.For getting a discrete-time model ,we need to use some discretization method.
Here, Euler Forward method is used as it is simple for first-order system.

$$\frac{dx}{dt} = \frac{x\left(k+1\right) - x\left(k\right)}{T_s}$$

where T_s is the sampling time and x(k+1) indicates the future value. Although Euler method is good for first order equation, it is not suitable forhigher order equation.

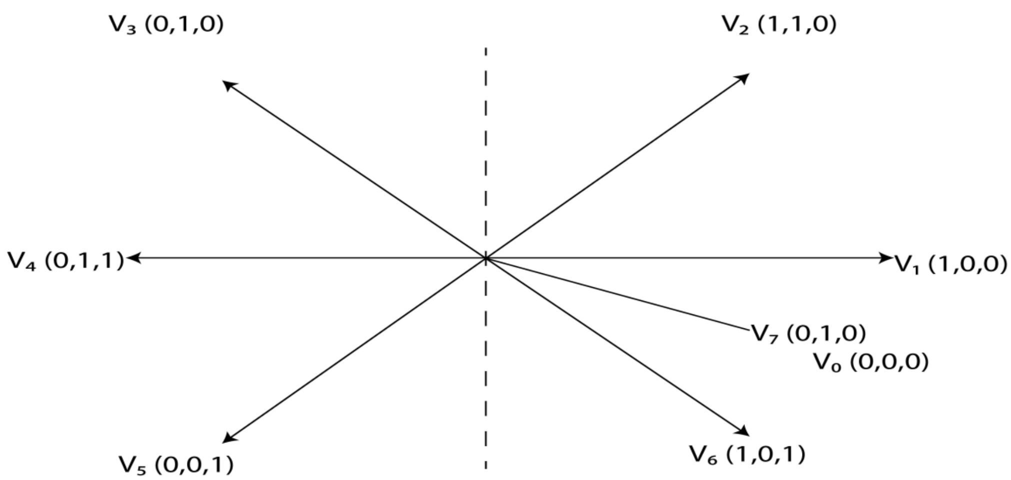

Figure 4.2: Generated voltage vectors by three-phase, two-level inverter

4.3.0.2 IMPLEMENTATION

While executing, model predictive control may confront some difficulties contingent upon the kind of stage used. The accompanying undertakings ought to be considered by the controller:

1) For all conceivable switching states, it must foresee the practices of the control variables.

2) To assess the cost function for each switching state.

3) To pick the switching state that reduces the cost function.

Depending on the intricacy of the control framework, all the figurings ought to be done inside the base inspecting time. In the most straightforward case like prescient current control, the testing time is pretty much nothing. Be that as it may, in applications like flux or torque control, the computation time decides the inspecting time.

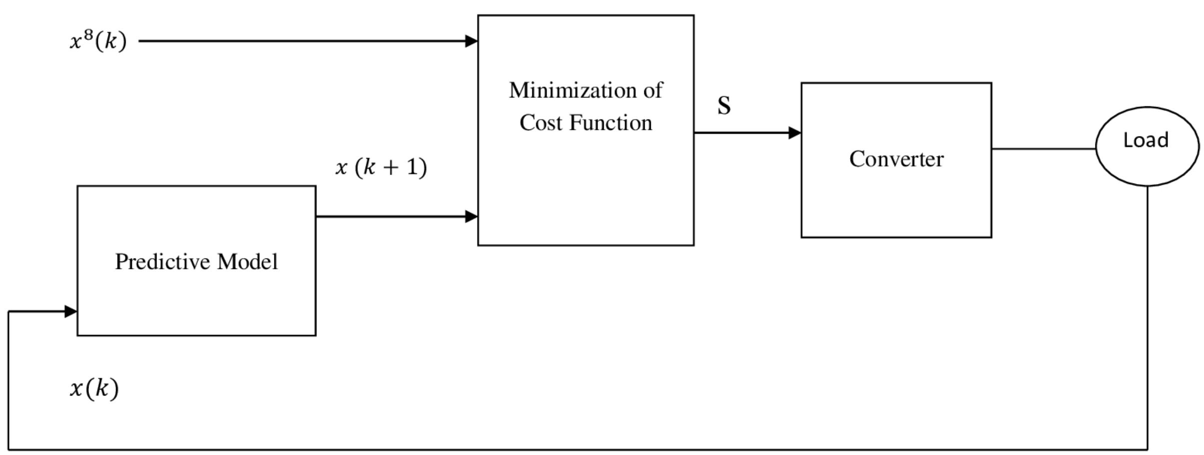

Figure 4.3: Block diagram of model predictive control

To pick the switching state that limits the cost work, all possible states are assessed and put something aside for the following. The quantity of calculations is straightforwardly identified with the quantity of conceivable exchanging states. For two-level three-stage inverter, it can ascertain effectively however for staggered and multi-stage inverters ,the figuring becomes difficult and another technique is embraced to lessen the quantities of computation.

4.3.1 GENERAL CONTROL SCHEME OF MPC FOR POWER INVERTERS

A general control conspire applied to Power converters is appeared in guaranteed figure. Right now, factor x(k) is applied to gauge what's to come esteem x(k+1)for each number of conceivable exchanging states. At that point all the potential qualities is checked in the cost work with the reference x(k) and different limitations to figure out which one makes the cost work least. At that point the ideal activation is picked and applied to the converter.

4.4 COST FUNCTION

To limit the blunder between the deliberate qualities and the reference esteems is the prime point of intensity converter control framework. This is communicated in the type of a cost work. The cost work is communicated in symmetrical coordinates and measures the deviation between the references and the anticipated values:

$$g = x\,(k + 1) + x^{p}\,(k + 1)$$

$$g = [i_a^* (k+1) - i_a (k+1)]^2 + [i_b^* (k+1) - i_b (k+1)]^2 + [i_c^* (k+1) - i_c (k+1)]^2 + \lambda_{dc} (V_{c1-} V_{c2})$$

Where $x_a^p (k+1)$, $x_b^p (k+1)$ and $x_a^p (k+1)$ are the phase elements of the predictive control vector. This prediction is found by obtaining the load model.

4.5 WEIGHTING FACTOR

A weighting factor is a weight given to an information point to allot it a lighter, or heavier, significance in a gathering. It is typically utilized for ascertaining a weighted mean, to give less (or more) significance to gather individuals. One of the prime benefits of Model Predictive Control (MPC) is that different control factors ,targets and requirements can be set in a solitary cost work what's more, simultaneously controlled. Right now, for example voltage, torque, or flux can be controlled while increasing additional control requests like exchanging recurrence decrease, regular mode voltage reduction etc. This can be executed by presenting the control focuses in the cost capacity to be resolved. Weighting factor is utilized for offering significance to the control targets. On the off chance that the weighting factor for a control target is higher than that of another control target, it will offer accentuation to limit the cost work for that control focus on whose weighting factor is high. The weighting ought to be planned carefully to get the ideal execution. Yet, there is no specific strategy for controlling weighting factor. The cost function with weighting factor is given beneath:

$$g = \lambda_a | x * (k+1) - x^p (k+1) | + \lambda_b | y * (k+1) - y^p (k+1)$$

Here, λ is the weighting factor. When $\lambda_a > \lambda_b$ the system will give emphasisto minimize the error of x. Again, when $\lambda_b > \lambda_a$ the system will giveemphasis to minimize the error of y. Thus user can decide which side to prefer which to not. By inserting the value as 0 or 1, total ignorance or full emphasize can be gained respectively. Other control scheme lacks this exibility.

4.7 DELAY COMPENSATION

As countless figurings is to be done in Model Predictive Control, a significant time delay happens. The yield execution is hampered by this delay on the off chance that it isn't considered in the controller plan. A prescient control strategy comprises of these means:

1. To measure the control variable.

2. To predict the control variable for the following examining time for the all

conceivable exchanging states.

3. To ascertain the cost work for every forecast.

4. To choose the exchanging state which limits the expense.

5. To apply the new exchanging state.

On the off chance that the count time is immaterial as for examining time , the delay isn't so significant. Yet, on the off chance that the computation time is equivalent with regard to examining time, there will be a deferral between the moment at which the estimation of the variable is estimated and the moment of utilization of the new exchanging state. As observed from the means, the framework computes the best exchanging state u(k) to accomplish the following estimation of control variable x(k+1)) at the time moment tk. Be that as it may all things considered the best exchanging state u(k) is applied to the framework at the moment t(k+1). This causes a one example deferral and makes the control variable move away from the reference. As a result, the control variable, for instance, load current will waver around the reference which will cause current wave. To repay the deferral, the figuring time is considered and the chose exchanging state is applied after the following inspecting instant. After postponementcompensation,the swell is limited. The modified ventures subsequent to considering delay are :

1. Estimating the control variable.
2. Applying the benefit of exchanging condition of past interim.

3. Estimation of the control factors at tk+1 moment utilizing past between interval exchanging state.

4. Predicting the control variable for the next sampling time tk+1 forall possible switching states.

5. Calculating the cost function for each possible output.

6. Selecting the best switching state which reduces the cost function.

7. Applying the most suitable switching state to the system.

4.8 SUPERIORITY OF MPC OVER OTHER CONTROLS

The purposes for the quickly developing of MPC are many. Despite the fact that was acquainted as a mean with control synthetic enterprises, presently a-days, MPC is similarly mainstream by and large fields, uncommonly in power hardware. Dominance of MPC over other control plans like PWM, PID control and so forth can be incorporated inside a couple of base highlights which are elite in MPC. A brief review is given beneath:

4.8.1 MULTI STEP PREDICTION

At first we start with an example on discrete time representation of a system

within control algorithm. Let's suppose MPC will predict future input x(k+1) at (k+1) sampling instant based on present variables x(k) and u(k). Thenwe take the representation as-

$$\boldsymbol{x(k + 1) = Ax(k) + Bu(k)}$$

Similarly, for (k + 2)th sampling instant we can write,

$$\boldsymbol{x(k + 2) = Ax(k + 1) + Bu(k + 1)}$$

Similarly, for (k + n)th sampling instant we can write,

$$\boldsymbol{x(k + n) = Ax(k + n - 1) + Bu(k + n - 1)}$$

Thus, MPC can provide optimization through multi step ahead, like (k+n)th sampling instant or total n step here . This feature has effectiveness over other control schemes. Also delay scan be compensated using this formula.

4.8.2 OUTPUT MODIFICATION WITHIN COST FUNCTION

In this feature, user can make the controller to emphasize upon certain variables while ignoring the others. Weighting factor is a good mean to performit. Already discussed, a weighting factor is a weight given to a data pointbasically to provide it a lighter, or heavier importance in a group.

This results in huge modification of output with the choice of the user. A n example is shown below-

$$g = \lambda_a|x*(k+1) - x^p\,(k+1)\,| + \lambda_b|y*(k+1) - y^p\,(k+1)$$

Here, λ is the weighting factor. When $\lambda_a > \lambda_b$ the system will give emphasisto minimize the error of x. Again, when $\lambda_b > \lambda_a$ the system will giveemphasis to minimize the error of y. Thus user can decide which side to prefer which to not. By inserting the value as 0 or 1, total ignorance or full emphasize can be gained respectively. Other

control scheme lacks this exibility.

4.5.1 OTHER FEATURES

Some other minor yet uncommon highlights of MPC can be referenced as-

1. MPC's idea is simple and straightforward.

2. Requirements can be embedded if vital. It will pick the most ideal yield despite everything remaining inside requirements.

3. It has a quick powerful reaction. For the most part quicker than a large portion of the techniques, setting aside very little effort to follow any given reaction.

Chapter 5

APPLICATION OF MODEL PREDICTIVE CONTROL ON NEUTRAL POINT CLAMPED INVERTER

Model prescient control (MPC) can be utilized to control the load current following as per reference and AC yield voltage of the inverter[6]. DC link voltage adjusting between a couple of capacitors can likewise be checked. We proposed a model just as the calculation for AC yields, including three stage current and voltage, DC link capacitor voltage adjusting and furthermore, switching frequency is calculated to give a detailed overview of power lossof the switching state changes and the compensation procedurelikewise given later. Regular activities like defer remuneration and the effect of weighting factor variety have been incorporated.

5.1 APPLICATION:

The conduct of the arrangement of Neutral-point cinched inverter is anticipated for every conceivable exchanging state by an appropriate calculation. The exchanging state that limits a given cost function is chosen to be applied during the next testing interval. NPC exhibits a high number of switching states (27 altogether) accordingly making us to permit some minor changes in the cost function and by and large process.

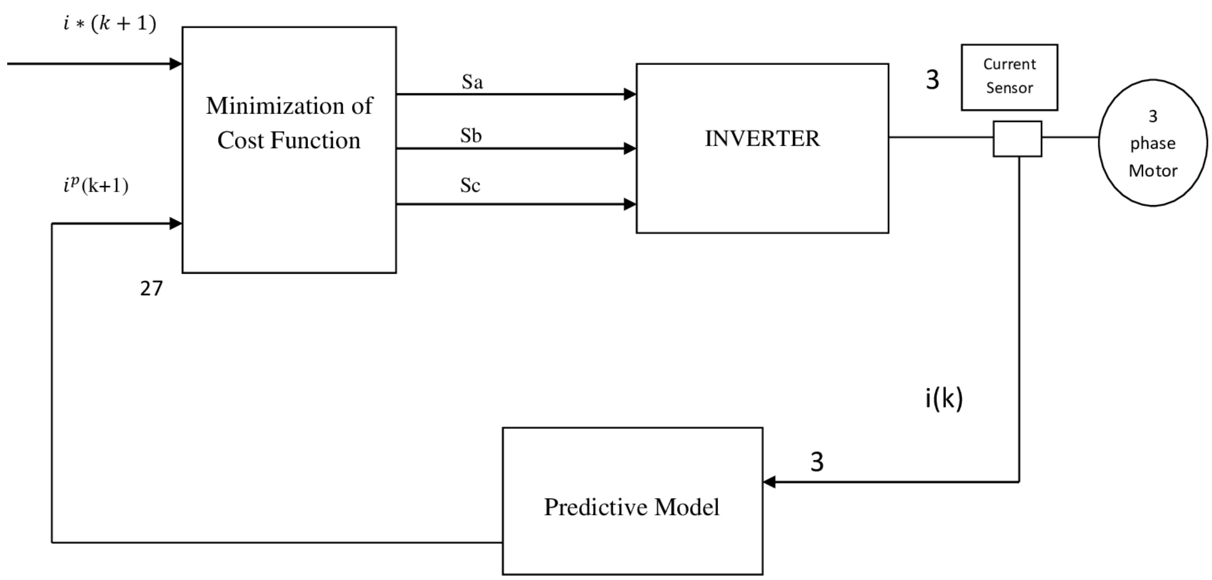

Figure 5.1: General MPC scheme for power converters

We can divide the whole application into six major steps-
1. System model construction
2. Switching states determination
3. State space representation in continuous time (Continuous time equation)
4. State space representation in Discrete time (Discrete time equation)
5. Capacitor voltage balancing discussion
6. Delay compensation
7. Cost function minimization
8. Switching frequency calculation

