

POWER QUALITY IMPROVEMENT BY EMPLOYING PWM TECHNIQUES AND FLC BASED SHUNT ACTIVE POWER FILTER

Dissertation submitted in partial fulfillment of the requirement for the award of degree
of

**Master of Engineering
in
Power Systems**

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JULY, 2014

CERTIFICATE

I hereby certify that the work which is being presented in this dissertation entitled, "**Power Quality Improvement by Employing PWM Techniques and FLC based Shunt Active Power Filter**", in partial fulfillment of the requirements for the award of degree of *Master of Engineering in Power Systems* at Thapar University, Patiala, is an authentic record of my own work carried out under the supervision of **Mr. Shakti Singh**, Assistant Professor, Department of Electrical & Instrumentation Engineering. The matter embodied in this dissertation has not been submitted for the award of any other degree to any other university.

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ACKNOWLEDGEMENT

Words are often less to reveal one's deep regards. With an understanding that work like this can never be the outcome of a single person. I take this opportunity to express my profound sense of gratitude and respect to all those who helped me through the duration of this work.

I would like to express my gratitude and thanks to my supervisor, **Mr. Shakti Singh, Assistant Professor**, Department of Electrical and Instrumentation Engineering, Thapar University, Patiala, for his patient guidance and support throughout this work. It was an honor and a privilege to work under him as a student. He also provides the help in technical writing and presentation style and I found his guidance to be extremely valuable.

I would also like to thank **Dr. Ravinder Agarwal, Professor and Head** and **Ms. Manbir Kaur, Associate Professor & PG Co-ordinator**, Department of Electrical and Instrumentation Engineering, Thapar University, Patiala, for providing this opportunity to carry out dissertation work.

I am also thankful to God and my friends who devoted their valuable time for the successful completion of dissertation. I express my feeling to all faculty and staff of Department of Electrical and Instrumentation Engineering, Thapar University, Patiala for successful completion of dissertation.

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ABSTRACT

Power quality issues are created in the power system mainly due to the nonlinear characteristics of power electronic based equipments. The large scale utilization of these nonlinear and time varying load lead to the distortion of current and voltage waveforms and simultaneously demands more reactive power from the supply. Harmonic distortion is identified as the cause of several power quality problems like extra power loss, heating in rotating machines, flicker and the communication circuit interference. To solve these problems active power filters have been developed, which is used to eliminate the harmonics and simultaneously compensate for the reactive power requirement.

In this work, pulse width modulation techniques and fuzzy logic control based three phase shunt active power filter is implemented for three phase three wire system in order to eliminate the harmonics and reactive power compensation and hence improving the power quality. Compensation is based on sensing the line currents only.

The system has been simulated using the Matlab/Simulink platform. Various simulation results are presented and performance of the different control techniques is compared and it is found that the performance of fuzzy controller is better than the other control techniques.

LIST OF ABBRIVATIONS

APF	-	Active Power Filter
ASD	-	Asynchronous Speed Drives
CSI	-	Current Source Inverter
CPWM	-	Chaos based Pulse Width Modulation
FLC	-	Fuzzy Logic Controller
GTO	-	Gate Turn-off Thyristor
IGBT	-	Insulated Gate Bipolar Transistor
IGCT	-	Integrated Gate Commutated Thyristor
MF	-	Membership Function
PC	-	Personal Computer
PI	-	Proportional Integral
PWM	-	Pulse Width Modulation
SMPS	-	Switch Mode Power Supply
SPWM	-	Sinusoidal Pulse Width Modulation
SRF	-	Synchronous Reference Frame
STATCOM	-	Static Synchronous Compensator
SVPWM	-	Space Vector Pulse Width Modulation
THD	-	Total Harmonic Distortion
UPQC	-	Unified Power Quality Conditioner
UPS	-	Uninterruptable Power Supply
VSI	-	Voltage Source Inverter

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CHAPTER 1

INTRODUCTION

1.1 Overview

Power quality is an important factor in the field of power system. In industrial and the domestic environment both the sensitive apparatus and non-linear loads are present because of this a heightened awareness of power quality is developing. Earlier the apparatus was designed to bear up the turbulences such as lightning, short circuits, and abrupt overloads without extra expenses. Now days, power electronics equipment prices would be considerably higher if the equipment were to be designed with the same toughness. Pollution has been brought into the power system mainly by nonlinear loads such as computer equipment with switched-mode power supplies, adjustable speed drives (ASD), photocopiers, fax machines, battery chargers, fluorescent light ballasts, and medical diagnostic apparatus. Due to their nonlinear characteristics as well as fast switching, power electronic apparatus creates most of the pollution problems. Most of the electrical pollution problems are created because of the nonlinear characteristics and reckless switching of power electronic apparatus. Nearly 60% to 70% of today's energy is managed by power electronic, the fraction is estimated to grow further in the years to come, this is mainly due to the fast growth of power electronic proficiency. There is a close contest between the pollution caused by the power electronic apparatus and their sensitivity, on one side and the new power electronic centered, controlled devices, having the capability to mitigate the problems produced by the power electronic on the other side [1].

Large scale utilization of power electronic apparatus produces the various unwanted effects like low efficiency of the overall system, reduced power factor and interference with the proximate communication network. Thus, it became necessary to overcome these unwanted effects. Typically, shunt passive filters, which comprises of tuned LC filters and high pass passive filters were used to mitigate the harmonics and improve the overall power factor. However, they have the limitation too, like they can produce the series resonance with the impedance of the source, thereby causing the harmonic amplification, in addition problems of fixed compensation and large size is also there [2].

The limitations of a passive filter can be overcome by using the active power filter (APF), they can be used as an impeccable solution to crack the problems caused by the

deficiency of electric power quality. The developing technology of power-electronic apparatus and the new progresses in the digital signal processing field have made its use possible. These APF can fully mitigate the problems caused by the nonlinear loads like harmonics, unbalances, reactive power, etc. So, APF can be called by the name of active power line conditioners [3].

On the basis of the type of converter used the APF can be classified as a current source inverter (CSI), or voltage source inverter (VSI), bridge structure. Further on the basis of topology can be classified as shunt, series or a combination of both. In addition to this APF are classified on the basis of a number of phases, as two wires and three or four wire three phase systems. Usually the current controlled voltage nourished PWM converter type shunt active filter has proved to be more efficient even if the load is extremely nonlinear. In addition to this voltage nourished inverter is lighter, economical, and stretchable to multilevel and multistep forms, to boost the performance with lower switching frequencies. Commonly the APF are developed on the basis of sensing the harmonics and the reactive volt-ampere requirements by the non-linear load. For achieving the above, a complex control scheme is required. The required compensating current can be resolved by sensing the load current which can be improved further by sensing only the line currents [4].

First of all the conventional proportional integral (PI), controllers was used to generate the reference signal for the APF. PI controller requires the exact linear mathematical modeling, which are not easy to obtain and didn't perform acceptably whenever there is the parameter variation, load disturbance and nonlinearity etc. [5]. The second technique which have been utilized is the sinusoidal pulse width modulation (SPWM), this is the easiest modulation scheme to be implemented in software. But this technique has the disadvantage that it fails to utilize the supply dc bus voltage fully which is applied to the VSI. This inability of SPWM technique led to the development of space vector pulse width modulation (SVPWM), which is effective in terms of reducing the total harmonic distortion (THD), the effective exploitation of supplied dc bus Voltage, so the output voltage with the SVPWM is 15% greater as compared to SPWM [6].

Chaos Based PWM (CPWM), this technique uses the chaotic-changing frequency to spread the harmonic continuously and evenly so as to suppress the peak harmonics [7,8].

Fuzzy logic Controller (FLC), has proved to be the best tool in control design developed by the zadeh. The benefits of FLC over the different technique are its high heftiness,

insensitivity to parameter variations, management of non-linearity and no need of mathematical modeling [5,9].

1.2 Objective of work

The objective of this work is to implement different PWM techniques and FLC based shunt APF for power quality improvement by eliminating the harmonics and compensating the reactive power. Brief comparison is carried out between the different control techniques.

1.3 Literature review

Fuchs and Masoum [1] introduced the subject of electric power quality. Presented the detailed classification of power quality and its causes. Detailed explanation was made on the measures for the power quality improvement along with poor power quality impacts on the power system and end user devices.

Akagi [2] proposed that, the term active power line conditioner should be used for the APF since the active power line conditioner would cover a larger sense than the APF. Discussed the active power line conditioners using the PWM inverters by considering the practical application.

Moreno-Munoz [3] discussed the active power line conditioners. Presented the common configuration of shunt and series APF. Control strategy and design are discussed for the shunt APF.

Singh et al. [4] considered the three/four pole topologies for the current controlled VSI, the power balance theory was employed. Prototype model of the APF was designed and tested for checking its effectiveness for harmonic elimination. Simulation and experimental results were discussed in detail.

Gupta et al. [5] proposed fuzzy logic controlled three phase shunt APF for eliminating the harmonics and thus improving the power quality. This improved the dynamic performance of shunt APF under the different load condition. The performance of the PI and FLC were compared under the different load condition.

Chelladurai *et al.* [6] analyzed the comparative advantages of SPWM and SVPWM techniques and also investigated the suitability of these techniques in a shunt APF. Proposed the method that manifested the effective utilization of dc bus voltage and also the reduction of harmonic at input side. Showed that with the SVPWM technique, there was only the minor improvement in the THD level.

Li *et al.* [7] proposed the simulated study of the periodic and chaotic behavior of the dc – dc converter for the certain parametric conditions. Proposed the chaos based PWM which distributes the harmonics evenly and continuously over the entire frequency range thereby reducing the EMI. Simulation and the experimental results were obtained to demonstrate the effectiveness of the proposed scheme.

Wei Cui *et al.* [8] implemented the CPWM technique for ac motors, in order to reduce the harmonic peaks and hence the acoustic noise. Simulation and experimental results show that the CPWM takes the advantage over the conventional PWM techniques.

Muthazhagi and Kumar [9] proposed the implementation of shunt APF for mitigating the current harmonics caused by the non-linear load condition for power quality improvement. Investigated the most effective control technique that was capable of reducing the harmonics. Made the comparison of the three control technique: PI controller, hysteresis current controller and FLC. Simulation results proved that the source current harmonics could be reduced and significant improvement in the power quality.

Ise *et al.* [10] proposed a method which defines the quality of power for the unbridled power quality service, on the assumption to supply the three levels of power quality like premium, high and normal quality power. A simple circuit for the single phase loads was also presented in this paper.

Jain *et al.* [11] proposed the fuzzy logic controlled three phase shunt APF for compensating the harmonics. The fuzzy control scheme was realized on a micro controller system. Performance of FLC was compared with the PI controller. Generation of the PWM pattern based on the carrier less hysteresis based current control to obtain the switching pulses.

Peng *et al.* [12] described quad series voltage source PWM converter for eliminating the ac harmonics. Proposed a new control circuit, focused on the transient states on the basis of reactive power theory. Designed a passive LC filter to remove the current ripples caused by PWM converter.

Kalaignan and Raja [13] proposed an innovating shunt APF with the PI controller. The ripple voltage of the PWM voltage source inverter was reduced by the PI controller, it is shown that PI controller was also useful in determining the switching angles for eliminating the harmonics.

Raviraj and Sen [14] described the comparison study of PI, sliding mode and FLC for the power converters. Focused on the some similarities of the FLC and sliding mode controller. Comparison of these controllers to supply voltage and load disturbance was studied and the results were presented.

Jain [15] discussed the steady state analysis and dynamic behavior of machines, power electronic equipment with the help of simpowersystems. Discussed the integration of simulink block with simpowersystem.

Kiran *et al.* [16] proposed the shunt APF which monitors the load current continuously so as to track the changes in the load harmonics. Instantaneous power theory with PI and hysteresis current control was used to estimate the performance of a shunt APF.

Huang and Wu [17] proposed a control algorithm for improving the performance of the three phase three wired APF under the voltage imbalance condition. A control circuit was simplified and the proposed algorithm was implemented as a prototype.

Chatterjee *et al.* [18] proposed the harmonic suppressor system and a control method for the reactive volt ampere compensation. The compensating process was very fast and that too without employing any complicated control logic. A mathematical model was developed and simulation results were presented.

Watanabe *et al.* [19] reviewed the conventional active and reactive power theory for the steady state analysis and the introduced the instantaneous power theory that was valid for the

steady state, transient state and also for the generic voltage and current waveforms. It has been shown that how this theory could be utilized for design and control of the APF.

Dixon *et al.* [20] proposed a new method which was based on the sample and hold circuit and was synchronized with the peak value of phase to neutral mains voltages. Sudden transient changes in the load were slow down by this method. The proposed method was very useful for the shunt APF to eliminate the harmonics.

Duke and Round [21] described the APF that uses the d-class asynchronous switching inverter for current distortion. Distortion component was determined using the synthetic sinusoid. Proposed an intelligent controller which maintains the APF performance at the optimal operating point under the different load condition.

Djeghloud *et al.* [22] considered the SVPWM studies for the three phase three level voltage and current inverters and established the mathematical models for the two converters, gave the SVPWM principle and applied it for generating the switching orders for the converters. A test system has been simulated using the MATLAB/SIMULINK

Charles and Vivekanandan [23] proposed a closed loop system for the shunt APF in which the SVPWM technique was implemented. Synchronous reference frame (SRF), theory was utilized for extracting the reference harmonic component from the nonlinear load current. The shunt APF generates the compensating harmonic current on the basis of switching pulse provided by the controller. A test system has been simulated using the MATLAB/SIMULINK and was able to improve the THD level by 30.18%.

Viswanath and Kapoor [24] proposed the comparative study by the simulations of hysteresis current control and SVPWM for generating the PWM pulses for a shunt APF. SRF theory was utilized for extracting the reference harmonic component from the nonlinear load current and the constant capacitor voltage method was adopted.

Das [25] discussed mainly the band pass filter and damped filters, their operation was described with respect to the system design and limitations. This approach showed that there is the limitation on system design large modifications could lead to damage to the filters. The

limitations faced by the designer with the new tools of harmonic analysis, measurement and system analyses were discussed.

Soares *et al.* [26] proposed the instantaneous active and reactive current component method for the shunt APF. To check out its effectiveness it was compared with instantaneous active and reactive power p-q method under the different mains voltage condition and various harmonic injection. Both methods were frequency independent, but for the distorted mains voltage the method proposed provides the better harmonic compensation.

Singh *et al.* [27] made the comparison of two types of current control technique. TMS320C31 digital signal processing was used for implementing the closed loop control scheme for three phase APF for direct and indirect current control techniques. A current controlled VSI has been used as APF.

Torrey and Al-Zamel [28] proposed an APF for the single phase system which consist of multiple nonlinear loads. H-bridge inverter forms the basis of APF. Details of the power circuit design, controller design and the spectral performance of a filter supporting the 364W as controlled and 884 W uncontrolled rectifiers have been presented. It has been shown that APF consumes 3% or less of the average power.

Machmoum *et al.* [29] described a simple voltage controller whose working was based on the power balance concept. Its structure and synthesis was generalized in such a manner so as to perform both the function of APF as well as PWM rectifier by sensing the active power required on the dc side and that too was done without adding the modification to the control circuit.

Singh *et al.* [30] discussed review on the APF configurations, control strategies and their selections for various applications. It provided broader view on the status of the APF technology to the applicant engineers.

Moran *et al.* [31] proposed the dynamic characteristic of a three phase APF which operates on a fixed switching frequency. Principle of operation of the PWM voltage source converter was discussed along with its control circuit and design. Finally the results were obtained with the 5-KVA prototype confirmed the feasibility of the proposed system.

1.4 Author's Contribution

In this work, five different control techniques like SPWM, SVPWM, CPWM, PI and FLC for the shunt APF have been compared and the performance of all are investigated. The control scheme for the PI and FLC involved the calculation of the reference source current by regulating the dc voltage of the VSI. The active component of the current is supplied by the source and the shunt APF supplied the rest of the component. In case of SVPWM and SPWM the calculation of the reference current is accomplished by using the SRF theory and for the CPWM, a chaotic sequence is generated by using the Matlab platform, in order to generate the switching signals. A design criterion has been described here in order to select the power circuit components. A detailed simulink model is developed for all the above techniques in order to predict the performance of different control techniques.

1.5 Organization of Dissertation

The body of the dissertation includes the following five chapters in addition to the first chapter:

- Chapter 2, presents the brief introduction about the power quality issues, assets and improvement techniques.
- Chapter 3, presents the description of shunt APF, compensation principle and the assessment of reference source current.
- Chapter 4, presents the various control schemes like PI, SPWM, SVPWM, CPWM, and the FLC.
- Chapter 5, presents the simulation result of various control techniques.
- Chapter 6, presents the conclusion and future work.

Chapter-2

Power Quality

Power Quality

The term power quality is defined as “set of factors outlining the properties of power quality as supplied to the user in common operating conditions in terms of continuousness of power supply and features of voltage like symmetry, frequency, magnitude and waveform” as described in the IEC and according to the IEEE standard. 1100-1999, power quality is defined as “the idea of powering and the grounding of electrical and electronic equipment in a way that is appropriate to the operation of that equipment and harmonious with the assumed wiring system and other linked equipment”.

As presented in these definitions, power quality includes all the concerned sides of the power supply. Aspects on power quality can be categorized into three categories, which are voltage stability, continuity of power supply, and voltage waveform [1].

These three aspects are further classified as below:

- a) Voltage stability
 - Under-voltage
 - Over-voltage
 - Voltage sag
 - Voltage swell
 - Phase shift
 - Flicker
 - Frequency
- b) Continuity of power supply
 - Momentary interruption
 - Temporary interruption
 - Sustained interruption
- c) Voltage waveform
 - Transient
 - Three phase voltage unbalance

- Harmonic voltage, current
- Notch

The main cause of the harmonics, notches, inter-harmonics and the neutral currents are the power electronic equipment. The main source of harmonics are rectifiers, switched mode power supply (SMPS), soft starters, HVAC using ASD etc [10].

Power electronics apparatus shows the various levels of sensitivity to power quality problems, which depends on the nature of disturbance as well as a type of the equipment. As per the IEEE-519 standard, the maximum tolerable values of harmonic pollution are stated in terms of THD which should be less than 5%.

Power electronic has three aspects in power distribution which are:

- a) One that presents appreciated the industrial and domestic equipment
- b) One that generates problems;
- c) One that assists to solve these problems [4].

2.1 Solution to power quality problems

The solution to the problem is to connect a harmonic filter for every nonlinear load connected to the power system. Different types of harmonic filters are there which include the passive, active, and hybrid configurations. The installation of active filters plays a very vital role in mitigating the power quality problems in the distribution networks like the remuneration of harmonic current and voltage, reactive power, voltage sags, voltage flicker etc. Eventually, this would confirm a system with improved reliability and enhanced power quality. Filters can only mitigate the harmonic currents or harmonic voltages at the connected bus, but they will not take into account the power quality of additional buses. A new age of active filters includes unified power quality conditioners (UPQC), and active power line conditioners, which overcome the disadvantages of conventional passive filters [2].

2.2 Power filter topologies

Depending on the type of application or problem to be resolved, APF can be employed as a shunt, series, or a combination of two (shunt-series type). These filters could also be employed with the passive filters to form the hybrid power filters.

The shunt-connected APF, with a self-controlled dc bus voltage, is similar in topology to that of a static compensator (STATCOM), employed for the reactive power compensation in a power system. Shunt APF mitigate the load current harmonics by inserting equal and opposite harmonic reimbursing current. Here the shunt APF functions as a current source inserting the harmonic components produced by the load nevertheless phase-shifted by 180° . The series APF inserts a voltage component in series with supply voltage and consequently can be viewed as a controlled voltage source, mitigating voltage sags and swells on the load side. In most of the cases, series APF work as a hybrid topology using the passive LC filters [4].

The series-shunt topology is a grouping of the series APF and the shunt APF. On the load side the shunt APF is connected and it can be utilized to mitigate the load harmonics. Whereas the series APF is installed at the source side and it behaves as a harmonic blocking filter. This topology is being called by the name of UPQC [10].

2.3 Voltage source converter

Generally the APF uses the voltage source converter type of topology, a capacitor is generally used as a voltage source at the dc bus, which acts as an energy storage device. This configuration is shown in the Fig 2.1. This converter converts the dc voltage into an ac voltage by accurately generating the gating signals for the power semiconductor switches. Even though for the each half cycle a single pulse can be applied to synthesize an ac voltage, for most of the demands which require the dynamic performance, pulse width modulation (PWM), is the technique which is generally used today [4].

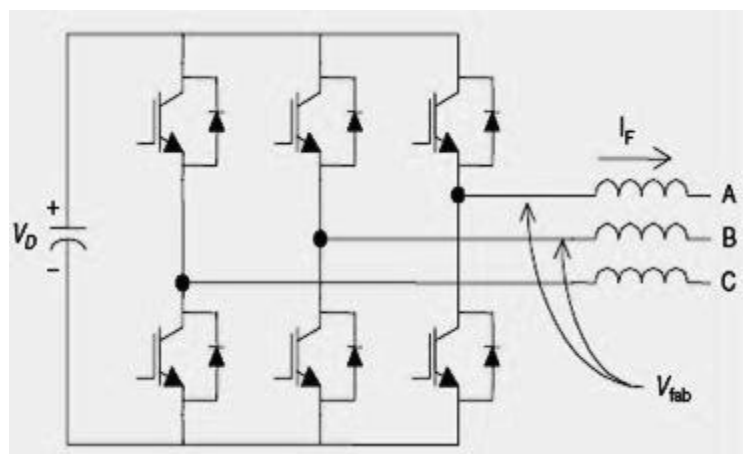


Fig. 2.1 Voltage source converter topology for active filters [15]

Fig. 2.2 shows the triangular carrier technique which is the most simplest and one of the common techniques by virtue of which the PWM works. The output voltage V_a is forced over a switching cycle, which is defined by the carrier period of V_{car} , that to be equal to the average amplitude of the modulating signal V_a^{ref} . The resulting voltages for a sinusoidal modulating signal must contain a sinusoidal fundamental component and unwanted harmonic components. By setting the carrier frequency as high as possible these unwanted harmonic components could be minimized using a frequency carrier as high as possible, which in-turn depends on the maximum switching frequency of the semiconductor device like IGBTs, GTOs, or IGCTs etc [11].

The modulation method as shown in the Fig.2.3 uses a triangular carrier wave, which is one of the many methods applied today for controlling of power inverters. Figure 2.3 shows the phenomenon of the generation of compensating current for a shunt APF using the three contrasting modulation techniques for CSI. These three techniques are called by the name as

- (i) Periodical sampling (PS): The power transistors of the APF are switched when there is the transitions of square wave clock of fixed frequency i.e. sampling frequency
- (ii) Hysteresis band (HB): Here the transistors are switched when the error become greater than the fixed value.
- (iii) Triangular carrier (TC): It compares the error in the output current with the fixed magnitude and the fixed triangular wave [12].

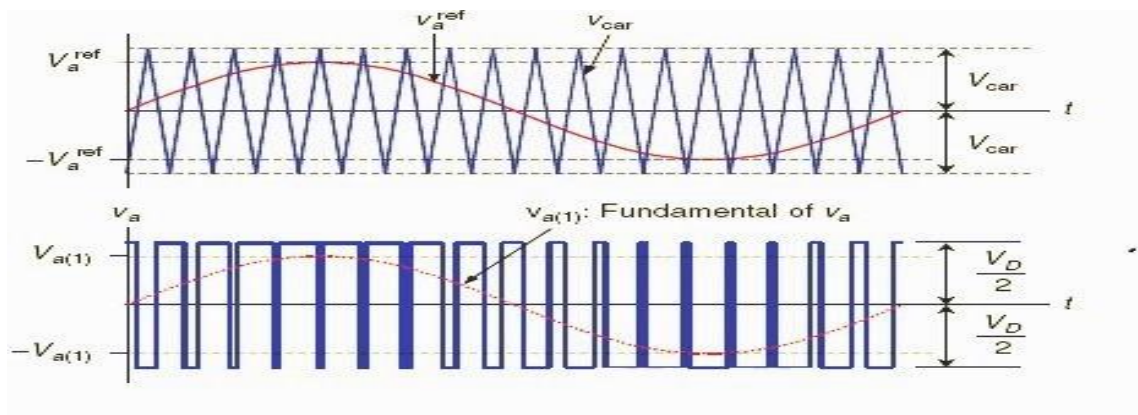


Fig.2.2 The PWM carrier Technique (triangular carrier) [15]

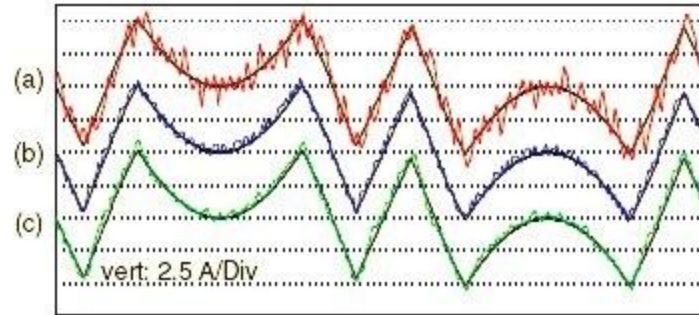


Fig.2.3 Current waveforms obtained using different modulation methods for an APF:

(a) PS method, (b) HB method, (c) TC method. [15]

Voltage source converters are desired over current source converter because of its higher efficiency and low initial cost. The voltage source converter can be readily operated in parallel so as to have higher rating and by having the precise control over the voltage source converter, their switching rate can be improved such that their respective switching times does not coincide. Hence, higher-order harmonics can be mitigated by using the converters without increasing converter switching rates[15].