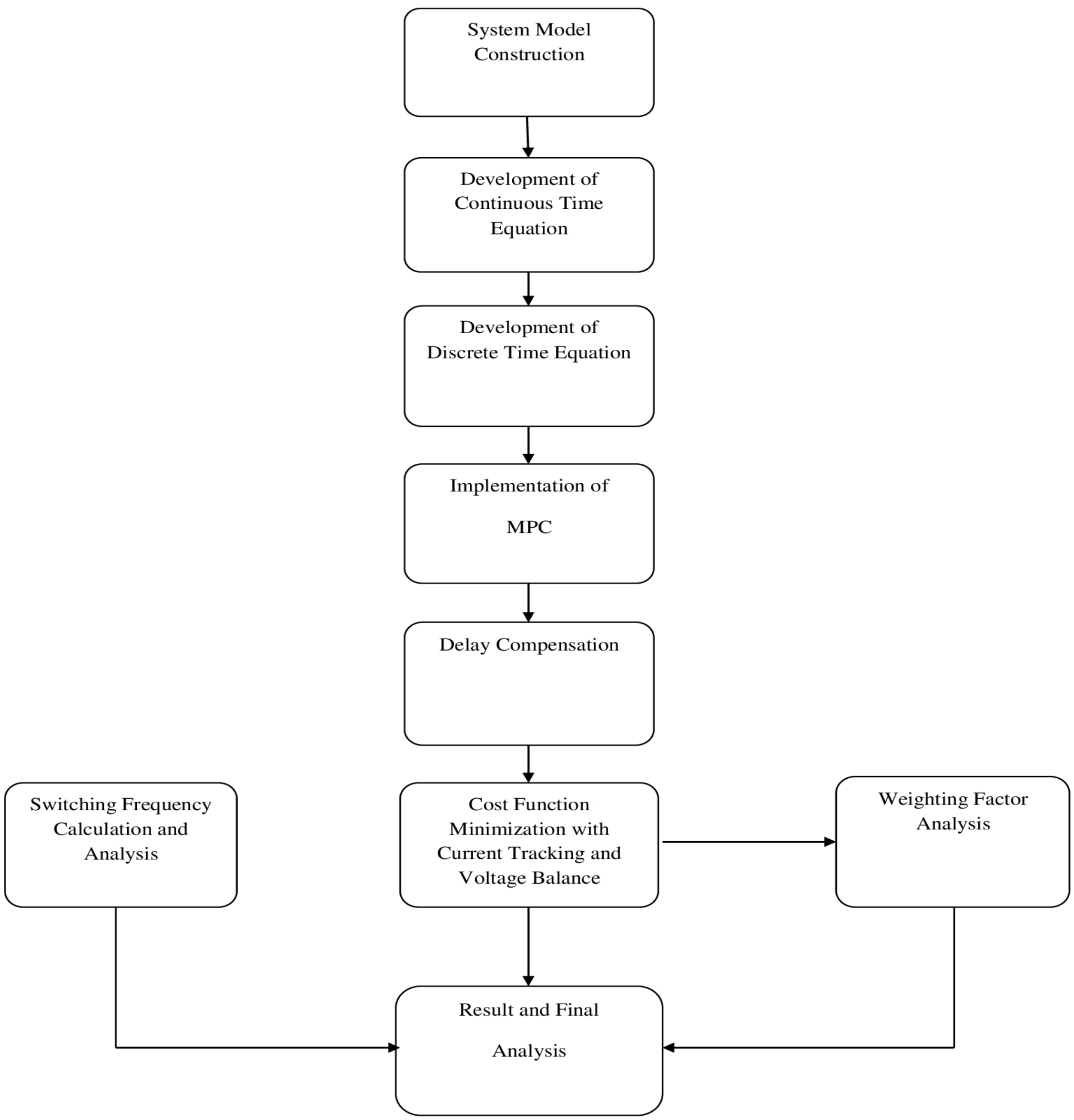

Figure 5.2: Block diagram of the overall process

5.1.1 SYSTEM MODEL:

The conduct of the arrangement of Neutral-point clipped inverter is anticipated for every conceivable switching state by a legitimate calculation. The exchanging state that limits a given cost function is chosen to be applied during the next examining interval. NPC introduces a high number of switching states (27 altogether), along these lines making us permit some minor changes in the cost function and generally speaking process.

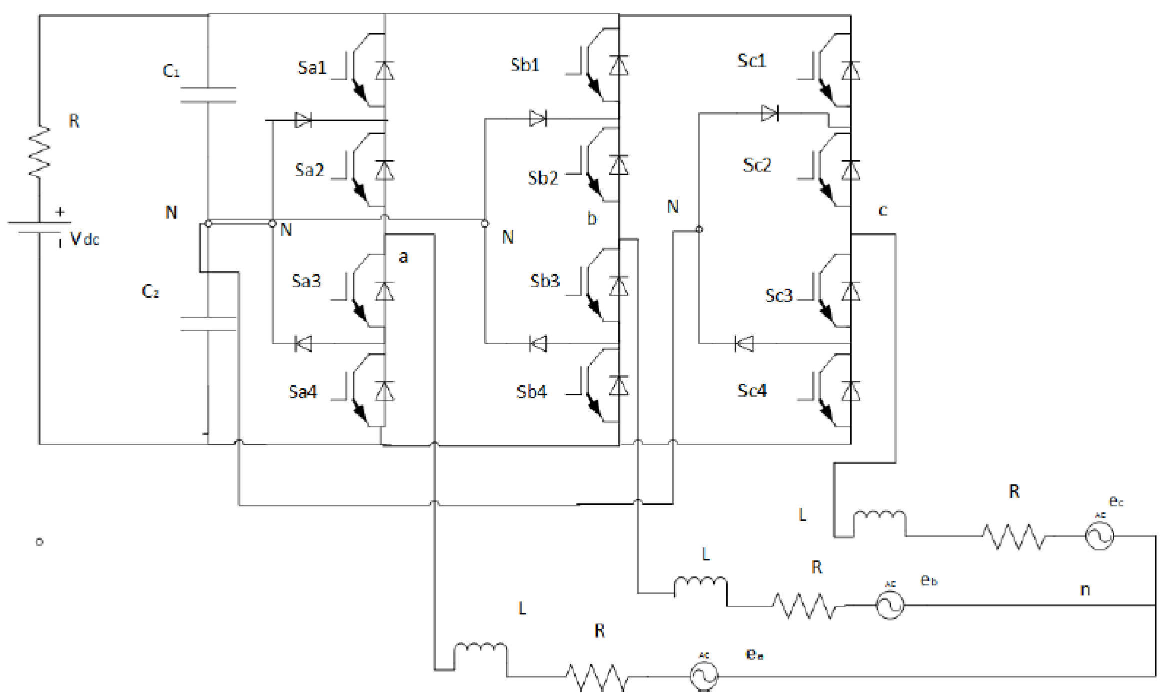

Figure 5.3: A model circuit for neutral point clamped inverter

This model allows the creation of three voltage levels to the output terminals. The details procedure will be discussed later.

5.0.1 SWITCHING STATES DETERMINATION

Three phase three leg inverter can have 3^3 or 27 switching states in total which are produced in 19 different voltage vectors. The switching states of each leg S_x with four IGBT switches named S_{x1} , S_{x2} , S_{x3} , S_{x4} which are named as corresponding switching states which are given below:

Here, x=a,b,c

S_x	Sx_1	S_{x2}	S_{x3}	S_{x4}	V_{x0}
+	1	1	0	0	$\frac{Vdc}{2}$
0	0	1	1	0	0
0	1	0	0	1	0
-	0	0	1	1	$\frac{-Vdc}{2}$

Table 5.1: Switching states of each leg in the converter model(for one phase)

Here "1" means that switch is turned on, "0" means switched off.
The condition of switching states "+" means that one end of the leg is connected with the positive port of source, the other end with load's neutral point.
Then, "0" means that one end of the leg is connected with the neutral point of DC link, the other end with load's neutral point and "-" means that one end of the leg is connected with the negative port of source, the other end with load's neutral point.As every two switches show opposite on-off state, six sets of signals are enough to control all of them.
Here,

$$V_{aN} = S_a \frac{V_{dc}}{2}$$

$$V_{bN} = S_b \frac{V_{dc}}{2}$$

$$V_{cN} = S_c \frac{V_{dc}}{2}$$

5.1.3 STATE SPACE REPRESENTATION IN CONTINUOUS TIME

Considering the definitions of variables from the inverter circuit model, the mathematical equations of load current for every phase can be rewritten as-

$$V_{aN} = Ri_a + L\frac{di_a}{dt} + e_a$$

$$V_{bN} = Ri_b + L\frac{di_b}{dt} + e_b$$

$$V_{cN} = Ri_c + L\frac{di_c}{dt} + e_c$$

The respective load current, voltage and back emf are –

$$i_a = \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix}$$

$$v_a = \begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix}$$

$$e_a = \begin{bmatrix} e_a \\ e_b \\ e_c \end{bmatrix}$$

Now, the vector differential equation can be shown as-

$$v = iR + L\frac{di}{dt} + e$$

Transforming it into time domain –

$$v\left(t\right) = Ri\left(t\right) + L\frac{di\left(t\right)}{dt} + e\left(t\right)$$

8.1.4 State Space Representation in Discrete Time

From the continuous time equation we get –

$$v\left(t\right) = Ri\left(t\right) + L\frac{di\left(t\right)}{dt} + e\left(t\right)$$

$$V_{aN}\left(k\right)=Ri_{a}\left(k\right)+L\frac{i_{a}\left(k+1\right)-i_{a}\left(k\right)}{T_{s}}$$

$$T_{s}V_{aN}\left(k\right) \quad = \quad RT_{s}i_{a}\left(k\right)+\mathrm{L}\ \{\ i_{a}\left(k+1\right)\ -\ i_{a}\left(k\right)\}\ +\ T_{s}e_{a}\left(k\right)$$

$$\frac{T_{s}}{2}V_{aN}\left(k\right)=i_{a}\left(k+1\right)-i_{a}\left(k\right)+\frac{R}{2}T_{s}i_{a}\left(k\right)+\frac{T_{s}}{2}e_{a}\left(k\right)$$

$$i_{a}\left(k+1\right)=\left(1-\frac{R}{2}T_{s}\right)i_{a}\left(k\right)+\frac{T_{s}}{2}V_{aN}\left(k\right)-\frac{T_{s}}{2}e_{a}\left(k\right)$$

Applying common mode voltage-

$$i_{a}\left(k+1\right)=\left(1-\frac{R}{2}T_{s}\right)i_{a}\left(k\right)+\frac{T_{s}}{2}\left[V_{aN}\left(k\right)-e_{a}\left(k\right)-V_{rN}\right]$$

$$=\left(1-\frac{R}{2}T_{s}\right)i_{a}\left(k\right)+\frac{T_{s}}{2}\left[V_{aN}\left(k\right)-e_{a}\left(k\right)-\frac{V_{aN}\left(k\right)+V_{bN}\left(k\right)+V_{cN}\left(k\right)}{3}\right]$$

$$=\left(1-\frac{R}{2}T_{s}\right)i_{a}\left(k\right)+\frac{T_{s}}{2}\left[\frac{2}{3}V_{aN}\left(k\right)-\frac{1}{3}V_{bN}\left(k\right)-\frac{1}{3}V_{cN}\left(k\right)-e_{a}\left(k\right)\right]$$

$$=\left(1-\frac{R}{2}T_{s}\right)i_{a}\left(k\right)+\frac{T_{s}}{2}\left[\frac{2}{3}*\frac{1}{2}V_{dc}S_{a}\left(k\right)-\frac{1}{3}*\frac{1}{2}V_{dc}S_{b}\left(k\right)-\frac{1}{3}*\frac{1}{2}V_{dc}S_{c}\left(k\right)-e_{a}\left(k\right)\right]-\frac{T_{s}}{2}e_{a}\left(k\right)$$

So applying this procedure for other three phases we get-

$$\begin{bmatrix} -i_a\left(k+1\right) \\ -i_b\left(k+1\right) \\ -i_c\left(k+1\right) \end{bmatrix} = \begin{bmatrix} 1-\frac{R}{2}T_s & 0 & 0 \\ 0 & 1-\frac{R}{2}T_s & 0 \\ 0 & 0 & 1-\frac{R}{2}T_s \end{bmatrix} \begin{bmatrix} i_a\left(k\right) \\ i_b\left(k\right) \\ i_c\left(k\right) \end{bmatrix} + V_{dc} * \frac{T_s}{2} \begin{bmatrix} \frac{1}{3} & \frac{-1}{3} & \frac{-1}{6} \\ \frac{-1}{6} & \frac{1}{3} & \frac{-1}{6} \\ \frac{-1}{6} & \frac{-1}{6} & \frac{1}{3} \end{bmatrix} - T_S \begin{bmatrix} -\frac{1}{2} & 0 & 0 \\ 0 & -\frac{1}{2} & 0 \\ 0 & 0 & -\frac{1}{2} \end{bmatrix} \left[\begin{matrix} e_a \\ e_b \\ e_c \end{matrix}\right.$$

5.1 DC Link Capacitor Voltage Balancing

As the model of a neutral point clamped inverter, two capacitors are utilized corresponding with the DC source with the end goal of partitioning the input voltage into two equivalent arrangements of capacitor voltages. The equivalent distribution or balancing of DC link voltages can be checked while embedding the most ideal switching state. With this objective, a statement of the distinction between capacitor voltages, likewise conveying a weighting factor has been remembered for the forthcoming cost function. The minimization of this term prompts an ideal equalization. MPC will choose the best switching state for the obvious most ideal voltage adjusting. The weighting factor is utilized to control the measure of minimization we need along these lines affecting the alternative for switching states MPC has [6]. The elements of DC link capacitor voltages can be produced utilizing beneath capacitor differential conditions-

$$\frac{dv_{c1}}{dt} = \frac{1}{C} i_{c1}$$

$$\frac{dv_{c2}}{dt} = \frac{1}{C} i_{c2}$$

Here, C is the capacitor voltage in this differential equations. For converting from continuous time equation to discrete time equation –

$$v_{c1}(k+1) = v_{c1}(k) + \frac{T_s}{C} i_{c1}$$

$$v_{c2}(k+1) = v_{c2}(k) + \frac{T_s}{C} i_{c2}$$

Here, currents i_{c1} (k) and i_{c2} (k) rely on the value of output currents and the switching states of the inverter. Despite the fact that the conditions can be utilized to create DC interface voltages very properly, we've taken the straight estimations of v_{c1} and v_{c2} from the created inverter model and embedded those as contributions to the controller, along these lines embeddings in the cost function with a weighting factor. The significance of the weighting factor is talked aboutlater.

5.2 WORKING PRINCIPLE

Model prescient control centers around the streamlining of the got information. The entire calculation depends on it. MPC's forecast ability of future best conceivable switching state fulfilling every single given prerequisite from the current condition is being utilized right now.