Chapter-3

Shunt Active Power Filter

Shunt active power filter

The shunt APF with a self-restrained dc bus, have a topology which is similar to that of a static compensator (STATCOM) that is utilized for reactive power compensation in power transmission systems. Shunt APF mitigate the load current harmonics by introducing equal and opposite harmonic compensating current. Here the shunt APF work as a current source introducing the harmonic components created by the load but shifted in phase by 180° .

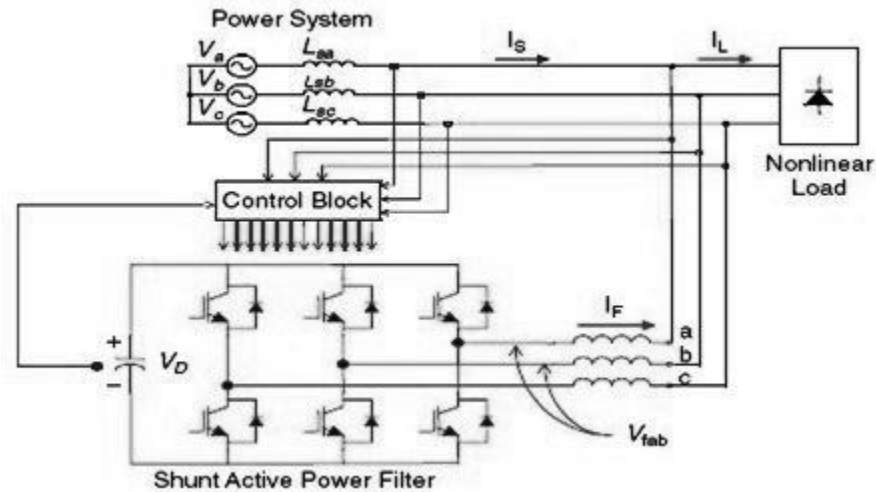


Fig.3.1 Shunt Active Power Filter [16]

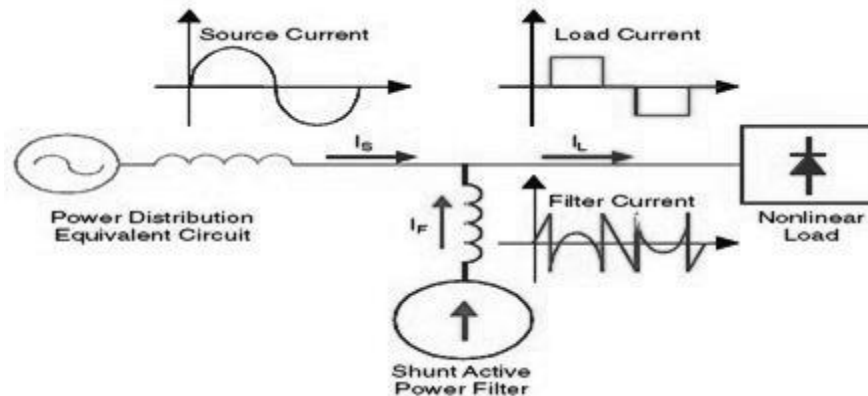


Fig. 3.2 Filter current I_F generated to mitigate the load current harmonics [16]

3.1 Basic compensation principle

Fig.3.3 below shows the basic compensation principle for the shunt APF. It is restrained to draw or supply the compensating current is from or to the utility, such that it can cancel out the current harmonics on the ac side, and causes the source current to be in phase with the source voltage. Fig.3.4 shows the different current waveforms. Curve A presents the load current waveform and curve B presents mains current and the Curve C presents the compensating current introduced by the shunt APF containing required harmonics necessary to make mains current sinusoidal.

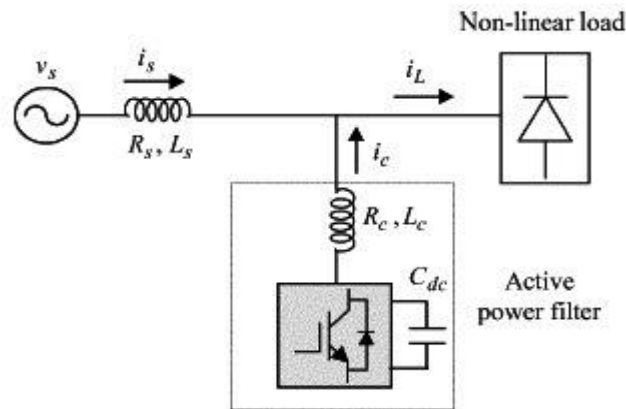


Fig. 3.3 Shunt APF basic compensation principle [11]

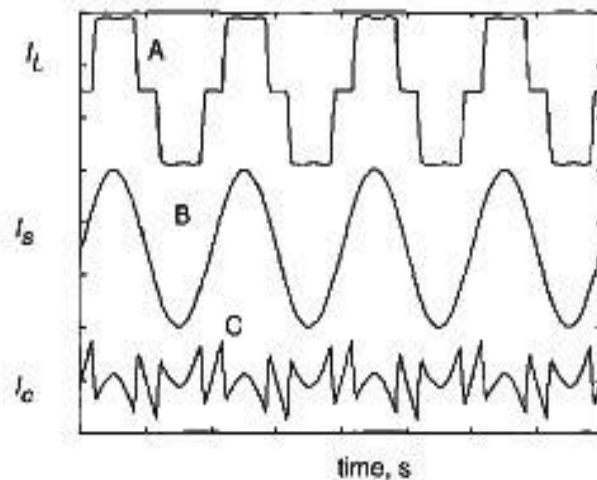


Fig. 3.4 Shunt APF: shape of load current, source and filter current waveforms [11]

3.2 Assessment of reference source current

From Fig.3.1 the instantaneous currents equation can be written as

$$i_s(t) = i_L(t) - i_c(t) \quad (3.2.1)$$

Where $i_s(t)$, $i_L(t)$ and $i_c(t)$ are the instantaneous values of the source current, load current, and filter current respectively.

Source voltage is given as

$$v_s(t) = V_m \sin \omega t \quad (3.2.2)$$

Where $v_s(t)$ and V_m are the instantaneous and peak value of the source voltage respectively.

Now on the connection of the non linear load, the load current will be composed of two components, namely fundamental component and the harmonic components and can be represented as

$$i_L(t) = \dots + \dots \quad (3.2.3)$$

The instantaneous load power is given by

$$P_L(t) = v_s(t) * i_L(t) = V_m I_1 \cos \phi_1 + V_m I_1 \sin \phi_1 \cos \phi_1 \sin \omega t + V_m \sin \omega t * \dots \quad (3.2.4)$$

$$= P_f(t) + P_r(t) + P_h(t) \quad (3.2.5)$$

Where $P_f(t)$, $P_r(t)$, $P_h(t)$ are instantaneous real, reactive and harmonic power respectively.

From equation (3.2.4), the real power drawn by the load is given by

$$P_f(t) = V_m I_1 \cos \phi_1 = v_s(t) * i_s(t) \quad (3.2.6)$$

From equation (3.2.6), after the compensation the current supplied by the source, is given by

$$i_s(t) = P_s(t) / v_s(t) = I_1 \sin \omega t \cos \phi_1 = I_{sm} \sin \omega t, \text{ Where } I_{sm} = I_1 \cos \phi_1 \text{ and } \cos \phi_1 \text{ is the displacement factor.}$$

The PWM converter is accompanied with switching losses , therefore the utility must supply a fraction directly above for converter switching as well as for the capacitor leakage losses in addition to the real power for the load. Therefore source supplied peak current is given by

$$I_{sp} = I_{sm} + I_{sl} \quad (3.2.7)$$

Where I_{sl} , I_l and I_{c1} are the fundamental component of source current, load current and filter current respectively.

If the APF supplies the total reactive as well as harmonic power, then $i_s(t)$ and the utility voltage will be in phase and purely sinusoidal. Now, the APF must provide the following compensation current given below

$$i_c(t) = i_L(t) - i_s(t) \quad (3.2.8)$$

Therefore, assessment of the fundamental component of the load current as the reference one is necessary for the accurate and the instantaneous compensation of harmonic as well as reactive power.

By controlling the dc side capacitor voltage the peak value of the reference current I_{sp} could be assessed. The main current should have to be sinusoidal and in phase with voltage irrespective the nature of the load current for the compensation of harmonics. The source current after the compensation is given by $i_{sa}^* = I_{sp} \sin\omega t$, $i_{sb}^* = I_{sp} \sin(\omega t - 120^\circ)$, $i_{sc}^* = I_{sp} \sin(\omega t - 240^\circ)$)

Where i_{sa}^* , i_{sb}^* , i_{sc}^* are the three phase reference source currents.

Where $I_{sp}(=I_1 \cos\Phi_1 + I_{sl})$ is the amplitude of the source current, whereas the phase angle could be fetch from the source voltages. Thus the shape and the phase of the source current are known and their magnitude needed to be determined.

3.3 Role of dc side capacitor

The dc side capacitor performs the two functions (a) dc voltage is maintained with small ripples in steady state (b) during the transient period, it act as an energy storage element to supply the power which is equal to the difference between the load and source and in the steady state, source supplied the power which is equal to the summation of power demanded by load plus that required to compensate the losses in APF, so as to maintain the dc voltage at the reference value.

The three primary parameters for the power circuit design are as follows:

- Filter inductance L_c
- DC side Capacitor C_{dc}
- Reference value of the dc side capacitor $V_{dc\text{ref}}$.

3.4 Selection of L_c and $V_{dc\text{ref}}$

These components are being designed on the basis of following factors:

- Source voltage shall be sinusoidal
- For filter inductance, the line current distortion on the ac side shall be less than 5%.
- Reactive power capability of APF shall be fixed.
- The PWM converter shall work in the linear modulation mode ($0 \leq m_a \leq 1$)

Where m_a , m_f is the amplitude and the frequency modulation factor respectively.

From the phasor diagram the reactive power supplied by the APF can be calculated as

$$Q_A = 3V_s I_{c1} = 3 V_s V_{c1} / \omega L_c (1 - (V_s / V_{c1})) \quad (3.4.1)$$

Where V_s , V_{c1} are the rms source voltage and fundamental component of ac side voltage of PWM converter.

Thus the APF can compensate the reactive power supplied by the utility if $V_{c1} > V_s$

Again, if we assume that the PWM converter is working in the linear modulation mode, then m_a can be given as $m_a = v_m / (V_{dc} / 2)$

Where $v_m = \sqrt{V_c}$ and $V_{dc} = 2\sqrt{2} V_{c1}$ for $m_a = 1$

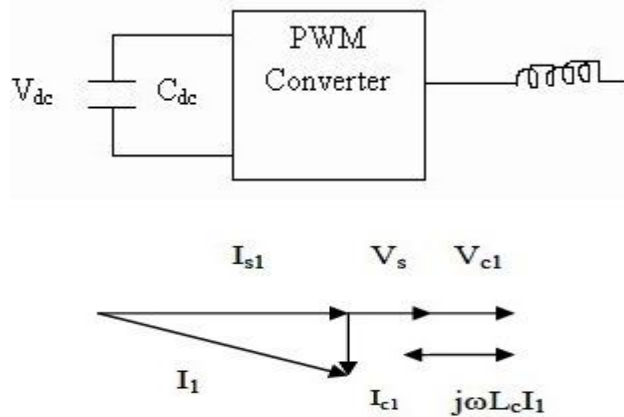


Fig. 3.5 APF and Phasor diagram [11]

The ripples of converter current are filtered out by using the filter inductor and thus its design is based harmonic current minimization principle. The ripple current can be expressed in terms of harmonic voltage, occurring at a frequency $m_f \omega$

$$I_{ch(mf\omega)} = V_{ch(mf\omega)} / mf \omega L_c \quad (3.4.2)$$

by solving the above two equations simultaneously, the value of L_c and V_{c1} can be found out and hence the value of V_{dcref} .

3.5 Design of capacitor on the dc side (C_{dc})

Principle of instantaneous power flow is used to design the C_{dc} . According to the requirement of peak to peak value of the voltage ripple ($V_{dcp-p(max)}$) and filter current ($I_{c1rated}$), the value of the capacitance on the dc side can be found as

$$C_{dc} = (\pi * I_{c1rated}) / (\sqrt{3} \omega V_{dcp-p(max)}) \quad (3.5)$$

CHAPTER 4

CONTROL SCHEME

4.1 PI control scheme

The diagram of shunt APF is shown below in the Fig.4.1 while the Fig.4.2 shows the control scheme realization. The dc capacitor voltage is compared with the reference value.