The NPC converter having three-stage three legs creates a sum of 33 or 27 switching states. At first, MPC calculation will consider every one of the 27 switching states which can be obtained by the state factors. This thought is prepared inside the current sampling time k. At that point the calculation chooses the best choice from all states which have the ideal cost function. Ideal expense work implies as immaculate as conceivable the consummation of the prerequisites furthermore, as least as conceivable the blunder seems to be. This incorporates the choice of best-switching state to follow the reference current for yield, for load voltage age with the most ideal capacitor voltage balance. MPC will choose it not crossing the preset confinements like inspecting recurrence, capacitor/inductor's worth and so on.

At last, the controller calculation applies this exchanging state during the entirety (k + 1) (future) testing period. Indeed, even with the utilization of modification of the state-space representation, deferral can be repaid applying states up to (k + 2), (k + 3) and so forth progressively far off future periods. The control calculation of streamlining and the total controlling techniques including postponing remuneration have been depicted as a flow chart afterward.

5.3 DELAY COMPENSATION

To deliver a control plot dependent on model predictive control and to implement it appropriately, a lot of computation is required. This computation takes a lot of time in this manner creating delay all the while. This deferral can hamper the presentation of the framework, so delay compensation ought to be included in the control algorithm. For instance, load current prediction flows on present examining moment k for the following testing moment (k+1) for all conceivable switching states can cause a delay as the figuring proceeds considerably after kth period is finished. In this way in the state space representation and ideal cost function, expectation from k inspecting moment is utilized for (k+2),(k+3),(k+4) and so forth sampling instants in this way compensates the delay.

The state equation in discrete-time state-space representation can be written as follows:

$$x\left(k+1\right)=Ax\left(k\right)+Bu\left(k\right)-Ee\left(k\right)$$

Similarly for (k+2)th sampling instant,

$$x\left(k+2\right)=Ax\left(k+1\right)+Bu\left(k+1\right)-Ee\left(k\right)$$

This can be used as the compensated equation. u(k +1) is the current state vector while u(k) is received using unit delay in simulation.(k + 1)th instant is determined first and then used to estimate (k + 2)th instant, in the cost function also.

5.4 COST FUNCTION

Cost function brings about a definitive advancement of the system[1-2][7]. The fundamental objective of the cost function is to limit the mistake between the anticipated furthermore, reference esteems. It will assist the controller by selecting the most ideal switching state for which blunder is least despite everything keeping up the requirements. The cost function, communicated as g is in this way is determined on each examining moment for each (absolute 27) states to watch that state's presentation. The advancement tracks with it. The optimized factors follow the rest of the process.

$$g = [i_a^* (k+3) - i_a (k+3)]^2 + [i_b^* (k+3) - i_b (k+3)]^2 + [i_c^* (k+3) - i_c (k+3)]^2 + \lambda_{dc} (V_{c1} - V_{c2})$$

A flowchart representing the overall process is given below:

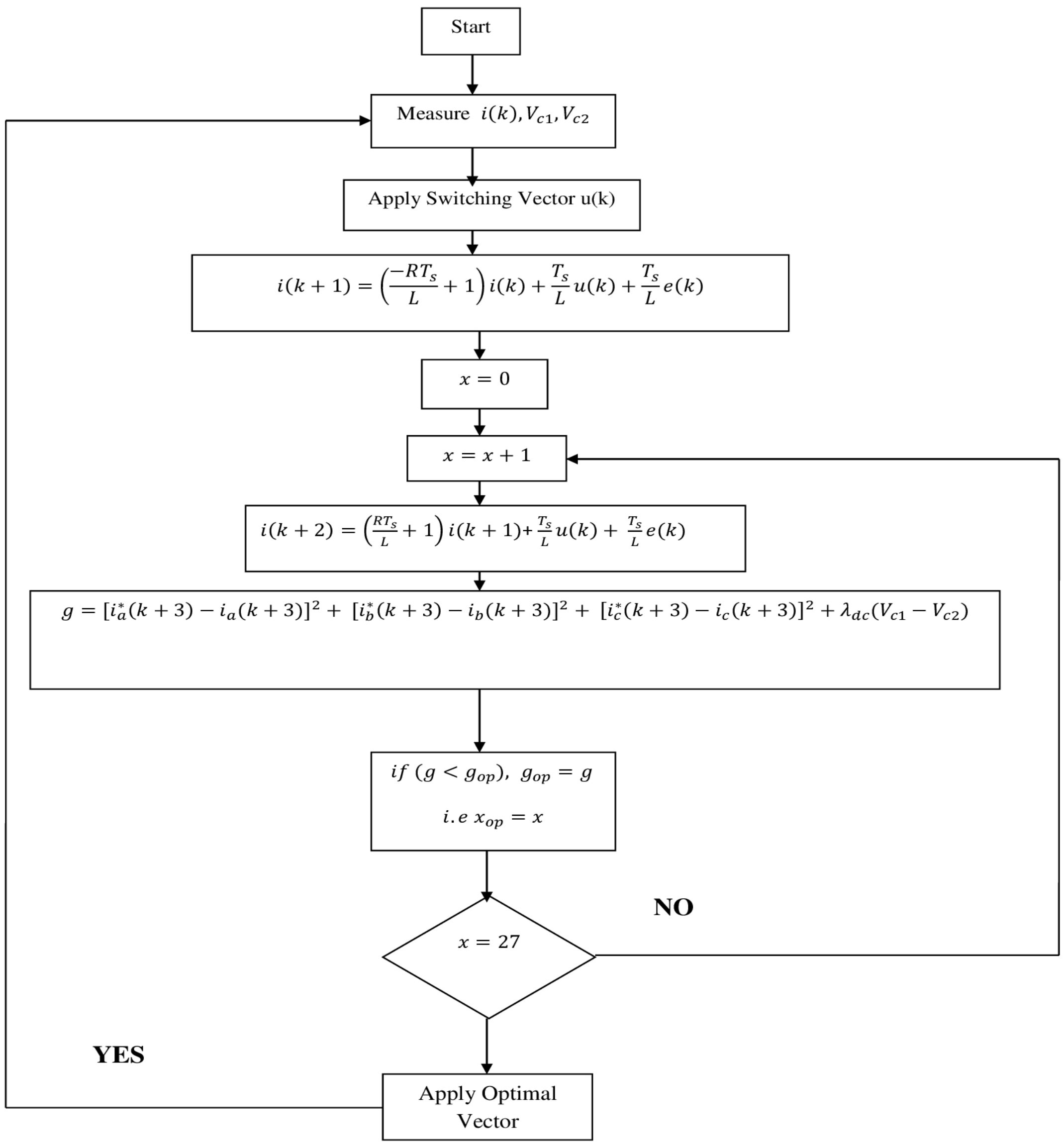

Figure 5.4: Flow diagram of predictive voltage control

Chapter 6

SPACE VECTOR MODULATION

In case of sinusoidal pulse width modulation (SPWM) we use a triangular wave as carrier signal and compare that with the message signal and produce PWM signals and in that we apply some common mode components like third harmonics component in order to reduce the harmonics for a voltage source inverter.

6.1 SPACE VECTOR

We know that a pulsating magnetic field is produced if we apply voltage in a single phase machine. Let's consider a three phase machine like a three phase induction motor or a three phase synchronous machine, we there get a three phase winding at the stator. Now to rotate the machine we apply sinusoidal three phase current and excite the three phase winding as result revolving magneto motive force (mmf) will be produced in the air gap. This revolving mmf is the example of space vector.

6.2 ADVANTAGE OF SVPWM OVER SPWM

The advantage that is obtained by injecting third harmonics in sine pulse width modulation, similar advantage is obtained by SVM method. On the other hand, everything that is possible by using space vector approach, is not necessarily possible by using triangular comparison approach as like bus clamping PWM which can be approached by SVPWM and not by SPWM.

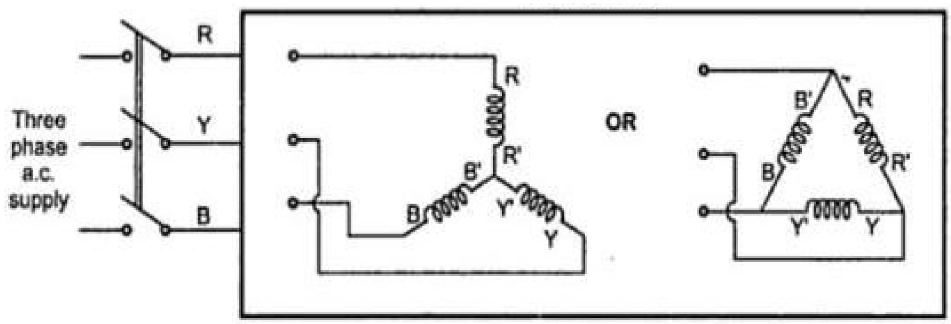

Fig 6.1: Three phase winding of an induction motor

Here, the application of three phase current in the three phases of a stator produces rotating space vector.

6.2.1 SPACE VECTOR TRANSFORMATION

The previously discussed revolving mmf can be produced by equivalent two phase winding. We can convert the three phase winding of the stator into equivalent two phase winding 90 degree phase shifted from each other. We can excite these windings of orthogonal phases by applying two phase current signal at orthogonal phase shifted from each other.

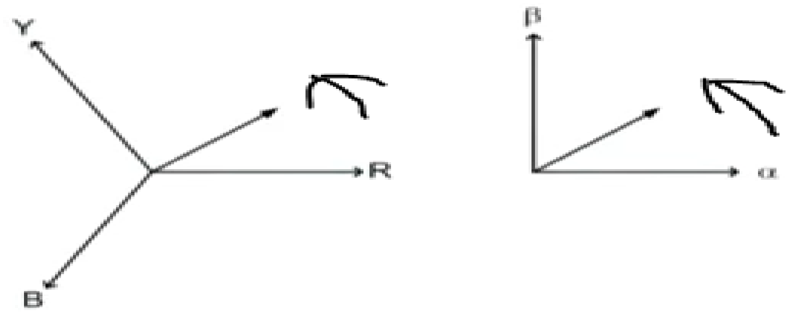

Fig 6.2: Alpha beta conversion

Here, the curved arrow mark represent the revolving space vector which resembles the three phase and equivalent two phase vector in both the figures.

6.3.2 SECTOR SELECTION

The reference space vector rotates in the space at a definite angular velocity. The path that the reference voltage vector rotates can be divided into six equilateral triangular sectors. For each 60 degree angle, the voltage vector traverses each sector for definite combination of switching states. By this way we can select the sector that the reference vector is passing through.

6.2.2 DWELL TIME CALCULATION

As we know that the reference vector can be synthesized in three stationary vectors. So, it is required to know the time for which a switch is OFF and ON state for a definite sampling period. So, the way to figure out the duty cycle time of the chosen switches for a sampling period is known as dwell time calculation. This duty cycle time can be obtained from the dwell time of the stationary voltage vectors.

6.2.2.1 SWITCHING SEQUENCE DETERMINATION

Although the switching sequence design for a given $\overrightarrow{V}_{ref}$ is not identical, there are few common obligations to be maintained in order to reduce switching losses while arranging the switching sequence. Those are:

1. While transiting from one switching state to another not more than two switches of same phase/leg should be involved during that particular dwell time.

2. Minimum number of switching is required while the $\overrightarrow{V}_{ref}$ transits from one sector to the next in the space.

Chapter 7

APPLICATION OF SVM ON TWO LEVEL INVERTER

a: On two level Voltage Source Inverter (VSI):

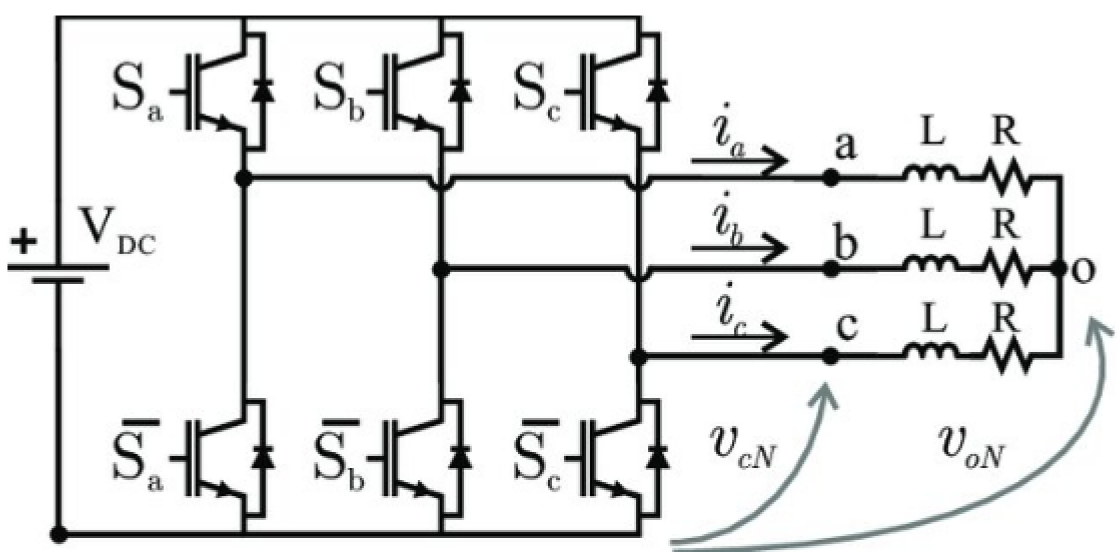

Fig 7.1: A two level Voltage Source inverter

Here, the voltage at ac side terminals R, Y, B are measured with respect to preferred terminal O. Such as V_{RO}, V_{YO}, V_{BO} . The value of the voltages depend on the state of the switches. For example, if the R phase top switch is ON then V_{RO} is $V_{DC}/2$. If the R phase bottom switch is on then the output of V_{RO} will be $-V_{DC}/2$. Same thing for phases Y and B. Just like there will be 8 different combinations which are called eight different states of the inverter [18]. So by this way the inverter produces eight sides sets of output voltages. From this we can determine which are the corresponding voltage vectors.