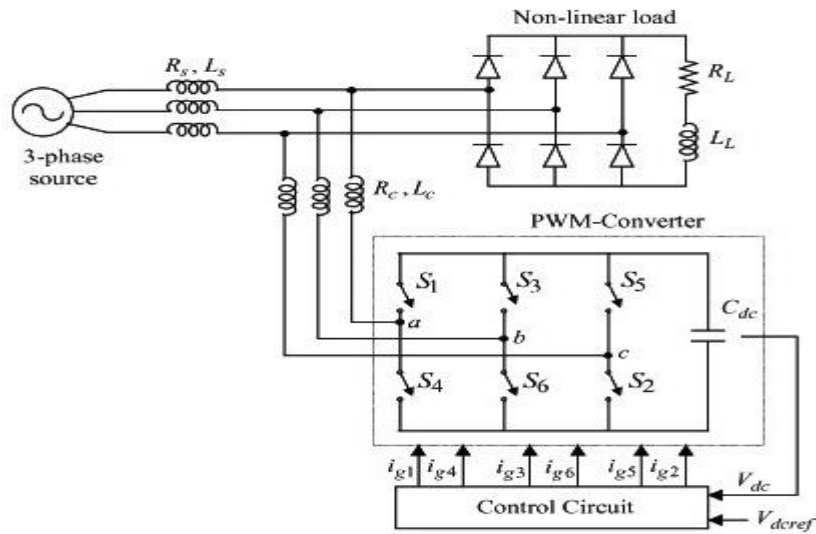


Fig. 4.1 Diagram of Shunt APF [15]

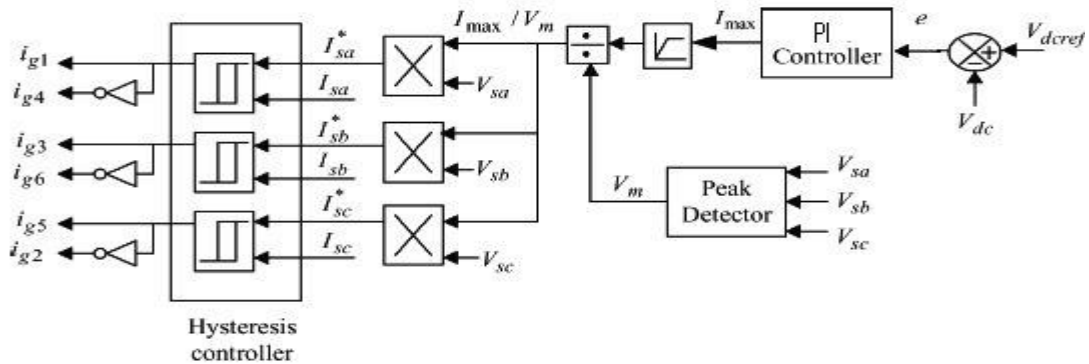


Fig. 4.2 PI Control Scheme [15]

The error signal is being fed to the PI controller. The maximum / peak value of the reference current is assumed as the output of the PI controller. Reference current is being further multiplied by the unit sine vectors like u_{sa} , u_{sb} , u_{sc} which are in phase with the voltage to obtain the reference currents (i_{sa}^* , i_{sb}^* , i_{sc}^*). Now the hysteresis based carrierless PWM controller is fed with the reference current and actual current to generate switching signals for the PWM converter. Difference in the value of reference current and actual current elects the operation of the switches. Current flows through the filter inductance L_c due to switching actions and is responsible for compensating the harmonic current and reactive power of load thus active power is only drawn from the source [9].

4.1.1 DC voltage control loop

Voltage control loop block diagram is shown below K_c is the transfer function of PWM converter and G_c is the gain for PI.

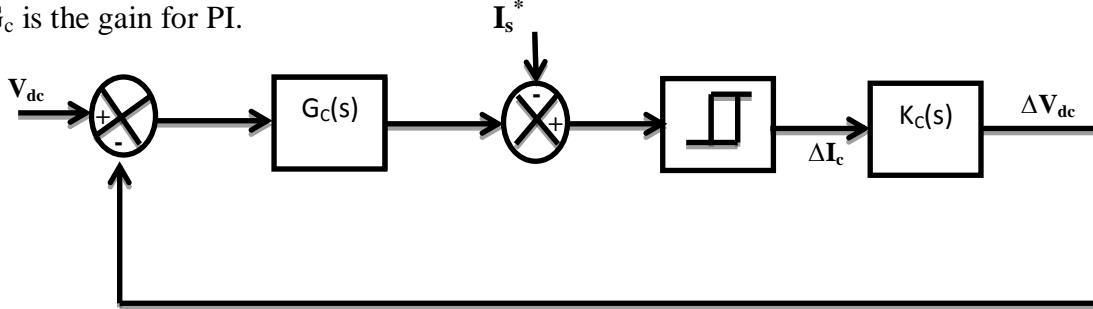


Fig. 4.3 Voltage control loop Block diagram [15]

4.1.2 PWM converter transfer function

By equating the associated average rate of change of energy, the derivation between the ac link and dc link quantities for the PWM converter could be obtained

$$P_{cap} = P_{conv} - P_{ind} \quad (4.1.2.1)$$

For linearizing the power equation a small change of ΔI_c is given to the input filter current I_c of the converter around a steady state operating point I_{co} . ΔV_{dc} is the small change given to the average dc voltage around its steady state operating point V_{dco} . The transfer function for a PWM converter at a particular operating point could be obtained as [12]

$$K_c = V_{dc} / I_c = 3[V_s - L_c I_{co} s - 2I_{co} R_c] / C_{dc} V_{dco} s \quad (4.1.2.2)$$

Where P_{cap} , P_{conv} and P_{ind} are the average power associated with capacitor, converter and inductor respectively. V_{dc} , C_{dc} are the capacitor voltage and current. V_c and I_c are the ac side voltage and current of converter.

4.1.3 Selection of PI controller parameters

Proportional Integral Derivative (PID) Controller can be called as PI, PD, P or I controller depending upon which control scheme is missing. PI controllers are particularly more common because in case of PID controller the derivative action is sensitive to measurement of noise. The proportional response can be altered by the multiplication of the constant K_p by the error. Where K_p is the proportional gain or the proportional sensitivity.

The output of the controller is proportional to the duration and the amount of error signal with the integral mode. The accumulated proportional offset over time which should have been corrected previously is calculated with the integral mode algorithm. With the integral controller the set point is approached quicker as compared to proportional controller and steady state error is eliminated [13,15].

4.2 SPWM control scheme

In this technique a sinusoidal waveform is produced by the filtration of output waveform having variable width. Good filtered sinusoidal output waveform is produced with the high switching frequency. By varying the amplitude and frequency of the reference and modulating voltage corrected output voltage is produced. Pulse width patterns of the output voltage is varied by changing the frequency and the amplitude of the reference voltage.

Fig.4.4 shows the comparison of low frequency sinusoidal modulating waveform with the high frequency triangular waveform. On the intersection of the triangular waveform with the sine waveform, a switching state is changed. The variable switching time in between the states is determined by the crossing positions [3].

In case of three phase SPWM, the control signal for the switching of device is produced by comparing the triangular voltage waveform ' V_T ' with the sinusoidal control voltages V_a , V_b , V_c , as well as by using the relative level of waveform. Fig.4.4 shows the output of the comparator which serve as the control signal for the switching device. In between $-V_{dc}/2$ and $V_{dc}/2$ voltage level, switching of the output pole voltage V_{a0} , V_{b0} , V_{c0} takes place where V_{dc} is the dc voltage. The amplitude of the triangular carrier waveform shall always be greater than the amplitude of the sine modulating waveform. If the triangular waveform is lesser than the sine waveform, the upper switch will turn ON and lower switch is OFF. Whereas on the occurrence of the reverse condition upper switch will be OFF and lower will be ON .

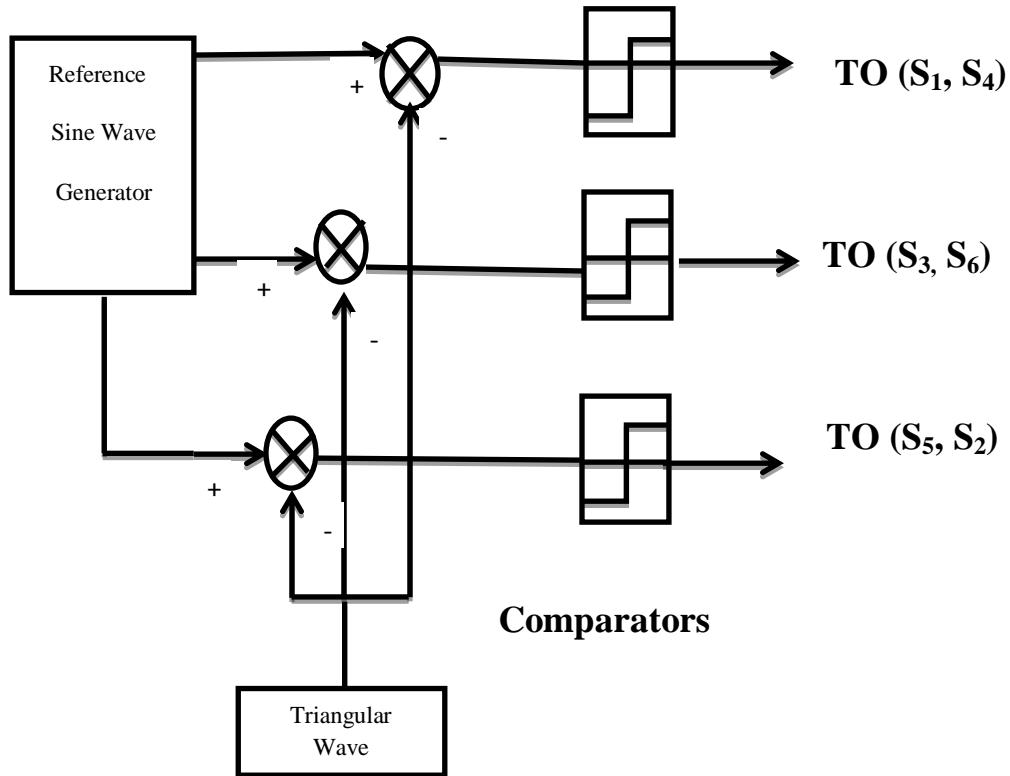


Fig. 4.4 Control Signal Generator for SPWM

On the basis of switching states positive or negative half dc voltage will be applied to each phase. Control signal logic is given by

S_1 is ON when $V_a > V_T$

S_4 is ON when $V_a < V_T$

S_3 is ON when $V_b > V_T$

S_6 is ON when $V_b < V_T$

S_5 is ON when $V_c > V_T$

S_2 is ON when $V_c < V_T$.

4.3 SVPWM control scheme

In this technique the reference voltage vector is decomposed into the voltage vector realizable on the six pulse inverter. Eight possible outputs are available on applying this theory to general six pulse inverter. Among the eight outputs two are the null voltage vectors, whereas

space apart. On the basis of the voltage waveform and region division

space vector can be obtained and defined. In either of the eight unique switching states inverter can be driven and each switching states corresponds to space vector [3].

Here V_0 is the null vector and has two patterns $V_0(000)$ and $V_0(111)$. Whereas six other voltage vector are marked from V_1 to V_6 , and divided into six regions discussed before. Fig.4.5 shows that space voltage vector. SRF is utilized for the extraction of harmonics. Here the separation of fundamental and harmonics is done before it being sent to the controller. In order to generate the switching signals for the PWM converter harmonic current is sent to the hysteresis current controller [4] .

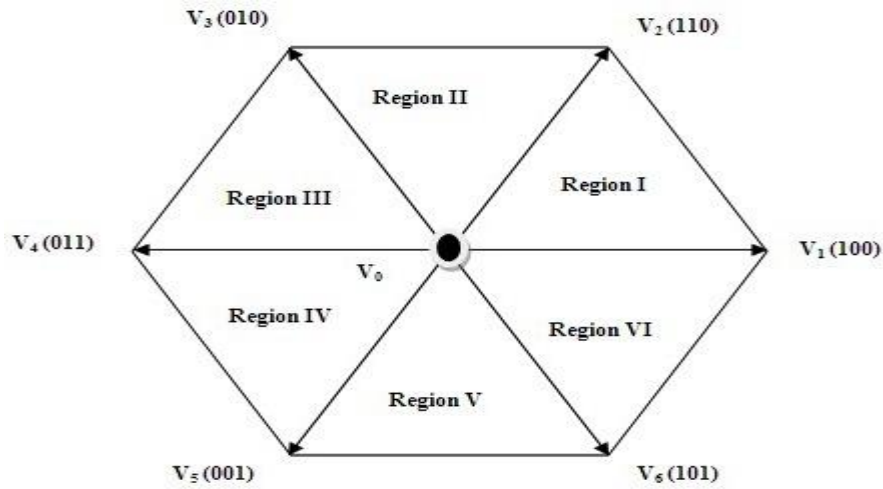


Fig. 4.5 Inverter states in the stationary reference frame [23]

The required space voltage vector V_k for the each state is obtained by the derivation of the current error vector (—). Now the desired space voltage vector $V_0^*(t)$ is determined by modulating the conduction period of the selected switch in accordance with the amplitude and angle of the desired components as shown in the Fig.4.6.