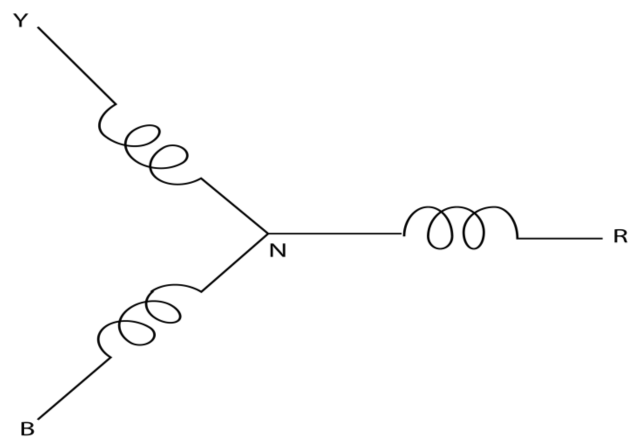

Fig 7.2: Star connected three phase winding

In figure 8.4 we can see that on end of each phase R, Y, B are connected to the middle point of each inverter leg and the other point of the phases are connected to the load neutral N [19]. Combining both the figures we can see for three phase balanced load-

$$V_{RN} + V_{YN} + V_{BN} = 0 \ldots\ldots\ldots\ldots\ldots (i)$$

$$V_{RN} + V_{NO} = V_{RO}... \text{.............................}(ii)$$

$$V_{BN} + V_{NO} = V_{BO} \dots\dots\dots\dots\dots\dots\dots (iii)$$

$$V_{YN} + V_{NO} = V_{YO} \dots\dots\dots\dots\dots\dots\dots (iv)$$

Adding equation (ii), (iii) and (iv) we get

$$V_{RO} + V_{B0} + V_{YO} = V_{RN} + V_{BN} + V_{CN} + 3_{NO} \dots\dots\dots (v)$$

Therefore, $V_{NO} = \frac{1}{3} * (V_{RO} + V_{BO} + V_{YO}) \dots\dots\dots\dots\dots\dots\dots\dots\dots (vi)$

and, $V_{RN} = \frac{1}{3} * (2_{RO} - V_{BO} - V_{YO}) \dots\dots\dots\dots\dots\dots ... (vii)$

$$V_{BN} = 1/3 * (2_{BO} - V_{RO} - V_{YO}) \dots\dots\dots\dots\dots\dots ... (vii)$$

$$V_{YN} = 1/3 * (2_{YO} - V_{BO} - V_{RO}) \dots\dots\dots\dots\dots\dots ... (vii)$$

$$V_{RO} = V_{YO} = V_{BO} = \pm .5_{dc}$$

The instantaneous phase voltages

$$V_{RN} = V \sin(\theta t) \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots (viii)$$

$$V_{YN} = V \sin\left(\theta t + \frac{2\pi}{3}\right) \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots (ix)$$

$$V_{BN} = V \sin\left(\theta t + \frac{4\pi}{3}\right) \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (x)$$

$$\begin{bmatrix} V_\alpha \\ V_\beta \end{bmatrix} = \frac{2}{3} * \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} V_{RN} \\ V_{YN} \\ V_{BN} \end{bmatrix} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (viii)$$

Here, 2/3 is an arbitrarily chosen constant. The advantage of using this constant is that, after transformation, the magnitude of two phase voltages will be that of three phase voltages.

Now, by expressing two transformed phase voltages in terms of a space vector we get,

$$\overrightarrow{V}_{ref}(t) = V_\alpha(t) + jV_\beta(t) = 2/3\left(V_{RN} + V_{YN}e^{\frac{j2\pi}{3}} + V_{BN}e^{\frac{j4\pi}{3}}\right) \ldots\ldots (ix)$$

$$|\overrightarrow{V}_{ref}| = \sqrt{V_\alpha^2 + V_\beta^2} \; and \; \theta = \tan^{-1}(V_\beta / V_\alpha)$$

From this following procedure we can find the value of the reference vector.

7.1Voltage Vectors Produced by VSI:

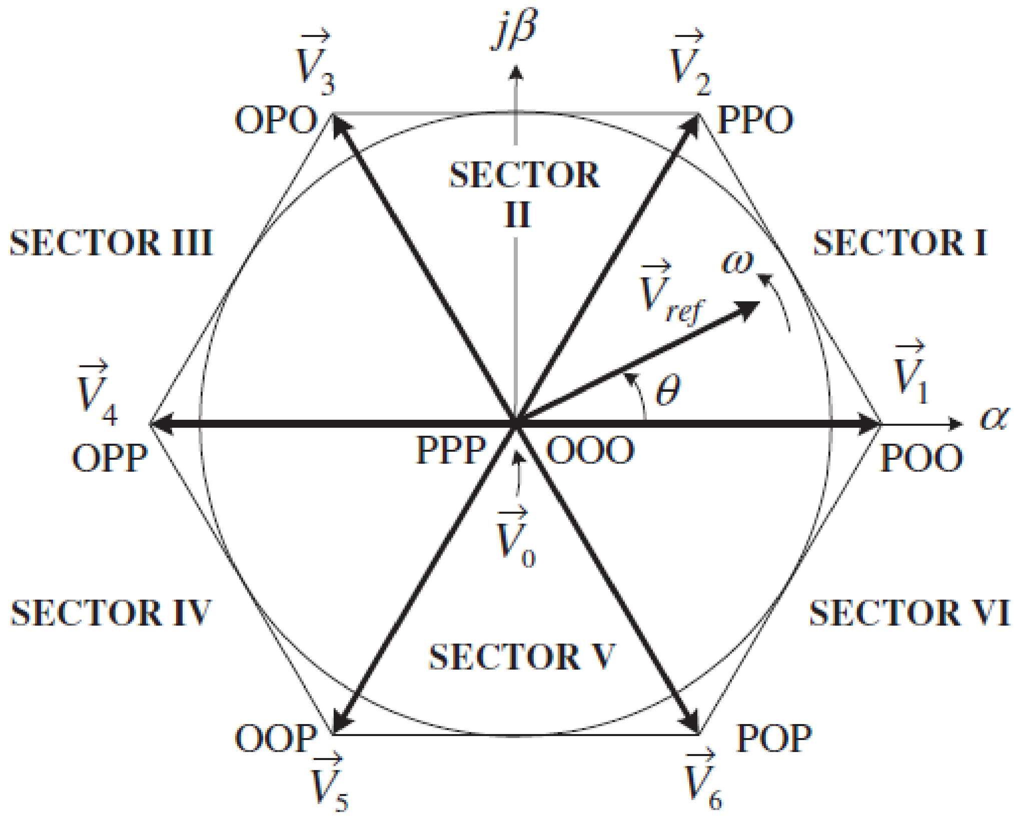

Fig 7.3: Voltage Vectors and inverter states

From this figure we can determine all the voltage vectors for all the corresponding inverter states [20]. Here, each of the vectors represent the states of the inverter connected in each phase. Such as for the vector $\vec{V_1}$ (PPO) the P indicates that top switch of R phase is ON and bottom switches of phases Y and B are OFF. Similar cases will occur for rest of the voltage vectors. From this switching states of the inverter we can easily figure out the generated load phase voltages. For example, from the figure for the switching state [POO] the generated load phase voltages are,

$$V_{RN} = \frac{2}{3}V_d,\ V_{YN} = -\frac{1}{3}V_d,\ V_{BN} = -\frac{1}{3}V_d \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (x)$$

Now, by substituting equation (x) in equation (ix) we can get the corresponding space vector $\overrightarrow{V}_1 = \frac{2}{3}V_d e^{j0}$ ....(xi)

By applying this procedure the other voltage vectors can be determined by the equation

$$\overrightarrow{V}_n = \frac{2}{3}V_d e^{\frac{j(n-1)\pi}{3}} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (xii)$$

Here, n= 1,2,3,4,5,6

7.1 DWELL TIME CALCULATION

By applying the principle of volt-second balancing we can calculate the dwell time for the selected switches i.e. stationary vectors for a definite sampling period [21]. From the figure 8e when $\overrightarrow{V}_{ref}$ falls into sector 1, it can be synthesized into three stationary voltage vectors $\overrightarrow{V_0}, \overrightarrow{V_1} and\ \overrightarrow{V_2}$ for sampling time Ts. By applying volt-second balance equation we get,

$$\overrightarrow{V}_{ref}Ts = \overrightarrow{V}_1 T_a + \overrightarrow{V}_2 T_b + \overrightarrow{V}_0 T_0 \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (xiii)$$

$$T_s = T_a + T_b + T_c \ldots\ldots\ldots\ldots\ldots\ldots\ldots (xiv)$$

Here, T_a, T_b and$T_c$are the dwell times for the stationary voltage vectors $\overrightarrow{V}_1$, $\overrightarrow{V}_2 and \overrightarrow{V}_3$ respectively.

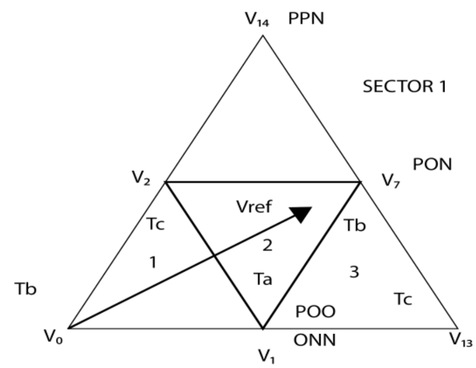

Figure 7.4: $\overrightarrow{V}_{ref}$ synthesized in $\overrightarrow{V}_1, \overrightarrow{V}_2 and \overrightarrow{V}_0$

The space vectors in equation (xiii) can be expressed as

$$\overrightarrow{V}_{ref} = V_{ref}e^{j\theta},\ \overrightarrow{V}_1 = \frac{2}{3}V_{dc},\ \overrightarrow{V}_2 = \frac{2}{3}V_{dc}e^{\frac{j\pi}{3}}\ and\ \overrightarrow{V}_0 = 0 \ldots\ldots\ldots\ldots\ldots\ldots (xv)$$

Substituting equation xv in xiv and splitting the values into real and imaginary axis we obtain $\overrightarrow{V}_{ref}cos\theta T_s = \frac{2}{3}V_dT_a + \frac{1}{3}V_dT_b$

and $\overrightarrow{V}_{ref}sin\theta T_s = \frac{1}{\sqrt{3}}V_dT_b \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots.. (xvi)$

Solving equation xvi and xiv we obtain

$$T_a = \frac{\sqrt{3}}{V_d}T_{sref}\sin\left(\frac{\pi}{3} - \theta\right) \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (xvii)$$

$$T_b = \frac{\sqrt{3}}{V_d}T_{sref}\sin(\theta) \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (xviii)$$

$$T_c = T_s - T_a - T_b \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (xix)$$

These three dwell time equations are only for sector 1 for $\theta = \pi/3$. Now, in case of other sectors $\theta will be replaced by \theta'$. In that case, $\theta^{'} = \theta - \frac{(k-1)\pi}{3} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (xx)\, for\ 0 \leq \theta' < \frac{\pi}{3}$.

A point to be mentioned that $\overrightarrow{V}_{ref}$ should be resolved into those three stationary vectors which lie to the nearest distance from the tip of the reference vector travelling an individual sector.

If we express the dwell time equations by modulating index m,

then, $m = \frac{\sqrt{3}}{V_d} V_{ref} \ldots\ldots\ldots.. (xxi)$

Now, for $m_{\text{max}} = 1$ we get, $V_{\text{ref, max}} = \frac{V_d}{\sqrt{3}} \ldots\ldots\ldots\ldots\ldots.. (xxii)$

Therefore, the maximum fundamental line to line voltage that can be produced by an SVM scheme will be

$V_{max,SVM} = \sqrt{3}\left(\frac{V_{ref,max}}{\sqrt{2}}\right) = \frac{V_d}{\sqrt{2}} \ldots\ldots\ldots\ldots\ldots\ldots.. (xxiii)$

On the other hand, the maximum fundamental line to line voltage that can be obtained from an SPWM scheme is

$$V_{max,SPWM} = 0.612 V_d \ldots\ldots.. (xxiv)$$

Dividing xxiv and xxiii we get $\frac{V_{max,SVM}}{V_{max,SPWM}} = 1.55 \ldots\ldots\ldots. (xxv)$

From this equation we can see that from SVM we can obtain 15% greater amplitude of fundamental voltage than that of SPWM. For this reason SVM is more advantageous than SPWM. However, we can obtain fundamental voltage of similar amplitude from SPWM by injecting third harmonics in that scheme.

7.3SWITCHING SEQUENCE ARRANGEMENT

Now maintaining the required obligations for switching losses and satisfying the design requirements we can draw the required switching sequenced for a sampling time period T_s . This time period T_s is divided into seven segments of selected vectors. From figure 8e and 8f we can see when the reference vector is in sector 1 it has got three nearest switching states. So, the $\overrightarrow{V}_{ref}$ when synthesized by three stationary voltage vectors $\overrightarrow{V}_0,\ \overrightarrow{V}_1\ and\ \overrightarrow{V}_2$ there will traverse in this sequence $OOO \rightarrow POO \rightarrow PPO \rightarrow PPP \rightarrow PPO \rightarrow POO \rightarrow OOO$. We can see that in each switching state transition not more than one state is changed. At the same time it ensures that not more than two switches of the same phase change its condition during this transition from one switching state to another. Figure 8g visualizes all the switching transition in sampling time of seven segments during the sampling time T_s.

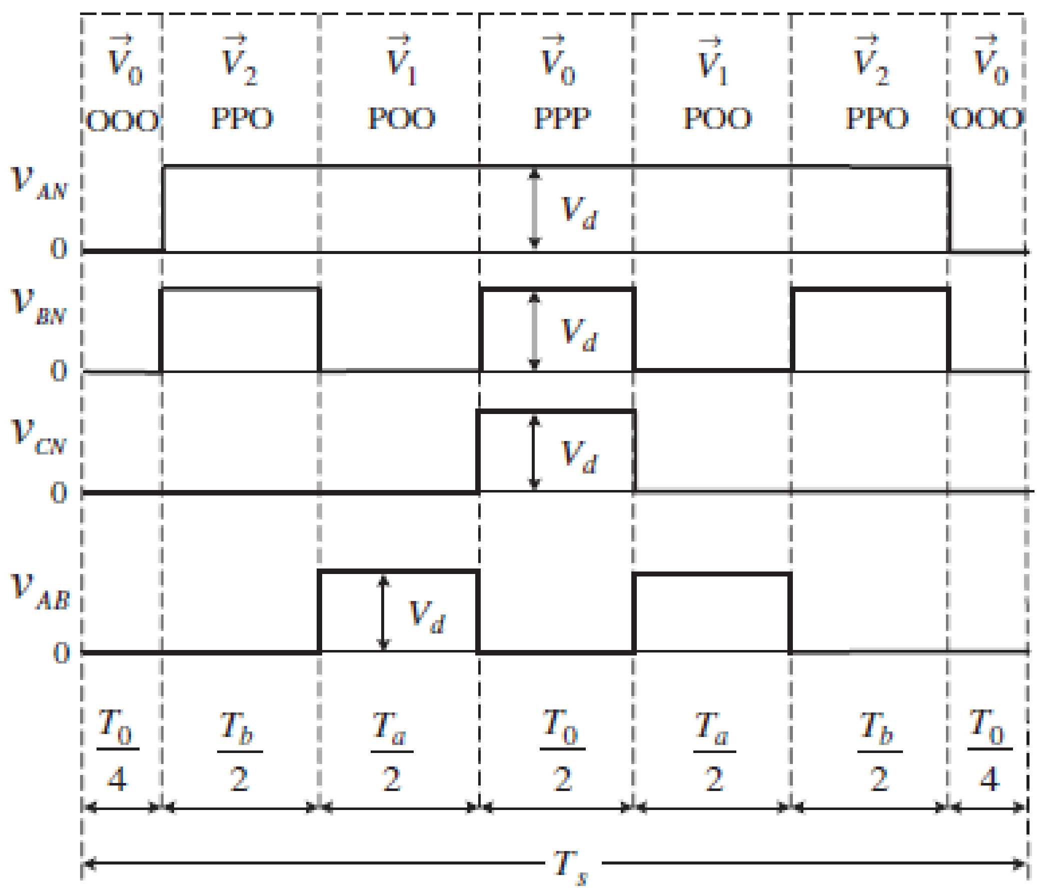

Figure 7.5: Seven Segment Switching Sequence for $\overrightarrow{V}_{ref}$ in sector 2

Chapter 8

APPLICATION OF SVM ON THREE LEVEL INVERTER

Our working procedure resembles the following flowchart.