Output voltage vector modulation, $V_0^*(t)$ is expressed as

$$V_0^*(t) = d_\alpha V_\alpha + d_\beta V_\beta \quad (4.3)$$

Where d_α, d_β represents the duty cycle of the space voltage vector adjacent to $V_0^*(t)$. In the Fig. 4.7 it can be seen that the voltage vector $V_0^*(t)$ is positioned in the region 1. The minimum value of the derivative vector of the current errors provided by -1 & -2 in the region 1. Thus V_1, V_2 & V_0 are the corrected space voltage vector for V_0^* .

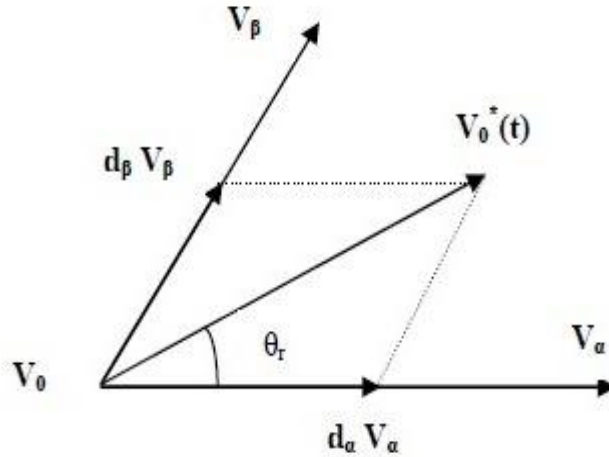


Fig. 4.6 Space vector output voltage component [23]

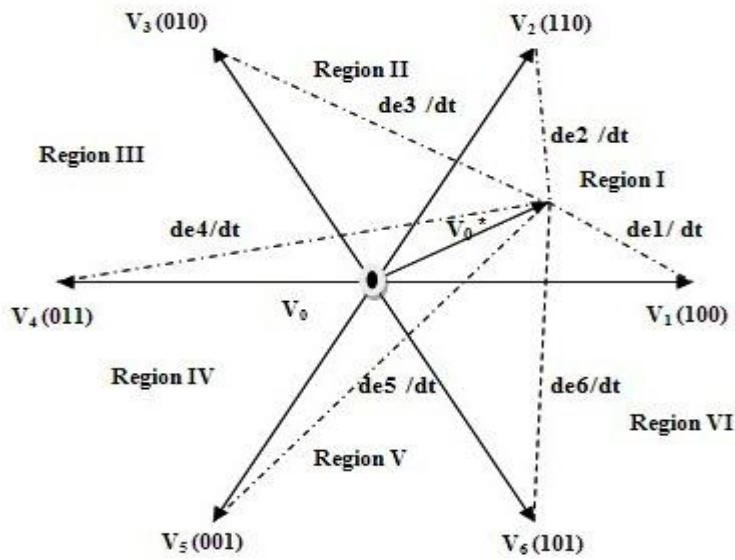


Fig. 4.7 Derivative vectors of current in the region [23]

Only the corrected and adequate vectors apply for the switching state on the basis of SVPWM principle. On the implementation of SVPWM technique to hysteresis current controller the unwanted number of switching can be decreased. For selecting the region and the appropriate space vector, the current error which is the difference between the reference and the actual current is fed into the hysteresis comparator [6].

Hysteresis comparator with two sets having different tolerance bands are used and each set is having three individual hysteresis comparator. The region of the output vectors is denoted

by the outer band controller. The desired space voltage vectors are denoted by the inner band controller. B_{a0} , B_{b0} , B_{c0} are the output signals with the outer band and B_{ai} , B_{bi} , B_{ci} are the output signals from inner band. These signals provides the information to the programmable logic array so as to produce the switching signal for the shunt active power filter [23].

Table 4.1 SVPWM based switching function table [23]

B_{a0}	B_{b0}	B_{c0}	B_{ai}	B_{bi}	B_{ci}	V_k			Region
						y1	y2	y3	
1	0	0	1	0	0	1	0	0	I
			1	1	0	1	1	0	
			Other cases			0	0	0	
1	1	0	1	1	0	1	1	0	II
			0	1	0	0	1	0	
			Other cases			0	0	0	
0	1	0	0	1	0	0	1	0	III
			0	1	1	0	1	1	
			Other cases			0	0	0	
0	1	1	0	1	1	0	1	1	IV
			0	0	1	0	0	1	
			Other cases			0	0	0	
0	0	1	0	0	0	0	0	0	V
			1	0	1	1	0	1	
			Other cases			0	0	0	
1	0	1	1	0	1	1	0	1	VI
			1	0	0	1	0	0	
			Other cases			0	0	0	

4.4 FLC control Scheme

Fig.4.8 shows the diagram of control algorithm for the shunt APF. The capacitor voltage on the dc side is sensed and compared with the reference value so as to implement the control algorithm for shunt APF in the closed loop. The change of the error $ce(n) = e(n) - e(n-1)$ and the actual error $e(n) = V_{dref} - V_{dcact}$ at the n^{th} sampling instant are the inputs to fuzzy process. Limited output of a fuzzy controller is taken as the amplitude of the reference current I_{max} which take care of the load active power demand and losses occurring in the system. By comparing the actual source currents with the reference current at hysteresis current controller switching signals are

generated for the PWM converter. And after the proper amplification and the isolation signals are given to a switching device [5].

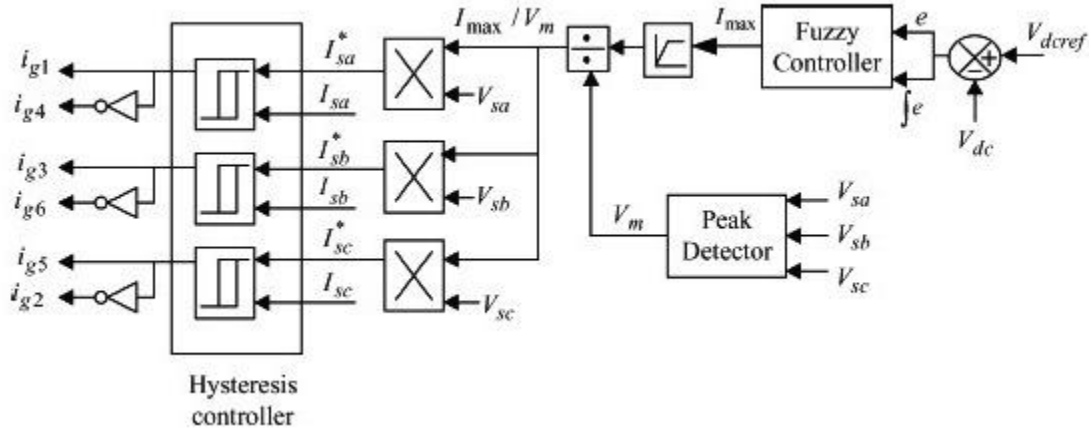


Fig. 4.8 Fuzzy control scheme [15]

4.4.1 Basic fuzzy algorithm

In this controller, by the evaluation of simple linguistic rules the control action is determined. Thorough understanding of the controlled process is required for the development of the rules. The main reason for its popularity is that it doesn't require the mathematical modeling. The internal structure of the fuzzy controller can be represented as shown in the Fig.4.9

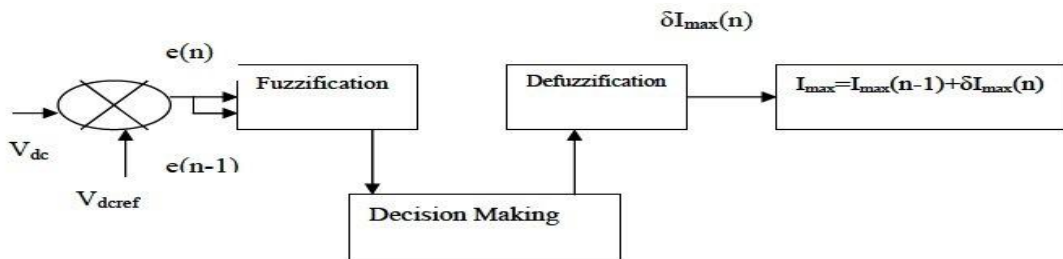


Fig. 4.9 Internal structure of the fuzzy logic controller [15]

On the basis of membership function (MF) the crisp inputs are converted into the linguistic variables in fuzzification process. A MF is a curve, which shows how the fuzzy variable value in certain domain can be mapped into the membership value μ in between 0 and 1. Different shapes are there for the MF as shown below in the Fig.4.10. On the basis of the rule the

OR or AND operation is done on the fuzzy variable. Consequent part of the rule is evaluated by the implication rule. Out of the number of available implication methods Mamdani is frequently used. In this method the fuzzy output is obtained by truncating the output at the value based on the degree of membership. In case of takagai-sugeno-kang method the output MFs are only constant or bear the linear relations with the inputs [9].

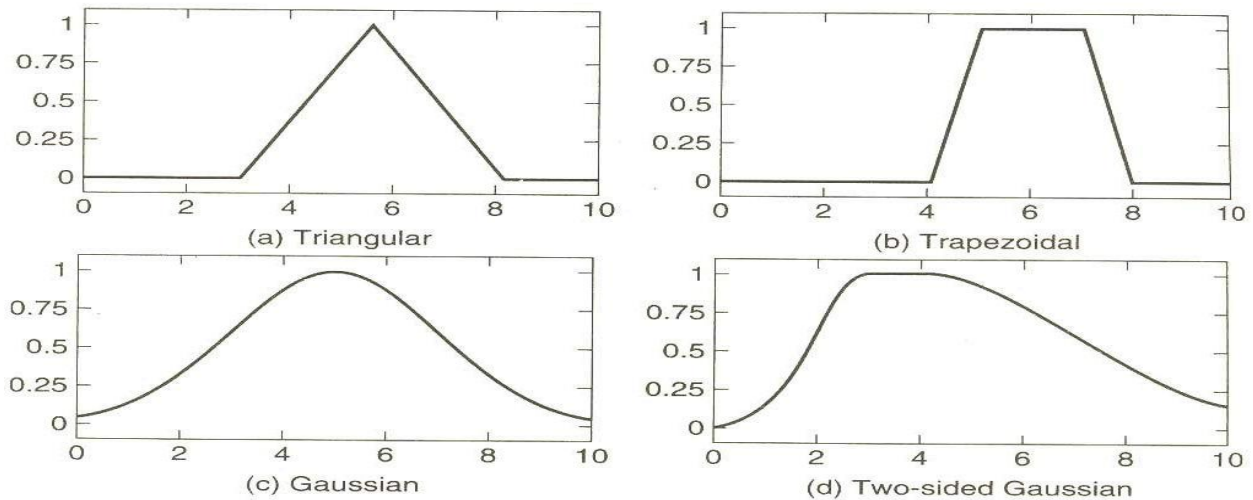


Fig. 4.10 Different types of MF [15]

As a result of aggregation and implication steps fuzzy outputs are obtained, that are the union of all the validated rules. Now the defuzzification is defined as the conversion of fuzzy output to crisp values. Center of Area (COA) and Height method are frequently used for the defuzzification. Here the error e and the change of error ce are used as numerical variables for the real system. In order to convert these numerical variables into linguistic one, the following fuzzy level or sets are chosen which are:

NB (negative big), NM (negative medium), NS (negative small), ZE (zero), PS (positive small), PM (positive medium) and PB (positive big).

The fuzzy controller can be characterized as follows

- For each input and output there are seven fuzzy sets
- For simplicity triangular MF is used
- Fuzzification is done using continuous universe of discourse
- Implication by using mamdani's 'min' operator
- The height method is used for defuzzification

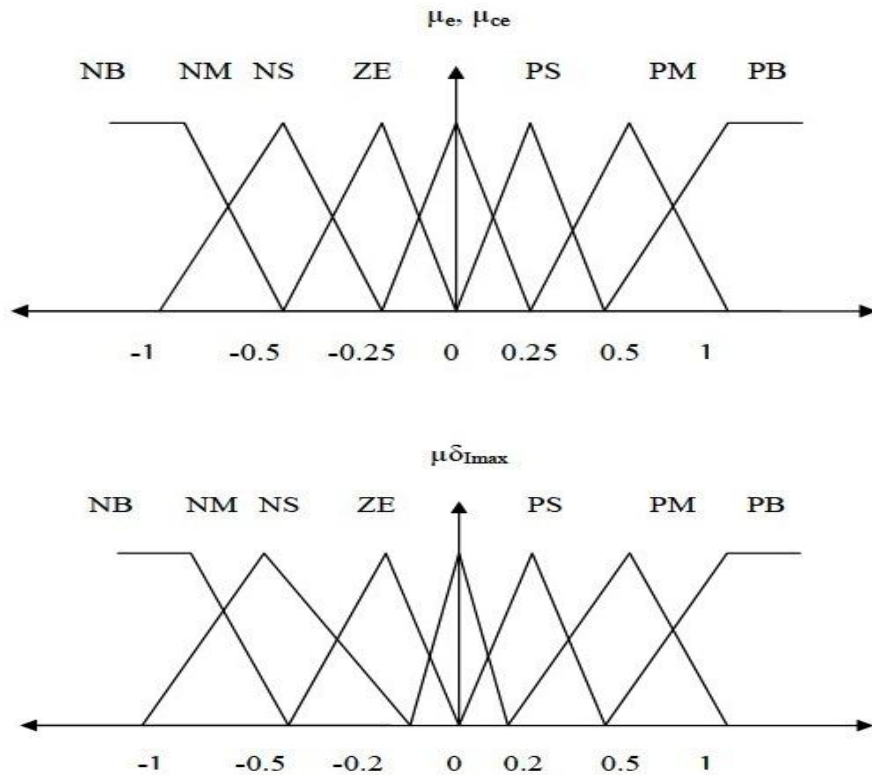


Fig. 4.11 Normalized triangular functions used in fuzzification [15]

(a) MF for e and ce

(b) MF for δI_{\max}

4.4.2 Design of control rules

Designing of the fuzzy control rules requires the rule describing, which relate the output model properties with the input variables. The rule design is mainly based on the natural feeling and the past experience, that's why FLC is independent of the system model. Input variables for the FLC are error e and change of error ce and the change in reference current δI_{\max} is the output. The shape of the time step response for a closed loop system should be as shown in the Fig.4.12 and the Fig.4.13 shows the phase plane trajectory for the step response that shows the mapping of error to the change in error [11].