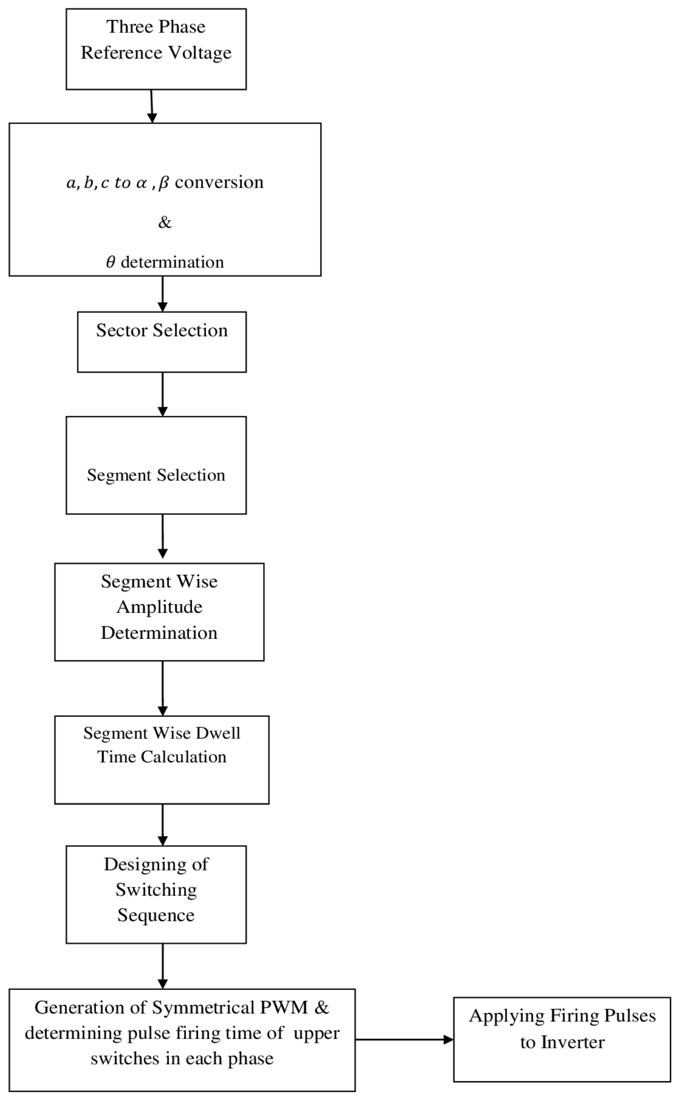

Figure 8.1: Work flow of Space Vector Modulation procedure

The R, Y, B to alpha-beta conversion and $\overrightarrow{V}_{ref}$ determination from $\overrightarrow{V}_{\alpha}$ *and* $\overrightarrow{V}_{\beta}$ discussed previously for two level inverter is same for three level one. The angle wise sector determination is also same for three level inverter. But as the name three level signifies the meaning, each inverter phase leg goes through three switching states $[P]$, $[O]\, and\, [N]$.

Considering all the three phases in account, we can find the position of 27 stationary space vectors and their respective switching states and determine the magnitude of different types of stationary space vectors.

Table 8.1 Stationary Voltage Vectors and their respective switching states.

Space Vector		Switching State		Vector Classification	Vector Magnitude
$\overrightarrow{V}_0$		PPP,OOO, NNN		Zero Vector	0
$\overrightarrow{V}_1$		P-type	N-type	Small Vector	$\frac{1}{3}V_d$
	$\overrightarrow{V}_{1P}$	PPO			
	$\overrightarrow{V}_{1N}$		ONN		
$\overrightarrow{V}_2$	$\overrightarrow{V}_{2P}$	PPO			
	$\overrightarrow{V}_{2N}$		OON		
$\overrightarrow{V}_3$	$\overrightarrow{V}_{3P}$	OPO			
	$\overrightarrow{V}_{3N}$		NON		
$\overrightarrow{V}_4$	$\overrightarrow{V}_{4P}$	OPP			

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	$\overrightarrow{V}_{4N}$		NOO		
$\overrightarrow{V}_{5}$	$\overrightarrow{V}_{5P}$	OOP			
	$\overrightarrow{V}_{5N}$		NNO		
$\overrightarrow{V}_{6}$	$\overrightarrow{V}_{6P}$	POP			
	$\overrightarrow{V}_{6N}$		ONO		
$\overrightarrow{V}_{7}$		PON		Medium Vector	$\frac{1}{\sqrt{3}}V_d$
$\overrightarrow{V}_{8}$		OPN			
$\overrightarrow{V}_{9}$		NPO			
$\overrightarrow{V}_{10}$		NOP			
$\overrightarrow{V}_{11}$		ONP			
$\overrightarrow{V}_{12}$		PNO			
$\overrightarrow{V}_{13}$		PNN		Large Vector	$\frac{2}{3}V_d$
$\overrightarrow{V}_{14}$		PPN			
$\overrightarrow{V}_{15}$		NPN			
$\overrightarrow{V}_{16}$		NPP			

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$\overrightarrow{V}_{17}$	NNP		
$\overrightarrow{V}_{18}$	PNP		

Among these 27 valid combination ofswitching states, 19 are identical. The way of determining the relationship between stationary voltage vectors and their switching states is already discussed in the previous chapter.

From Table 8.1 we can see that there are 3 zero vectors ($\overrightarrow{V}_0$), 6 small vectors ($\overrightarrow{V}_1 \rightarrow \overrightarrow{V}_6$) , 6 medium vectors ($\overrightarrow{V}_7 \rightarrow \overrightarrow{V}_{12}$) and 6 large vectors ($\overrightarrow{V}_{13} \rightarrow \overrightarrow{V}_{18}$) .

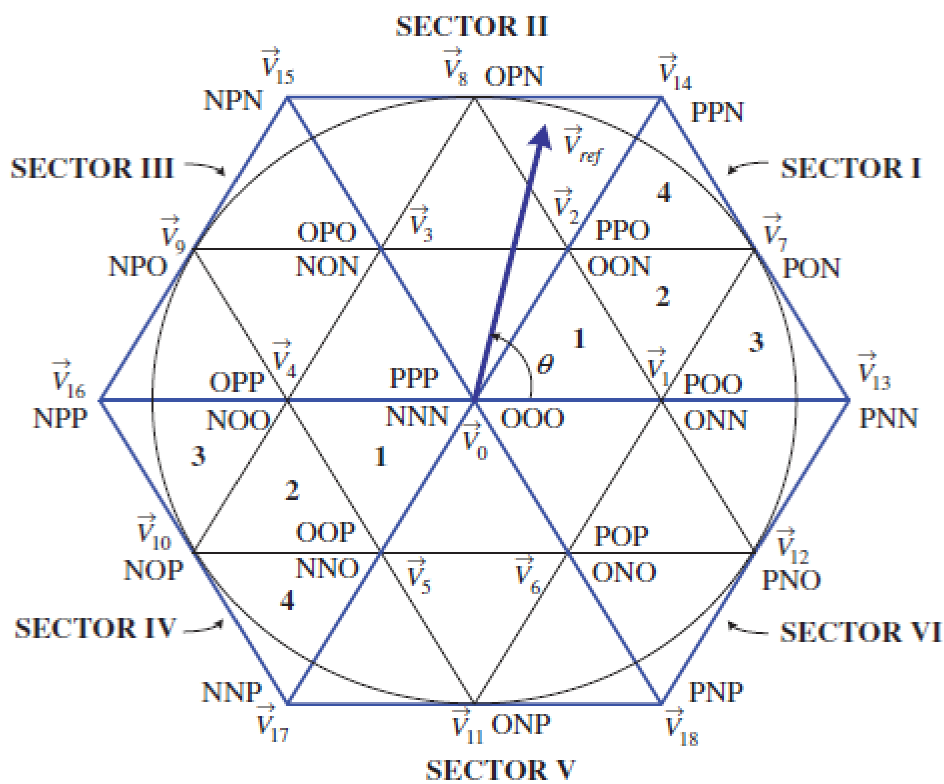


Figure 8.2: Division of Sectors and Region for three level SVM

8.1 RELATIONSHIP AMONG MAGNITUDE OF REFERENCE VECTOR AND SEGMENTS IN A SECTOR

As we can notice that, in case of level SVM in order to minimize the total harmonic distortion each sector (I-VI) is divided into 4 regions (1,2,3,4). So, it is mandatory to determine the amplitude ofthe reference vector for each of the region

.

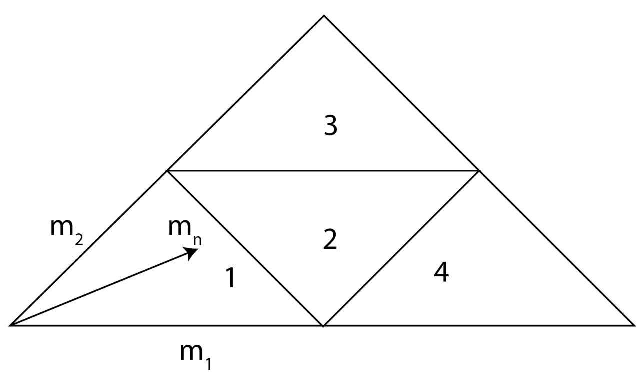


Figure 8.3: Length of reference vector in a segment at sector I

Here, in the figure 8.2 (a), m_1 = d-c = $m_n cos\alpha - m_2 \cos\left(\frac{\pi}{3}\right)$ .... (8.1)

Now, $m_2 = a = \frac{b}{\sin\left(\frac{\pi}{3}\right)} = \frac{2}{\sqrt{3}}b = \frac{2}{\sqrt{3}}m_n sin\alpha$ .... (8.2)

Putting m_2 in equation (8.1) we get

$$m_1 = m_n cos\alpha - \left(\frac{2}{\sqrt{3}}m_n sin\alpha\right)\cos\left(\frac{\pi}{3}\right) = \frac{m_n 2}{\sqrt{3}}\sin\left(\frac{\pi}{3} - \alpha\right) \text{............} (8.3)$$

Here, $m_n = \frac{2}{\sqrt{3}} m_a \left[m_a = modulationindex = \frac{\sqrt{3} V_{ref}}{V_d} \right]$ from previous chapter

Now, for $\overrightarrow{V}_{ref}$ in region 1 $\rightarrow m_1,\ m_2$<0.5 and $m_1 + m_2 < 0.5$

$\overrightarrow{V}_{ref}$ in region 2 $\rightarrow m_1, m_2 < 0.5 \quad and\ m_1 + m_2 > 0.5$

$\overrightarrow{V}_{ref}$ in region 3 $\rightarrow m_2 > 0.5$ and

$\overrightarrow{V}_{ref}$ in region 4 $\rightarrow m_1 > 0.5$

8.2 SEGMENT WISE DWELL TIME CALCULATION

The procedure for calculating dwell time will be as same as that for two level SVM discussed in the previous chapter. In this case from figure 8.1 we can see that the reference vector $\overrightarrow{V}_{ref}$ is in region 3 of sector II. So, in order to calculate the dwell time of $\overrightarrow{V}_{ref}$ in that particular region, we should take three nearest stationary vectors $\overrightarrow{V}_2,\ \overrightarrow{V}_8\ and\ \overrightarrow{V}_{14}$ into account. So in that case from volt-second balancing equation we get,

$$\overrightarrow{V}_{ref} T_s = \overrightarrow{V}_2 T_a + \overrightarrow{V}_8 T_b + \overrightarrow{V}_{14} T_c \ldots\ldots\ldots\ldots\ldots\ldots\ldots.. (8.4)$$

By following the same procedure as in chapter we can determine the $T_{a,}$ T_b and T_c.

$$T_a = T_s \left[1 - 2m_a \sin\left(\frac{\pi}{3} + \theta\right) \right] \ldots\ldots\ldots\ldots\ldots (8.5)$$

$$T_b = T_s \left[2m_a \sin(\theta) - 1 \right] \ldots\ldots\ldots\ldots\ldots\ldots.. (8.6)$$

$$T_c = T_s \left[2m_a \sin\left(\frac{\pi}{3} - \theta\right) + 1\right] \ldots\ldots\ldots\ldots\ldots\ldots (8.7)$$

The dwell times that can be evaluated similarly for each of four regions in each sector. By this way, when $\overrightarrow{V}_{ref}$ is rotated at an angle $\frac{n\pi}{3}$ from sector I, the dwell times in that particular sector will be equal that in sector I [22].

8.3 DESIGNING SWITCHING SEQUENCE

Keeping in account the basic criterion for minimizing switching loss as discussed in the previous chapter the switching sequence is designed for this three level SVM [23]. From figure 8.1 as the reference vector is in sector 2. So the switching sequence for that sector will be as follows:

Region1: PPO-OPO-OOO-OON-NON- and return

Region2: PPO-OPO-OPN-OON-NON- and return

Region3: OPO-OPN-NPN-NON- and return

Region4: PPO-PPN-OPN-OON- and return.

The switching sequence for each phase is derived in figure 8.3 for region 1 of sector II.

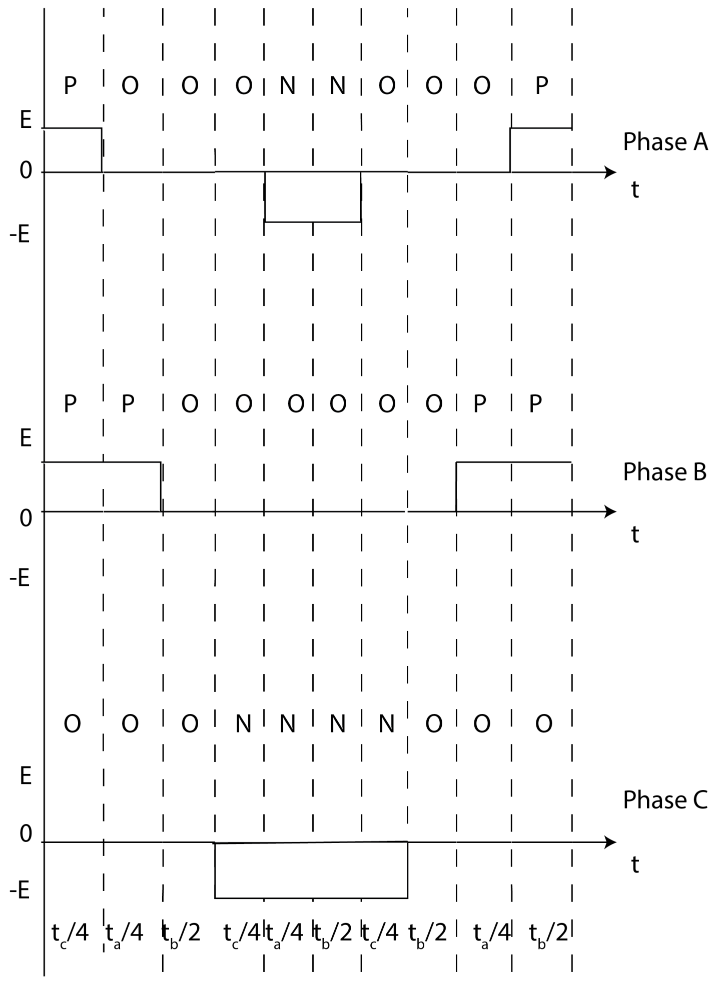
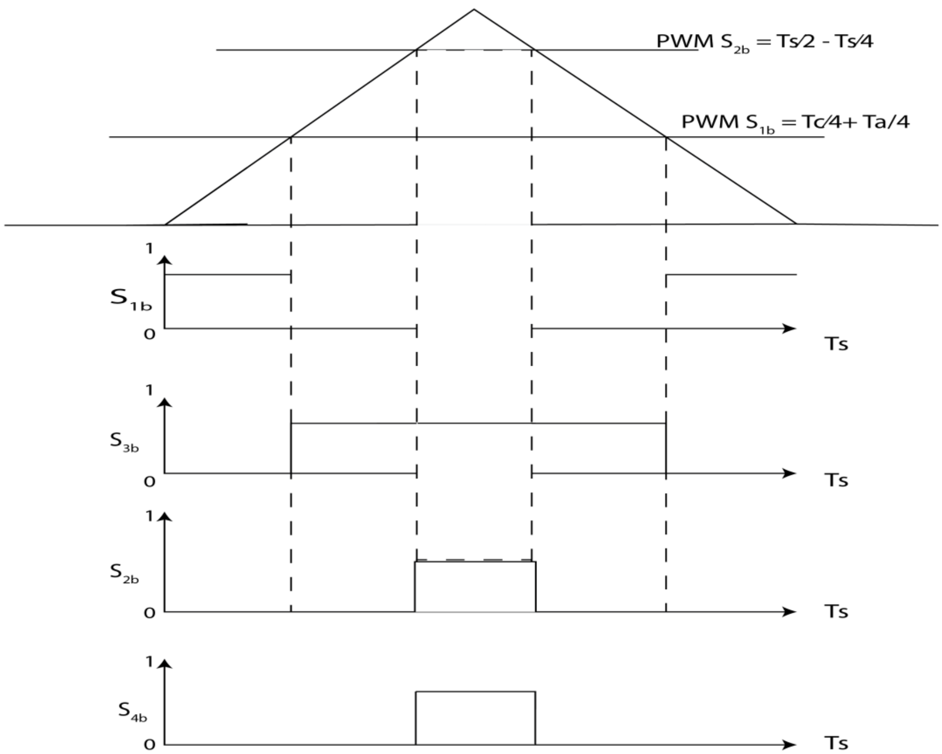


Figure 8.4: Settings of firing time for sector 2 phase Y

8.4 GENERATION OF A SYMMETRICAL PWM AS A GATE PULSE OF UPPER SWITCHES OF EACH LEG



As shown in figure 8.4, two PWM generators are used to convert the three level voltage waveform (E, O and -E) in figure 8.3, of each phase into two level of switches (0 and 1) [24]. We know that the upper two switches of each leg are complementary to the lower ones for example (S_{1b}'=S_{3b} and S_{2b}'=S_{4b}) [25]. So, the time when any one of the upper switch is ON=1 then its complementary lower switch will be OFF=0 and vice-versa [26]. By this way the firing time of upper arms can be obtained for regions in sector II. PWM_S_{1b} and PWM_S_{2b} are the two PWM generators in the figure which are used to control the firing time wave shape of the switches [27].

Figure 8.5: Firing settings of time

Therefore, by this way the gate pulse is being generated for the upper leg of each switch for sector I.

Now, for determining the gate pulses for other sectors we applied a simplified technique called shifting and reversing method [28]. Here, when the reference vector swings from sector I to sector II, the phase voltages shift and at the same time mirrors themselves [29]. It is accomplished by exchanging of PWM signals between to corresponding phases [30].

8.5 PHASE VOLTAGE SHIFTING AND MIRRORING

It be achieved by exchanging the PWM signals between two corresponding phases [31]. Such as, if the phase voltages in sector I are V_r, $V_y$and V_b, then the phase voltage of sector II will be $e^{\frac{\pi}{3}j}$ times of each phase voltage resulting in V_y,$V_b$and $V_r$for three phases [32]. Then mirroring of the phase voltages occur by reversing the PWM signals of switches of upper arm with that of lower arm [33]. Suppose for switching state P, $S_1$and S_2 are OFF and S_3 and S_4 are OFF. By mirroring the switches S1 and S2 are ON and S3 and S4 are ON and this sate is known as N The mirroring of state O will be [34] .So, the resulting voltage in phase R, Y, B will be $-V_y$, $-V_b$ and $-V_r$ respectively [35]. By this process, the switching time for each switches in each sector is determined.

Table 8.2: Reversing and Mirroring of Phase Voltage:

Sector	**Phase Voltage**	**On Time**	
		S_1	S_2
I	V	PWM_S_{1b}	PWM_S_{2b}
II	-V	T_s/2– PWM_S_{2b}	T_s/2- PWM_S_{2b}

Chapter 9

RESULTS AND COMPARISON BETWEEN SVM AND MPC ON NPC

We have done the comparison between MPC and SVM on the basis of the value of the parameters for which the NPC inverter gives the best response [36]. The parameters that we have taken into are load resistance (R), load inductance (L), sampling time (T_s), DC source voltage(V_{dc}), back electromagnetic force (E).

9.1 DIFFERENCE ON THE BASIS OF LOAD CURRENT TRACKING THE REFERENCE CURRENT

For MPC: Values of the parameters for which we got the best response are

Table 9.1

Parameters	**Identification**	**Values**
R	resistance	10 Ω
L	inductance	90 e^{-3} mH
T_s	Sampling time	32 e^{-6} sec
E.M.F	Back Electromotive Force Peak Value	25 volt
V_{dc}	DC Source Voltage	620 volt

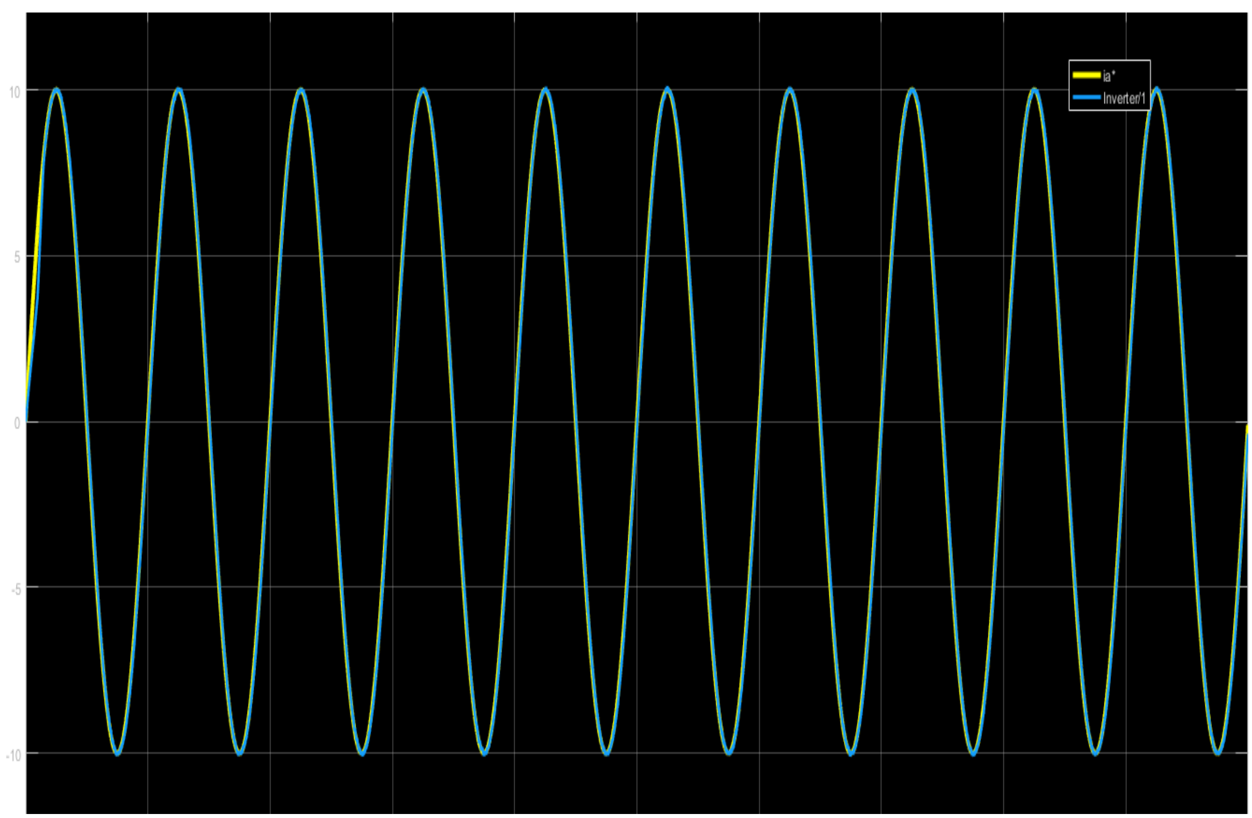


Figure 9.1: Load current (blue) tracking the reference current(yellow)

For SVM:

Table 9.2

Parameters	**Identification**	**Values**
R	resistance	40 Ω
L	inductance	20 e^{-3} mH
T_s	Sampling time	3 e^{-4} sec
E.M.F	Back Electromotive Force Peak Value	5 volt
V_{dc}	DC Source Voltage	400 volt

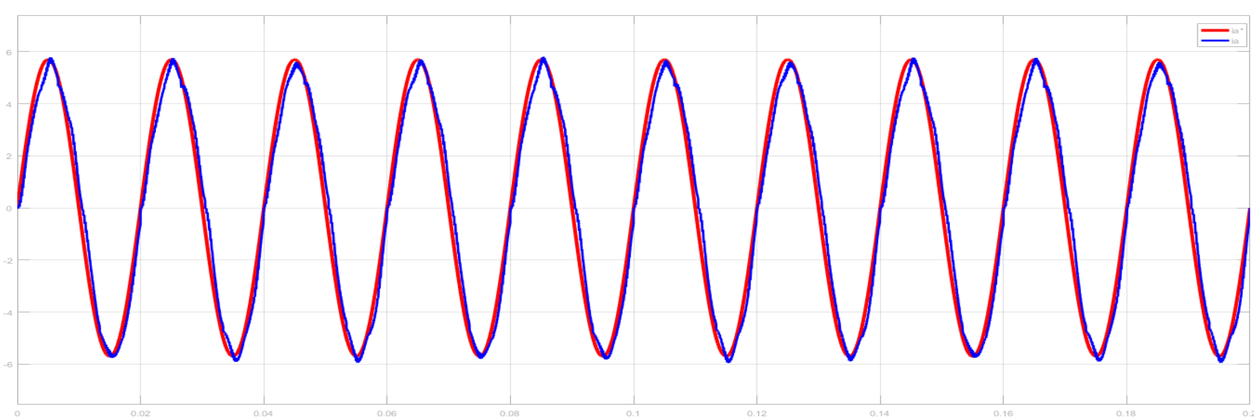


Figure 9.2: Load current(blue) tracking the reference current(red)

9.2 Three Phase Load Current Waveform of NPC

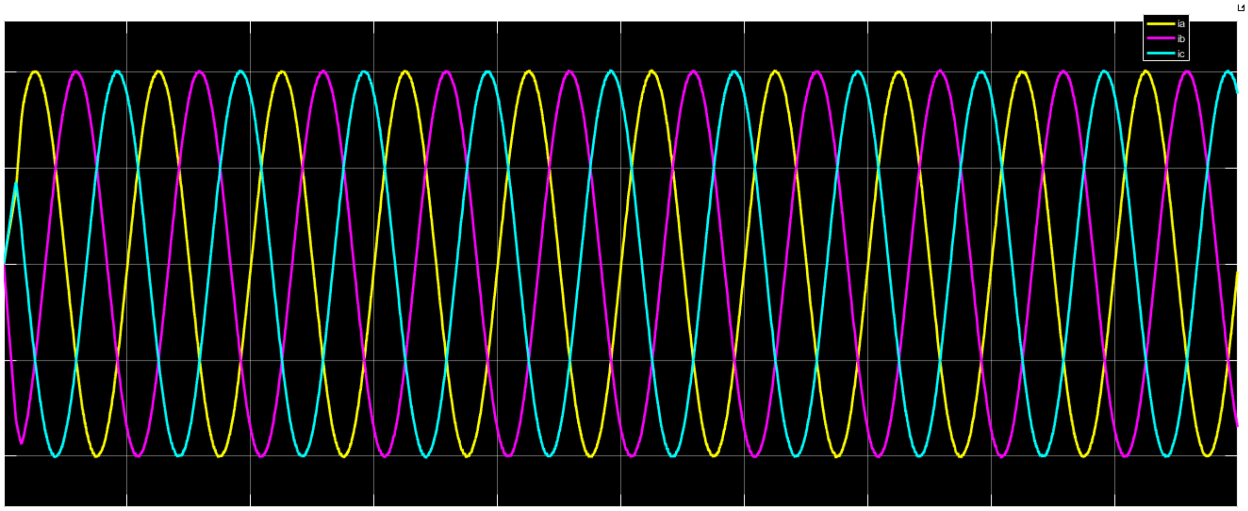


Figure: 9.3: Load Current (three phase) for MPC

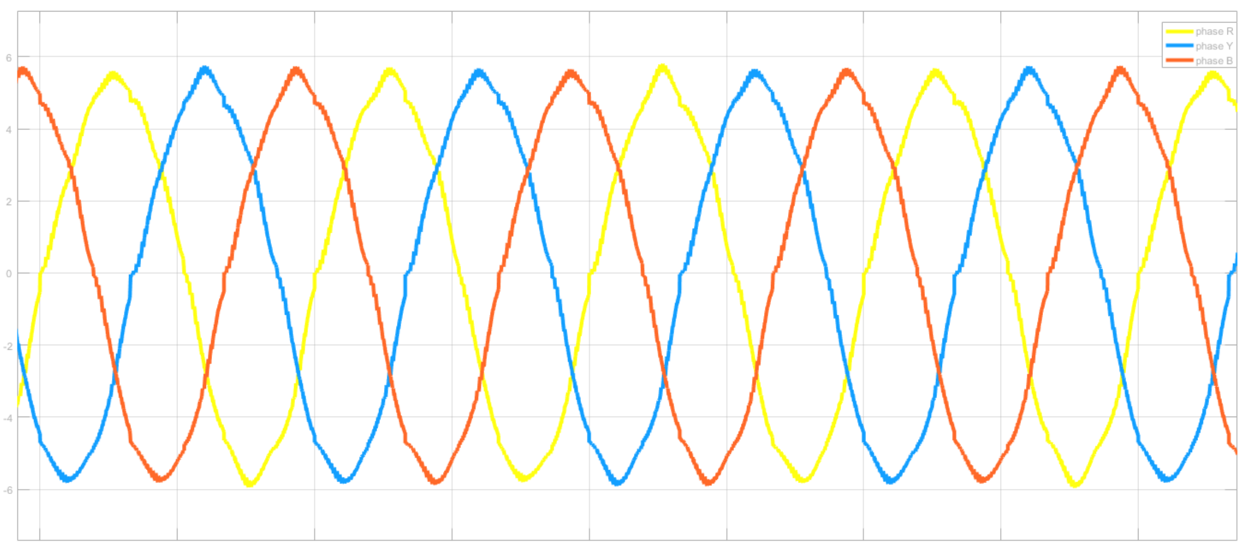


Figure 9.4: Load Current (three phase) for SVM

9.3 COMPARATIVE ANALYSIS

From these above figures we have found that the phase current across load of NPC in case of SVM is more distorted than that of MPC.