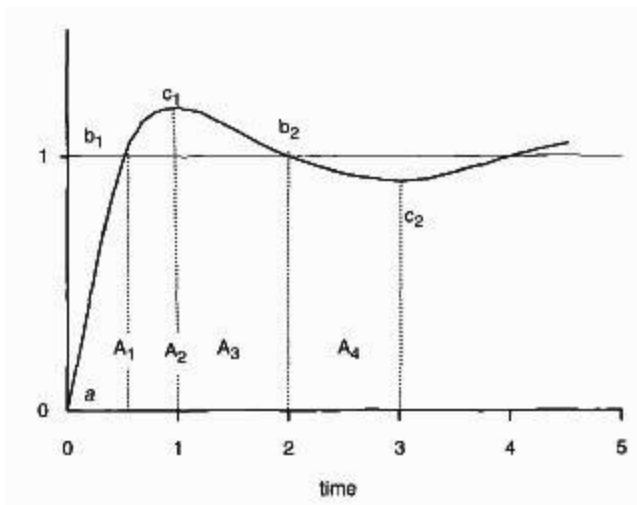


Fig. 4.12 Time step response of a closed loop system

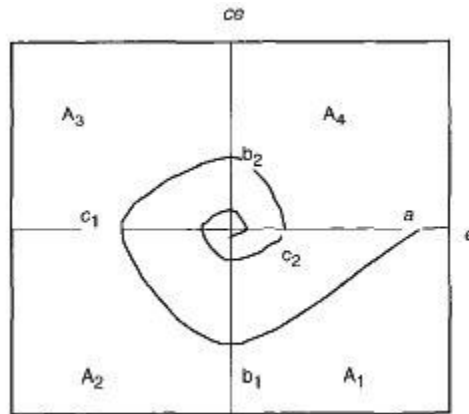


Fig. 4.13 Phase plane trajectory of step response [15]

Origin of the phase plane is the equilibrium point of the system. A_1, A_2, A_3, A_4 , are the four regions in which the time response has been divided. In addition, there are two sets of points: crossover point (b_1, b_2) and peak point (c_1, c_2). Response area is identified using the index, which is defined as

A_1 : if $ce < 0$ & $e > 0$, A_2 : if $ce < 0$ & $e < 0$

A_3 : if $ce > 0$ & $e < 0$, A_4 : if $ce > 0$ & $e > 0$

For Cross over index

b_1 : for $e > 0$ to $e < 0$ & $ce < 0$

b_2 : for $e < 0$ to $e > 0$ & $ce > 0$

For Peak valley index

c_1 : $ce = 0, e < 0$ and for c_2 : $ce = 0$ & $e > 0$

Now the rule base is framed on the basis of four regions, the phase plane trajectory of e & ce and two sets of points. Rule R_1 for the region 1 shortens the rise time.

R_1 : if $e > 0$ & $ce < 0$ then δI_{max} is > 0

Similarly, rule R_2 for the region 2 reduces the system response overshoot.

R_2 : if $e < 0$ & $ce < 0$ then δI_{max} is < 0

On the similar grounds formation of the rule for the other region is done. Below shows the rule base table on the basis of which rules are framed [14,15].

Table 4.2 Control Rule Base

		Error(e)							
		b_1				b_2			
		A_2							A_1
		NB	NM	NS	ZE	PS	PM	PB	
c_1	NB	NB	NB	NB	NB	NM	NS	ZE	
	NM	NB	NB	NB	NM	NS	ZE	PS	
$ce(\geq)$	NB	NB	NB	NM	NS	ZE	PS	PM	
	ZE	NB	NM	NS	ZE	PS	PM	PB	a, c_2
	PS	NM	NS	ZE	PS	PM	PB	PB	
	PM	NS	ZE	PS	PM	PB	PB	PB	
	PB	ZE	PS	PM	PB	PB	PB	PB	A_4
		A_3							

4.5 CPWM control scheme

In this technique the PWM patterns are generated by selecting the chaotic sequence so that evenly distributed current spectrum could be obtained with the minimum peak harmonics. Fig.4.14 shows the chaos circuit that has been implemented to obtain the necessary chaotic sequence. In case of conventional SPWM and SVPWM control techniques, working is on the fixed switching frequency owing to which cluster harmonics are present in the output waves. But CPWM makes the utilization of chaotic changing switching frequency in order to spread the harmonics uniformly in the wide band area. The chaos circuit shown below has the negative

resistance and because of this negative resistance, chaos circuit is able to generate the continuous chaotic sequence by properly selecting the circuit parameter [7].

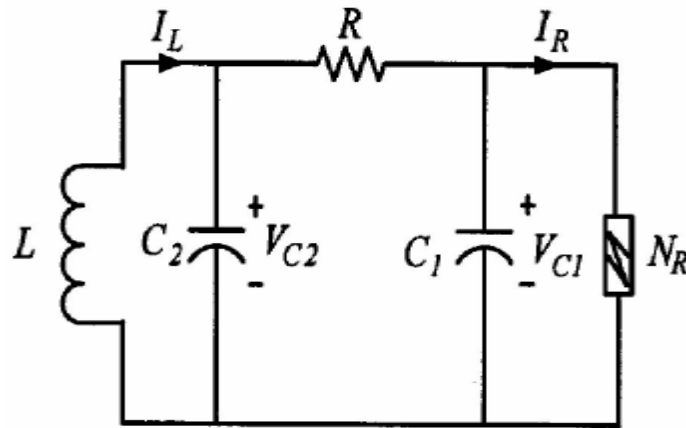


Fig.4.14 Chaos circuit [8]

$$\begin{aligned} di_L/dt &= -(1/L) V_{C2} \\ dV_{C2} / dt &= (1/ C_2) i_L - (G/C_2) (V_{C2}- V_{C1}) \end{aligned} \quad (4.5)$$

$$dV_{C1}/dt = -(1/C_1) f(V_{C1}) + G/C_1 (V_{C2}- V_{C1})$$

Here $f(V_{C1})$ represents the characteristic of negative resistance and $G = 1/R$.

4.5.1 Chaotic sequences

Consider a simple one-dimensional tent map

$$= \quad (4.5.1)$$

The tent map is a simple function capable of chaotic motion. It is highly dependent on the initial value . Where is a proper fraction.

1. Assume as a rational number, and its denominator has the form $2m$, then after $m+1$ iterations the sequences end with 0; otherwise after finite iterations the sequences

return to themselves, and so generates an orbit which is eventually repeating after the fixed interval.

2. If α is an irrational number, then orbit never ends with 0 and never with cycles. The iteration of the tent map exhibits chaotic behavior.

A periodic orbit of a map has been defined here to have the period t . Now, if the orbit successive cycles through t distinct points, then all fractions which have the form $2d/\alpha$ will create a periodic $2 \times$ orbit G_c of the map, where both c and d are positive integers. Multiplied all numbers in G_c by c results in a set of positive integers H_c . Rewriting map as follows:

$$x_{n+1} = \begin{cases} \alpha x_n & \text{if } 0 \leq x_n < 0.5 \\ \alpha(1-x_n) & \text{if } 0.5 \leq x_n < 1 \end{cases} \quad (4.5.2)$$

Where $n = 0, 1, 2, \dots, n \in [1, 0.5(\alpha - 1)]$. If α not a multiple of 5, iteration may create a periodic $2 \times$ orbit

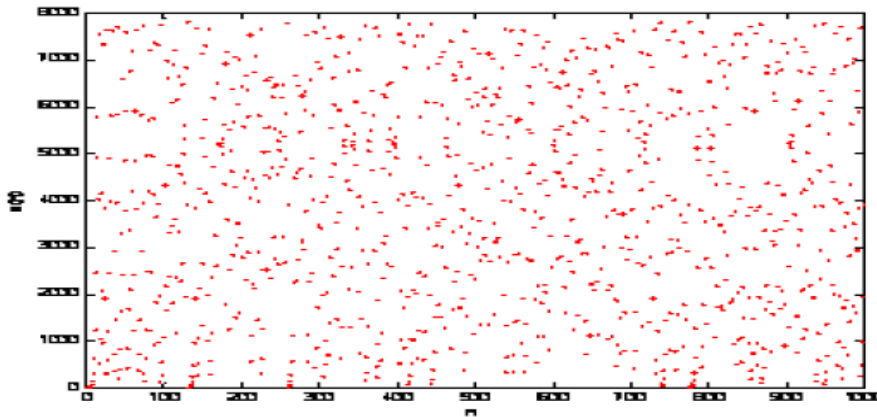


Fig.4.15 Positive integer sequences of uniform distribution derived from Eq. (4.5.2), $c=6$ [35]

The arbitrary periodic orbit can be obtained by using different value of c . One of the positive integer sequences generated by iteration equation corresponds to $c=6$ as shown in Fig. 4.15 chaotic sequences are generated deterministically from the dynamical system [35].

$$(4.5.3)$$

Where

f is a smooth function on \mathbb{R} .

Resulting bounded sequence of values x_i where $i=1$ to infinity is chaotic if

1. $\{x_i\}$ is not asymptotically periodic
2. No lyapunov exponent vanishes
3. The largest lyapunov exponent is strictly positive

4.5.2 Chaos-based PWM Generator

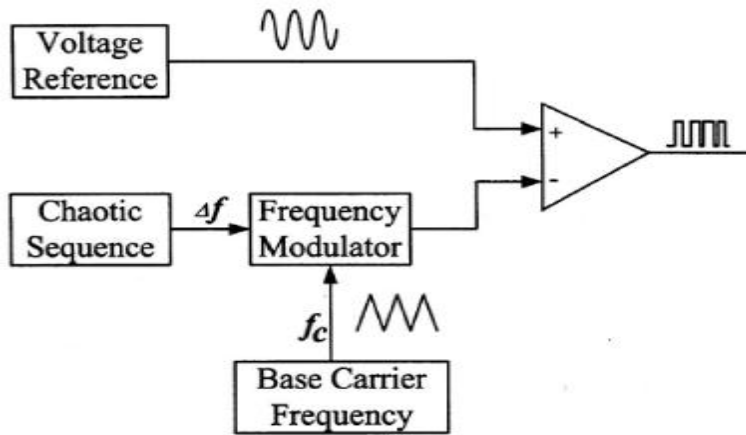


Fig. 4.16 Chaos based PWM generator [8]

Fig.4.16 represents the possible scheme for the generation of PWM signals by using the chaos based PWM for the switching of device employed in the shunt APF. For generating the chaotic sequence matlab platform is used, which gives the necessary chaotic sequence needed for generating the firing sequence for the switching devices [8].

CHAPTER 5

SIMULATION RESULTS AND DISCUSSION

The system discussed above is modeled by using the MATLAB/ Simulink and the performance of the various control scheme is analyzed. System parameters used for the simulation study are provided in the Table 5.1. THD of source current is 30.06% before compensation.