The total harmonic distortion of load current that we have obtained from Simulink THD block is

For MPC: 0.6%

For SVM: 5.8%

The switching frequency that we obtain from MPC for these parameters is 12.42 kHz whereas for SVM it is 1.19 kHz.

The switching frequency for SVM is much smaller than MPC which is also a major reason for the greater THD of SVM than MPC.

9.4 Three Output Phase Voltage Waveform of NPC

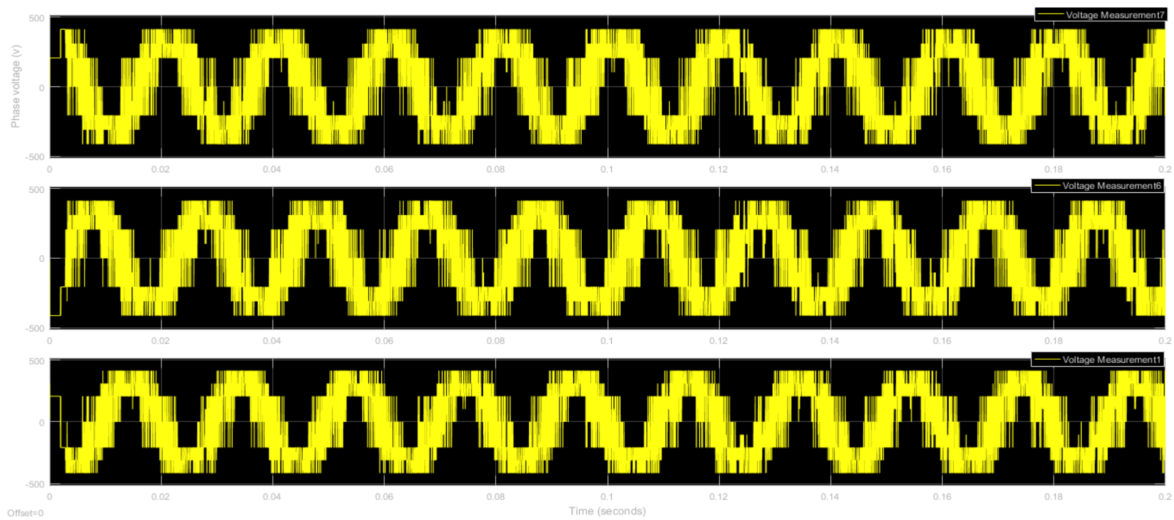


Figure 9.5:Three Level Three Phase Load Voltage Waveforms for MPC

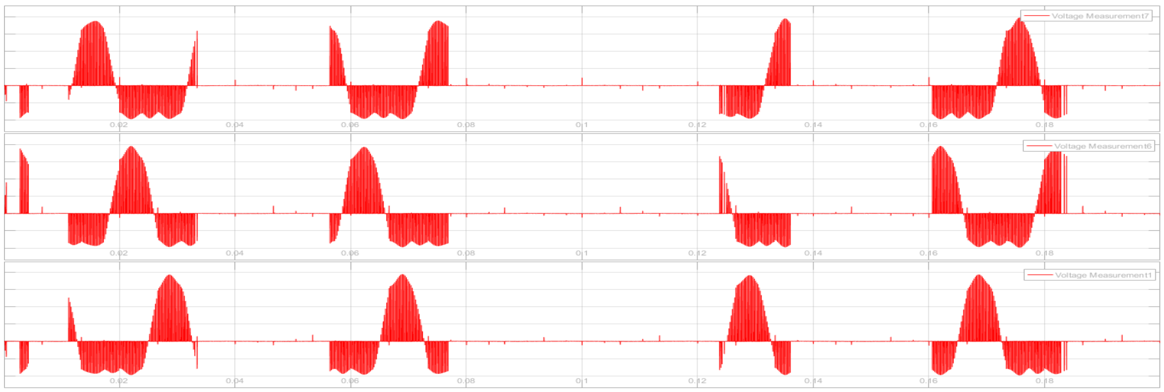


Figure 9.6: Three Level Three Phase Load Voltage Waveform for SVM

9.5 Line to line Voltage Waveform for NPC

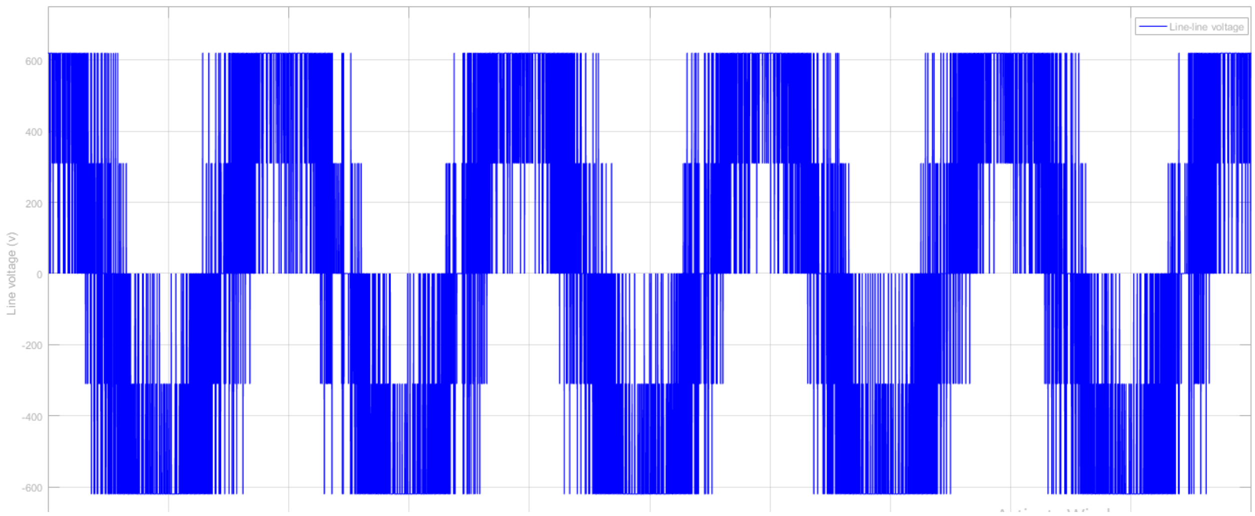


Figure 9.5: Line to Line Voltage (V_{RY})for MPC.

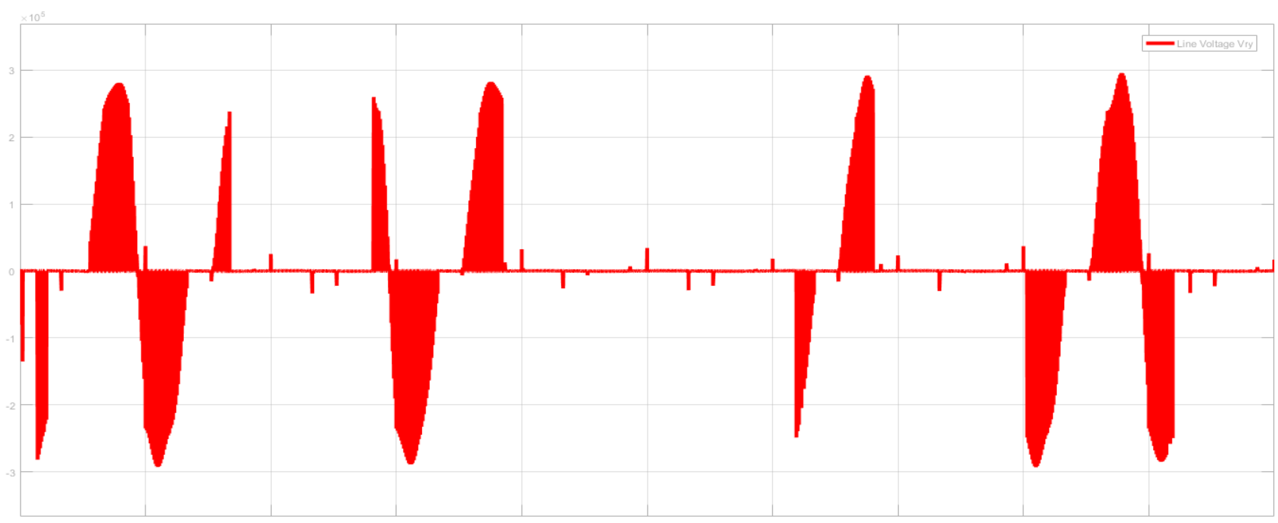


Figure 9.6: Line to Line Voltage (V_{RY}) for SVM

9.6 COMPARATIVE ANALYSIS

Here, we can see that the output voltage waveform obtained by SVM technique is too much distorted than that of MPC [37]. One of the main reasons for this distortion is that, in case of SVM we synthesized the reference vector situated in a region into three most nearest stationary voltage vectors [38]. For this reason there was a deviation between the actual value of the reference vector and the calculated value [39]. The amplitude of the reference vector in a certain region of a sector was considered variable upto certain range which failed ensure the real tracking of the value of the reference voltage. The more number of regions can be formed in a sector, the more possibility to reduce distortion will be obtained [40].

In case of MPC, we coined a term called cost function optimization, which helped us to select the value of the instantaneous voltage least deviated from the reference vector algorithmically.

9.7 CAPACITOR VOLTAGE BALANCING

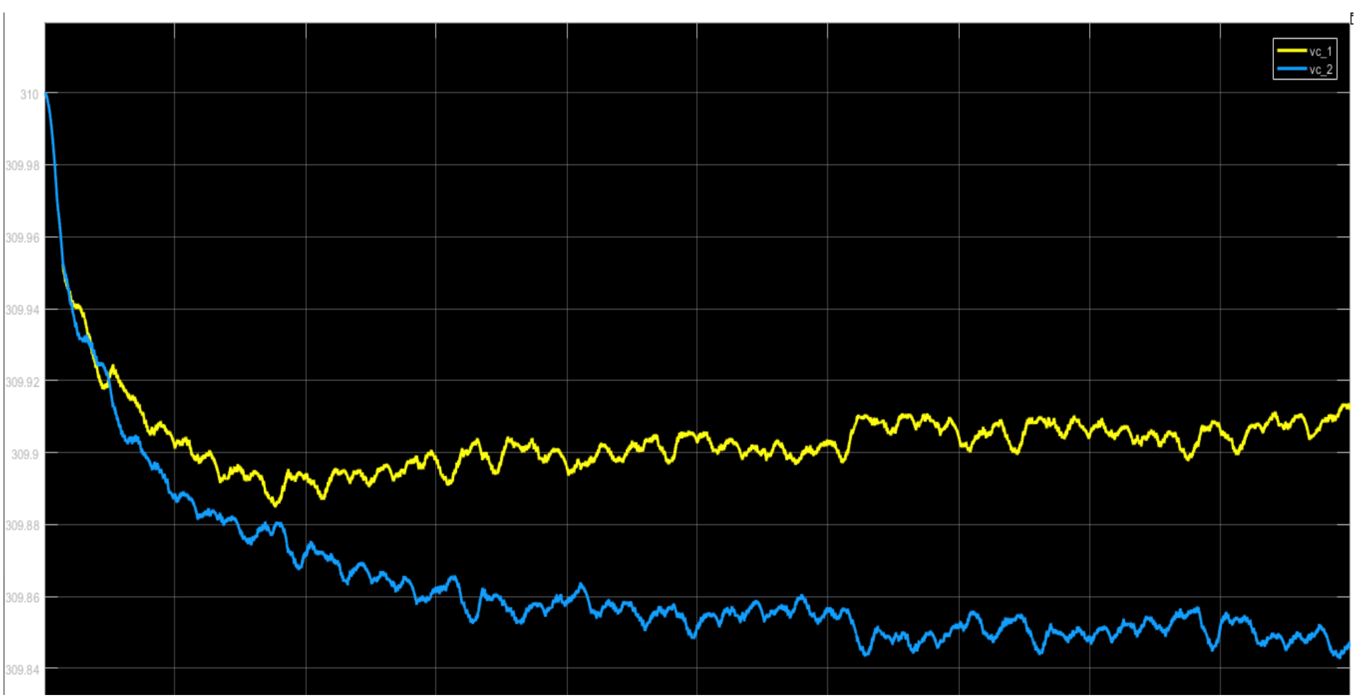


Figure 9.7: Capacitor Voltage Balancing by MPC for C= 250 mF

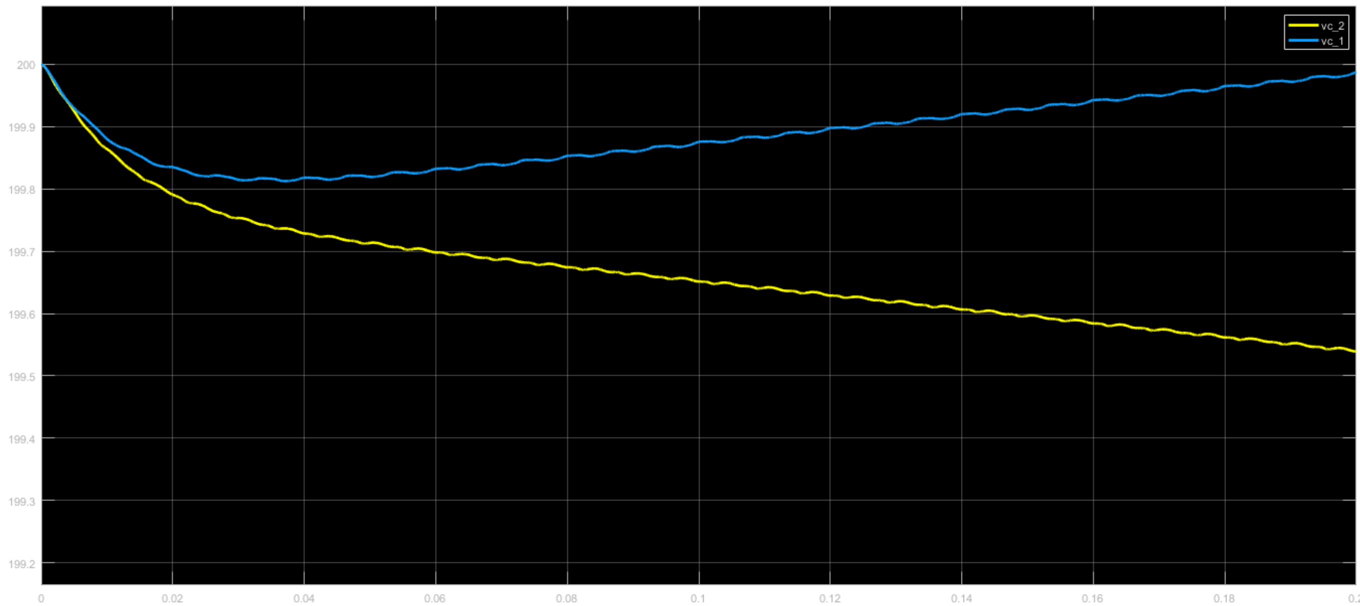


Figure 9.8: Capacitor Voltage Balancing by SVM for C=250 mF

We have tried to minimize the voltage difference between two capacitors of NPC for both the techniques. As discussed in section 4.6, weighting factor is a very powerful term for NPC which plays a very important role in minimizing the voltage difference between the capacitors with a very simplified algorithm whereas such a simplified algorithm is very hard to obtain in case of SVM [41]. So, from the above wave shapes we can see in case of MPC the difference between the two capacitor voltages during the simulation period is about 0.06V and it is more or less stable.

But, in case of SVM the difference during the simulation period is 0.41V. Although, this difference is also very low, but as we can see, the difference is increasing gradually.

9.8 BALANCED CAPACITOR VOLTAGE IN MPC BY APPLYING WEIGHTING FACTOR

The wave shape in figure 9(g) that we obtained from MPC for the weighting factor 0.002. By changing the weighting factor from 0.002 to 0.02 we got the following curve.

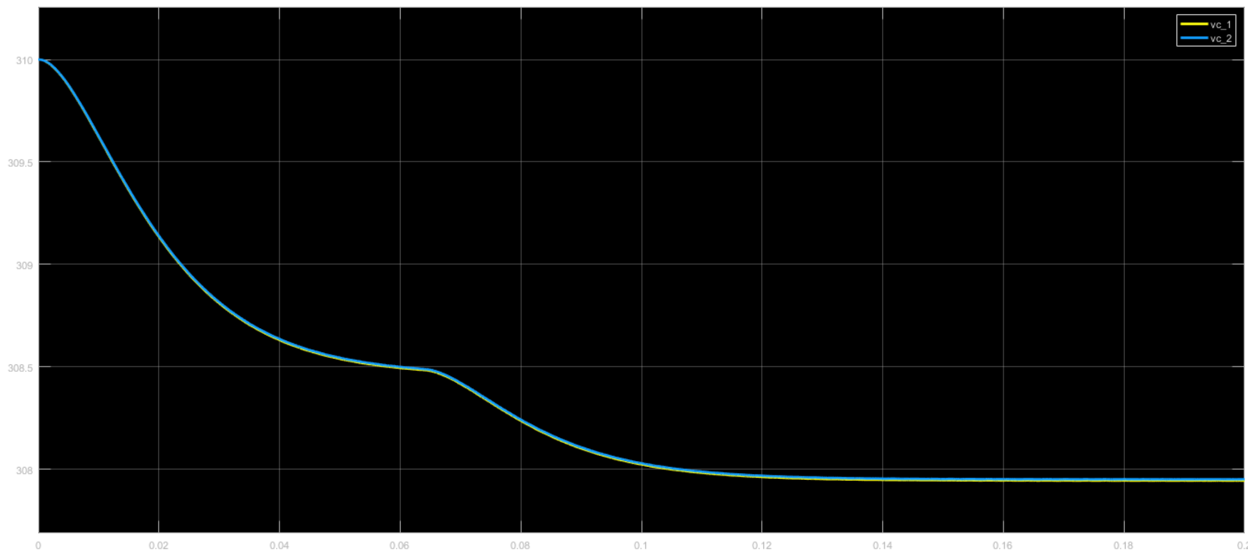


Figure 9.9: Capacitor Voltage Balancing in MPC by increasing weighting factor

Chapter 10

CONCLUSION AND FUTURE PROSPECTS

10.1 CONCLUSION

In this paperwork, we have applied different parameters of load and control techniques (MPC, SVM) on Neutral Point Clamped Inverter for induction motor and observed the response of the inverter for each of them. In case of MPC, an arbitrarily chosen constant has been selected for the optimization of cost function instead of going through any algorithmic approach. On the other hand, a simplified algorithm has been followed for allocating reference vector in different region of different vectors for SVM to minimize calculation complexities.

10.2 FUTURE WORK AND IMPROVEMENT

In this thesis work, we have applied two different control techniques on Neutral Point Clamped Inverter known as MPC and SVM. In these cases, the above mentioned procedures have been applied for balanced load only. With proper research, the performance can be applied on unbalanced load in future. More improvised procedures can be adapted to minimize the difference between capacitor voltages and thus reduce the total harmonic distortion. THD needs to be reduced by following an algorithmic process.

APPENDIX

This chapter appendix is given to give the reader necessary tools to understand the process described above and can implement it in simulation environment. The simulation process have been done using MATLAB Simulink. The MATLAB code is not given here due to some copyright issues, but all the necessary figures are given so that any one can easily develop the code for themselves. This appendix only gives the overview of MATLAB implementation of MPC and SVM techniques on NPC inverter.

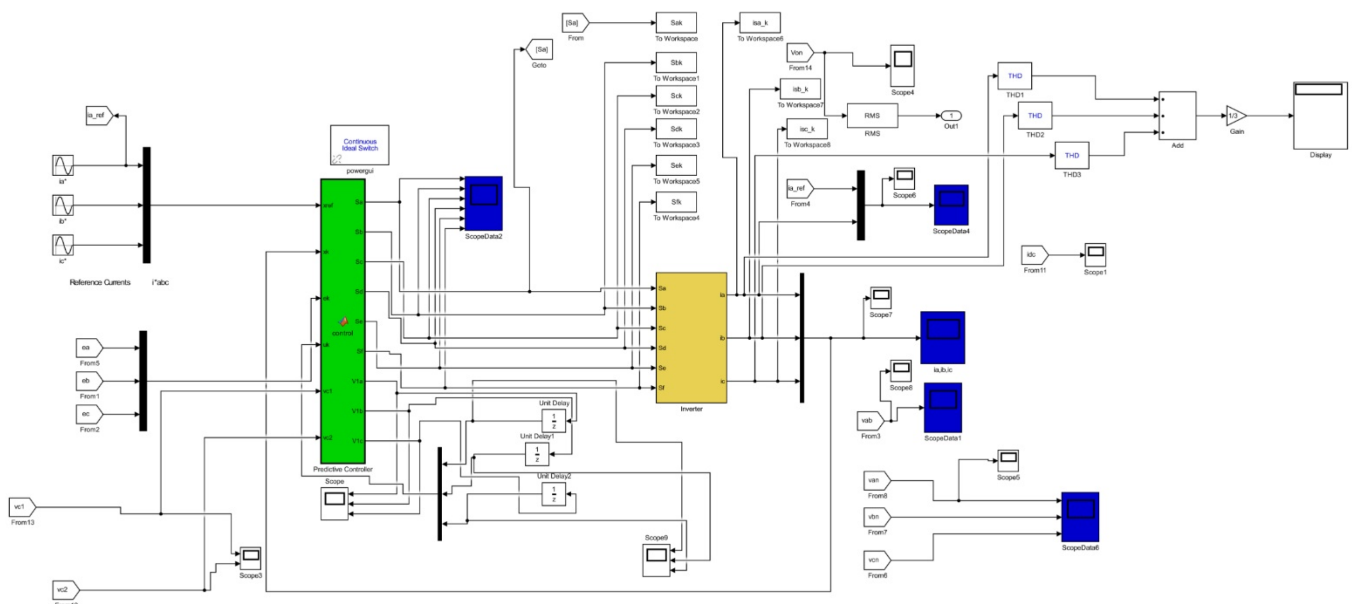


Figure 10.1: Simulink MPC Block Model of three level three leg NPC inverter

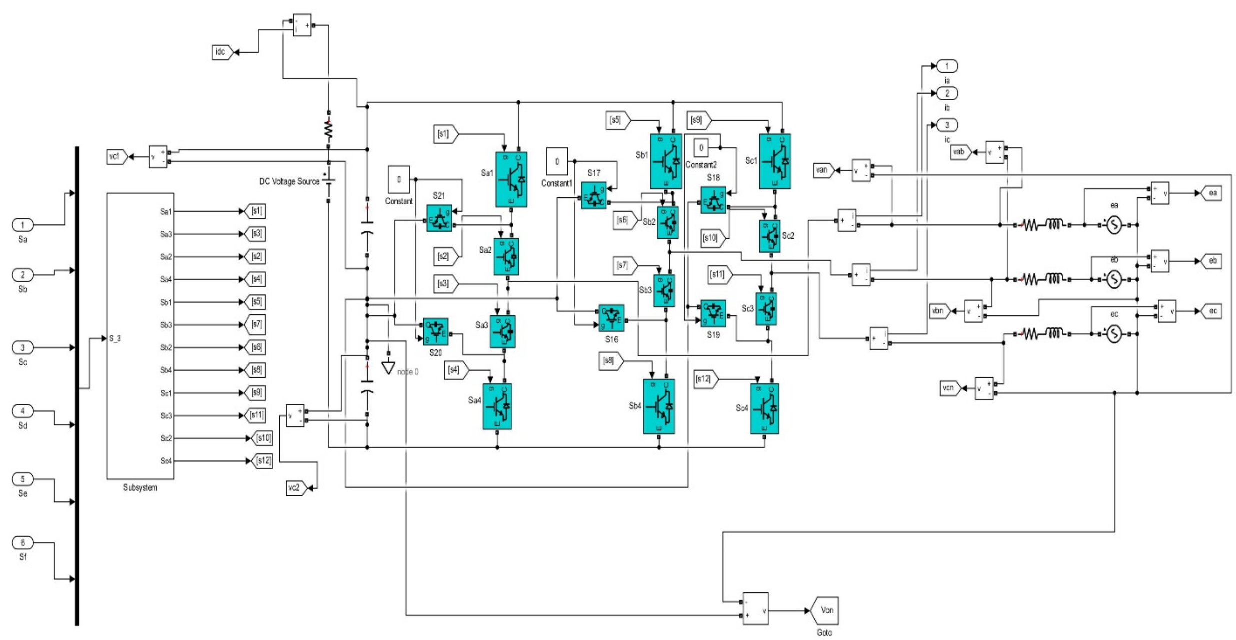


Figure 10.2: Inverter Circuit Diagram for Both MPC and SVM

Here, a circuit based model is developed to maintain the real time characteristics of the inverter. Here all the elements like filter current, load current, neutral line current, capacitor voltage, line voltage switching states etc have been checked using ‘go to’ Simulink box that contain that value and can be received by using ’from’ Simulink box.

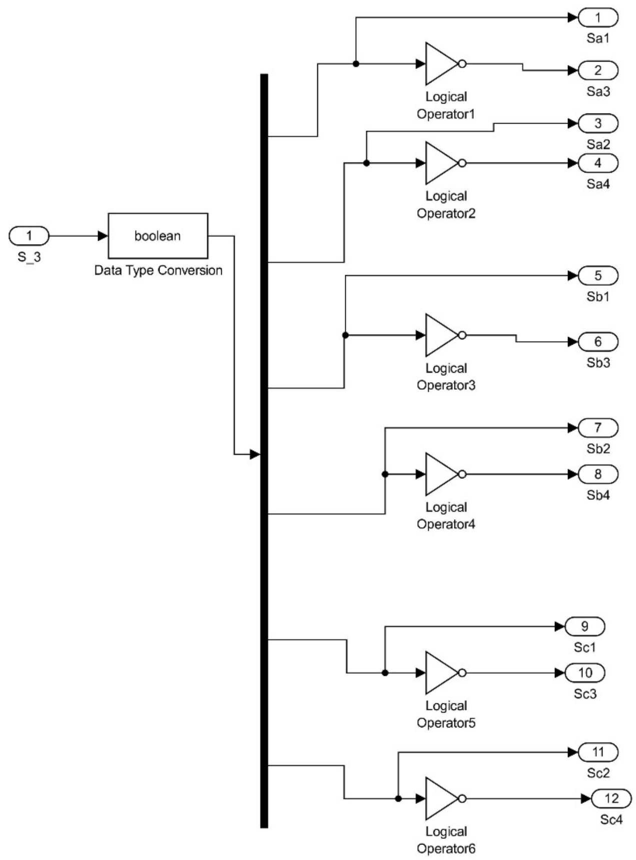


Figure 10.3: Switching states received and extracted by subsystem

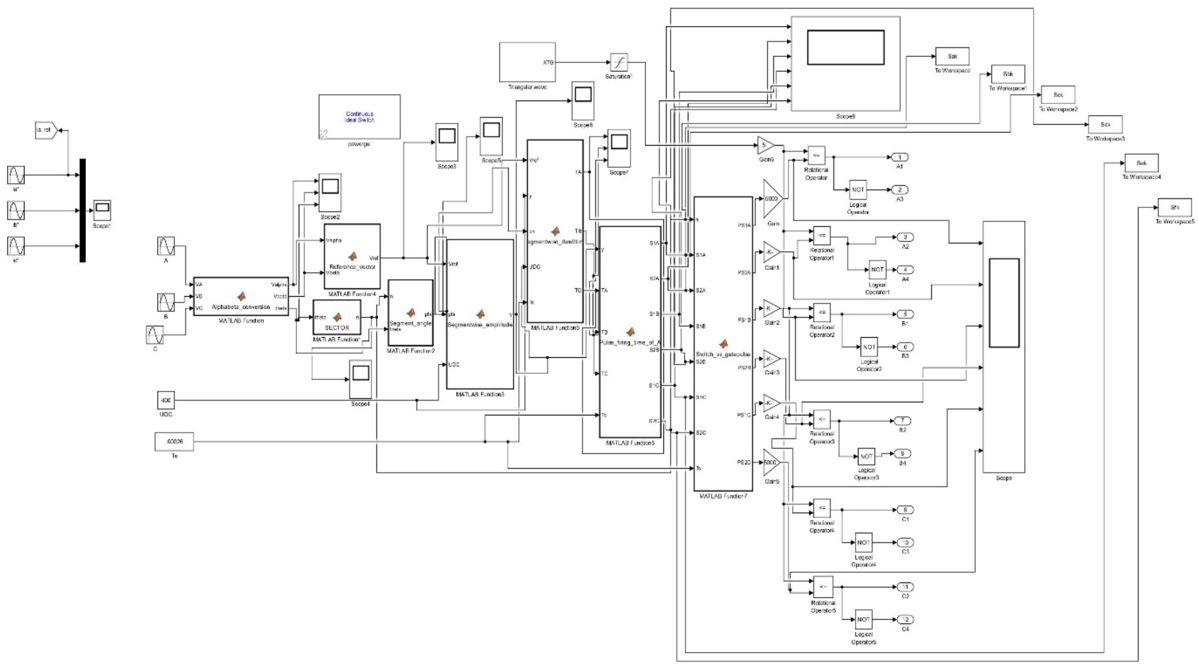


Figure: 10.4 Simulink Block Circuit Model for SVM Algorithm.

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