Table 5.1 System parameter used in simulink

System parameter	Values
Source voltage	325 V (peak)
System frequency	50 Hz
Source inductance	0.15mh
Filter inductance	3.35mh
Load impedance (R_L, L)	$20\Omega, 20\text{mH}$
Reference dc link voltage	700 V

5.1 Without controller

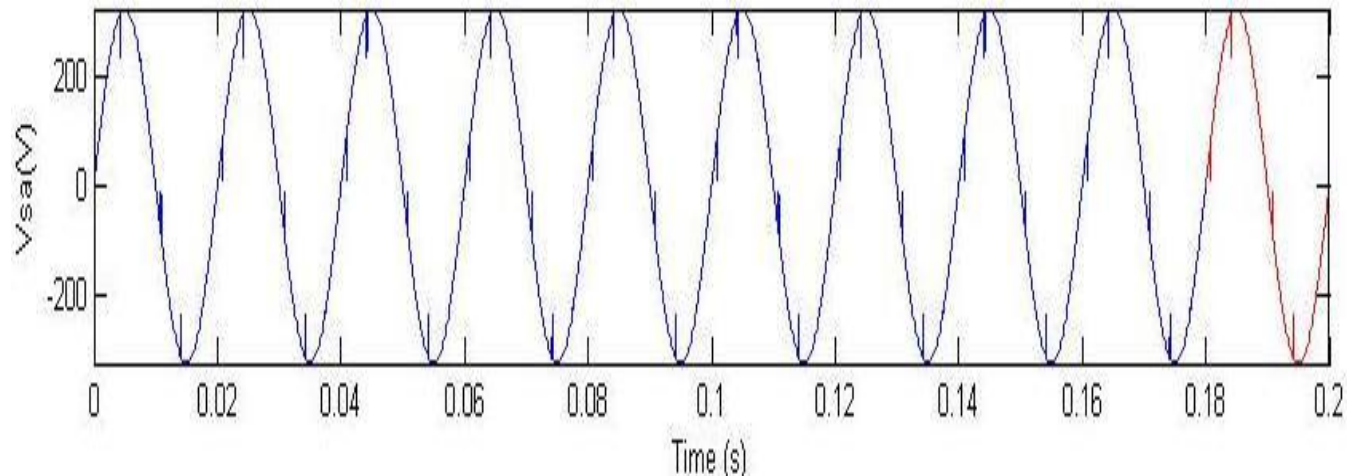


Fig.5.1 Source voltage

The above source voltage versus the time waveform is obtained by the simulation of the model given in Fig.1 of the appendix section. This waveform shows that the presence of nonlinear load distort the source voltage but that distortion is very small.

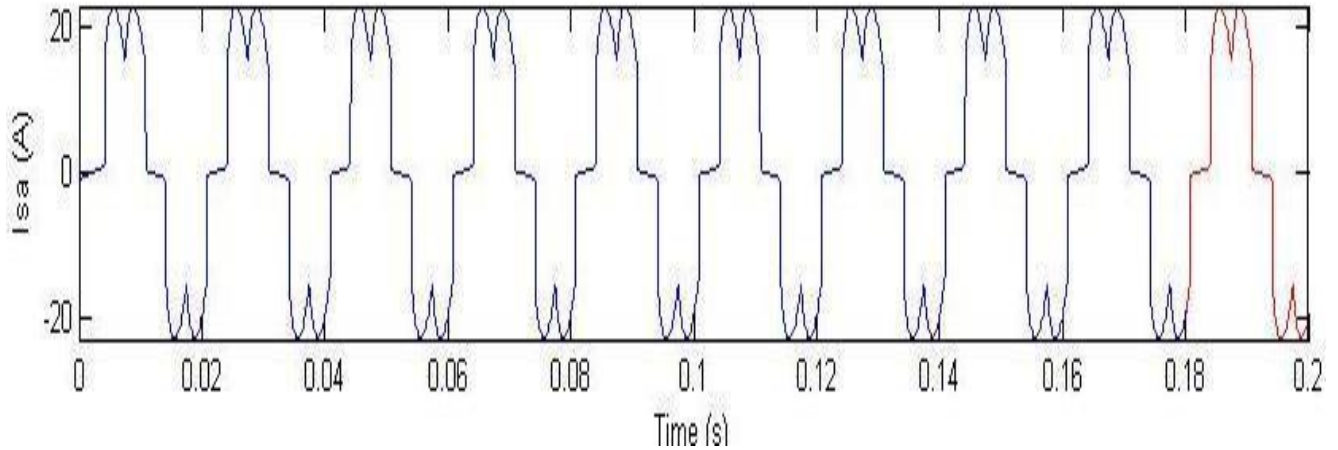


Fig.5.2 Source current

The above source current versus the time waveform is obtained by the simulation of the model given in Fig.1 of the appendix section. This waveform shows that the source current is largely distorted by the presence of nonlinear load.

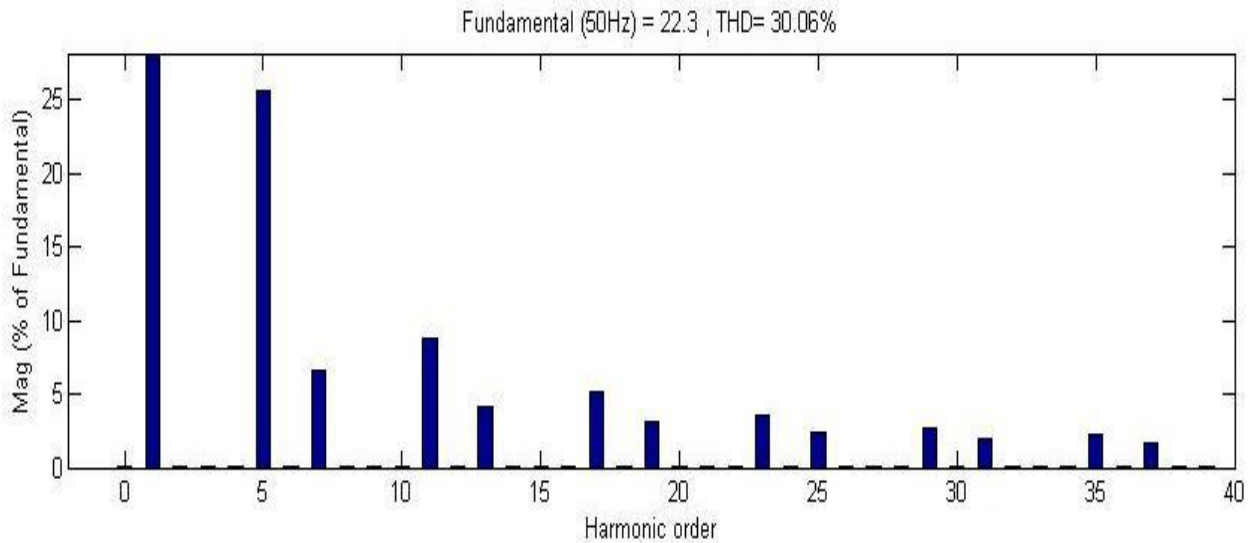


Fig. 5.3 Source current THD

The above bar chart is obtained by the simulation of the model given in Fig.1 of the appendix section. This shows the fast fourier transform analysis of the source current waveform in the bar chart form, here mainly the odd order harmonics (not the multiple of three) are present, % THD of the source current is 30.06.

5.2 With PI control

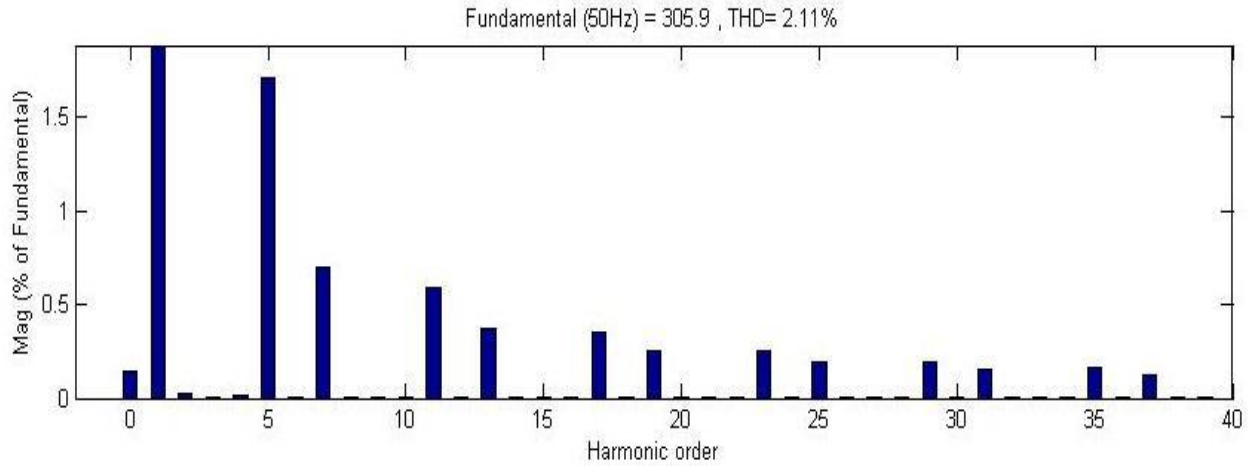


Fig. 5.4 Source current THD

The above bar chart is obtained by the simulation of the model given in Fig.2 and Fig. 6 of the appendix section. This shows the fast fourier transform analysis of the source current waveform in the bar chart form, %THD level of the source current is 2.11%.

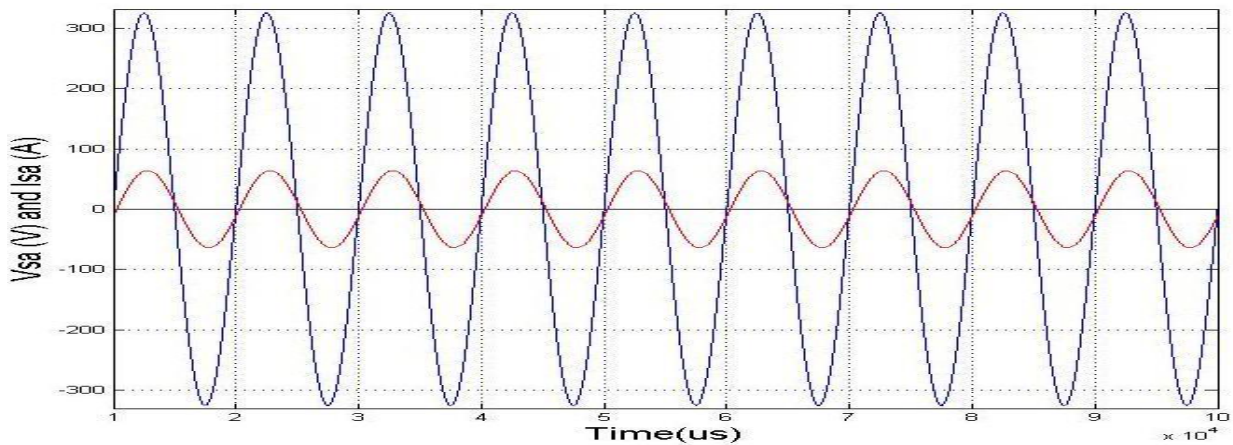


Fig. 5.5 Voltage and current in phase

The above voltage and current versus the time waveform is obtained by the simulation of the model given in Fig.2, Fig.4 and Fig. 6 of the appendix section. This shows that the voltage and current waveforms becomes sinusoidal and thus, the power factor improves.

The value of the power factor angle and the power factor with the PI controller is given below:

Power factor angle in degree: 10.66, Power factor: 0.9827

5.3 With SPWM control

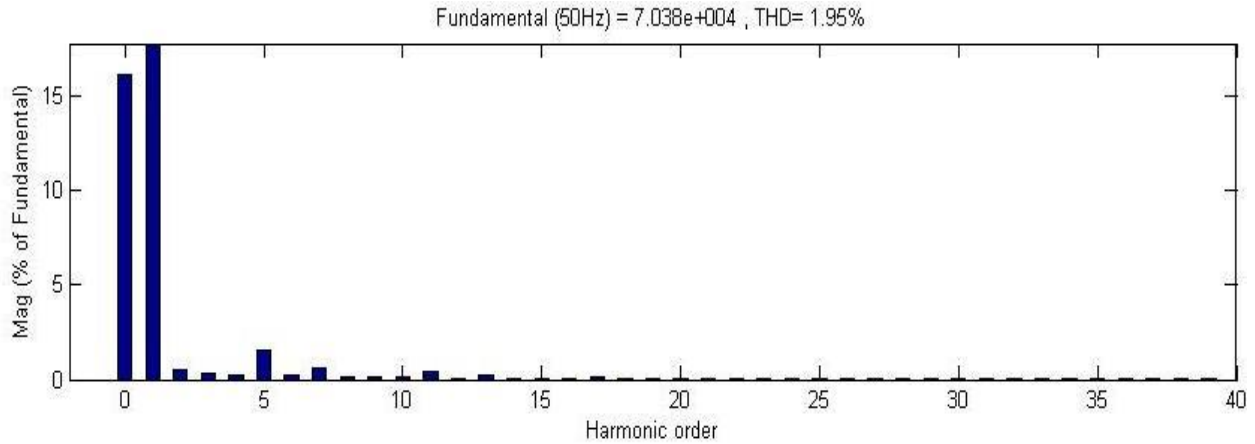


Fig. 5.6 Source current THD

The above bar chart is obtained by the simulation of the model given in Fig.2 and Fig.5 of the appendix section. This shows the fast fourier transform analysis of the source current waveform in the bar chart form, %THD level of the source current is 1.95%.

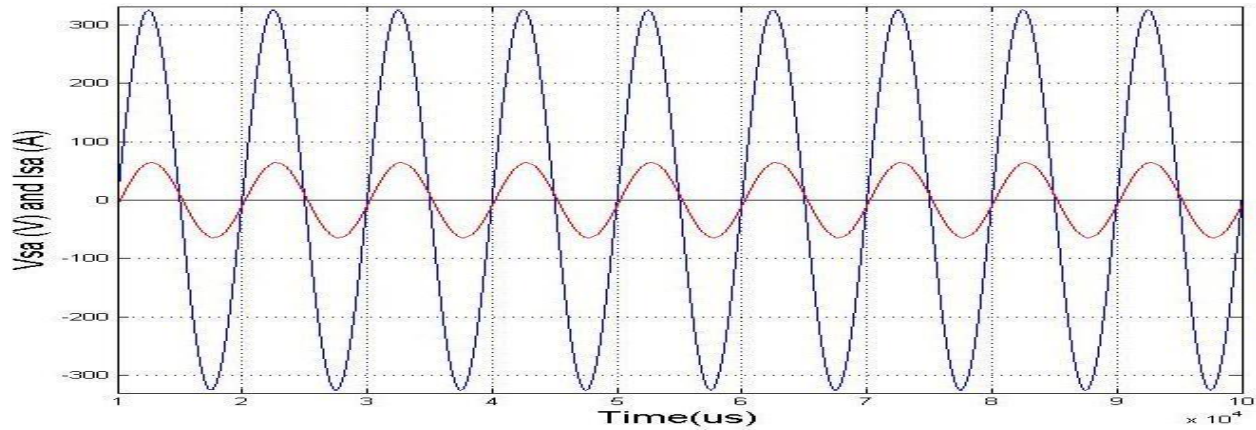


Fig. 5.7 Voltage and current in phase.

The above voltage and current versus the time waveform is obtained by the simulation of the model given in Fig.2, Fig.4 and Fig.5 of the appendix section. This shows that the voltage and current waveforms becomes sinusoidal and thus, the power factor improves.

The value of the power factor angle and the power factor with the SPWM controller is given below:

Power factor angle in degree: 8.892

Power factor: 0.987

5.4 With SVPWM control

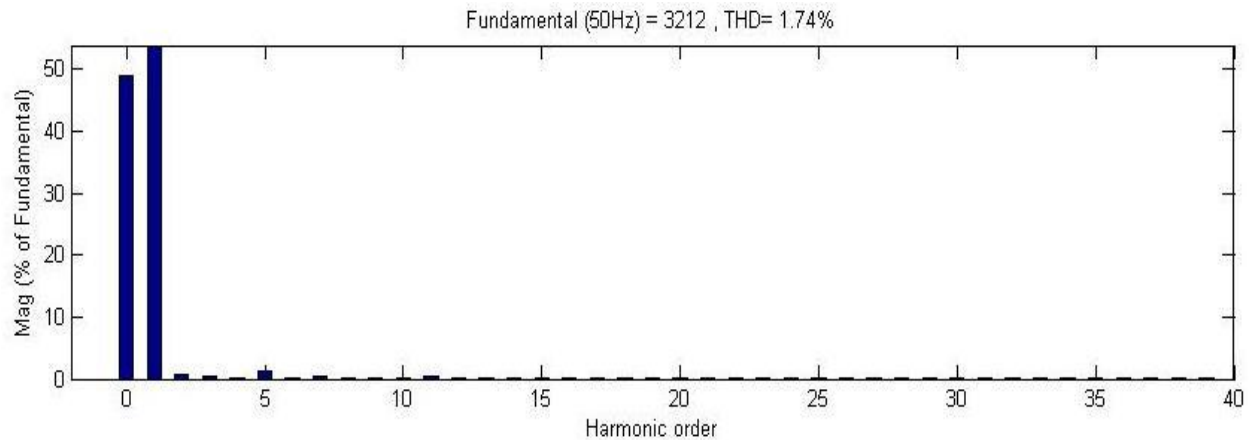


Fig.5.8 Source current THD

The above bar chart is obtained by the simulation of the model given in Fig.2 and Fig.7 of the appendix section. This shows the fast fourier transform analysis of the source current waveform in the bar chart form, %THD level of the source current is 1.74%.

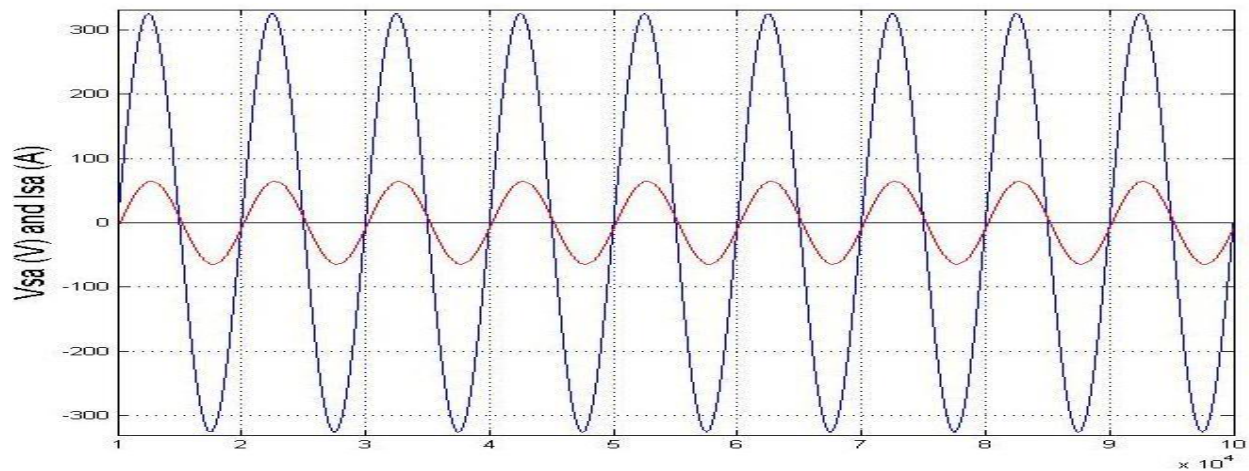


Fig.5.9 Voltage and current in phase

The above voltage and current versus the time waveform is obtained by the simulation of the model given in Fig.2, Fig.4 and Fig.7 of the appendix section. This shows that the voltage and current waveforms becomes sinusoidal and thus, the power factor improves.

The value of the power factor angle and the power factor with the PI controller is given below:

Power factor angle in degree: 8.208

Power factor: 0.9897

5.5 With CPWM control

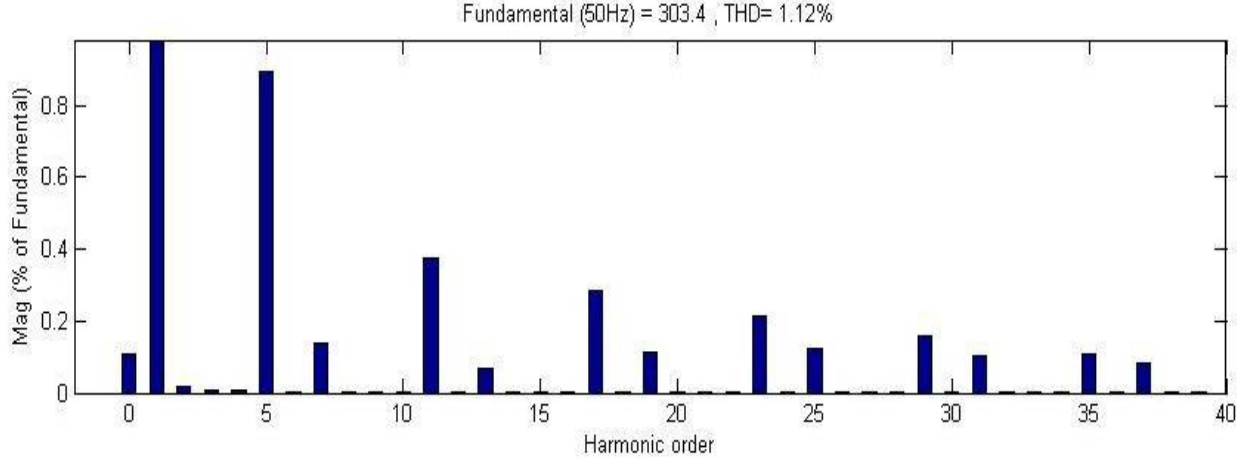


Fig. 5.10 Source current THD

The above bar chart is obtained by the simulation of the model given in Fig.2 and Fig.8 of the appendix section. This shows the fast fourier transform analysis of the source current waveform in the bar chart form, %THD level of the source current is 1.12%.

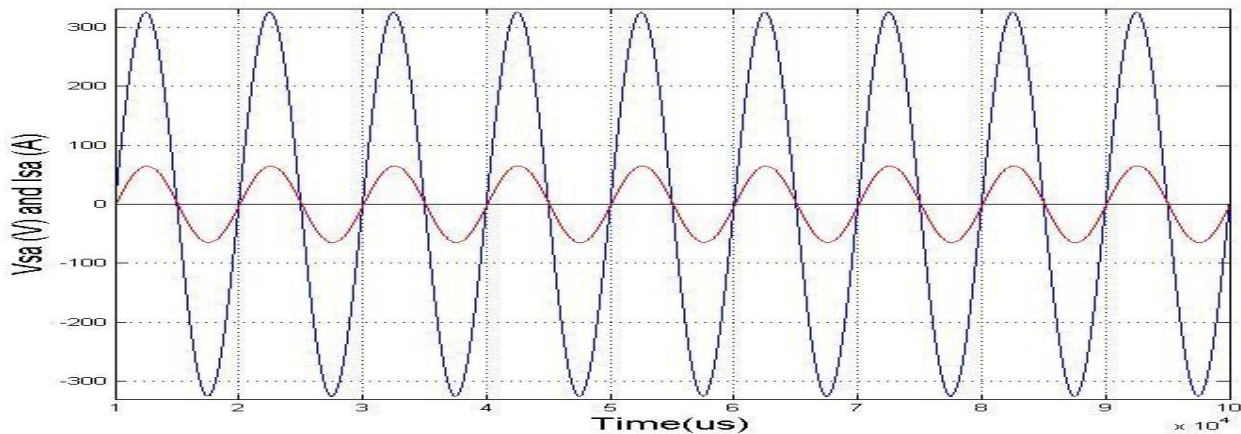


Fig. 5.11 Voltage and current in phase.

The above voltage and current versus the time waveform is obtained by the simulation of the model given in Fig.2, Fig.4 and Fig.8 of the appendix section. This shows that the voltage and current waveforms becomes sinusoidal and thus, the power factor improves.

The value of the power factor angle and the power factor with the CPWM control is given below:

Power factor angle in degree: 3.564

Power factor: 0.9980

5.6 With FLC control

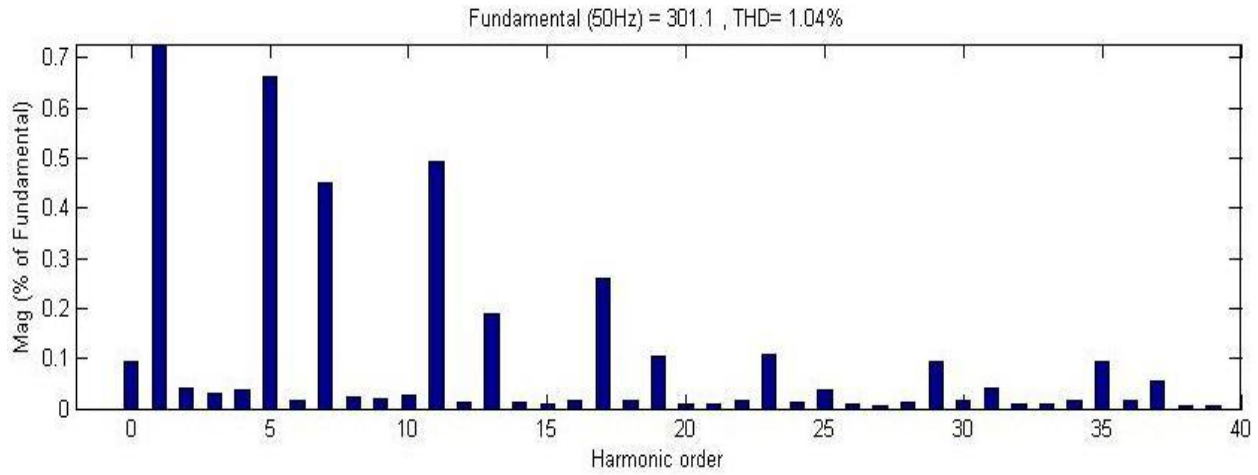


Fig.5.12 Source current THD.

The above bar chart is obtained by the simulation of the model given in Fig.2 and Fig.9 of the appendix section. This shows the fast fourier transform analysis of the source current waveform in the bar chart form, %THD level of the source current is 1.04%.

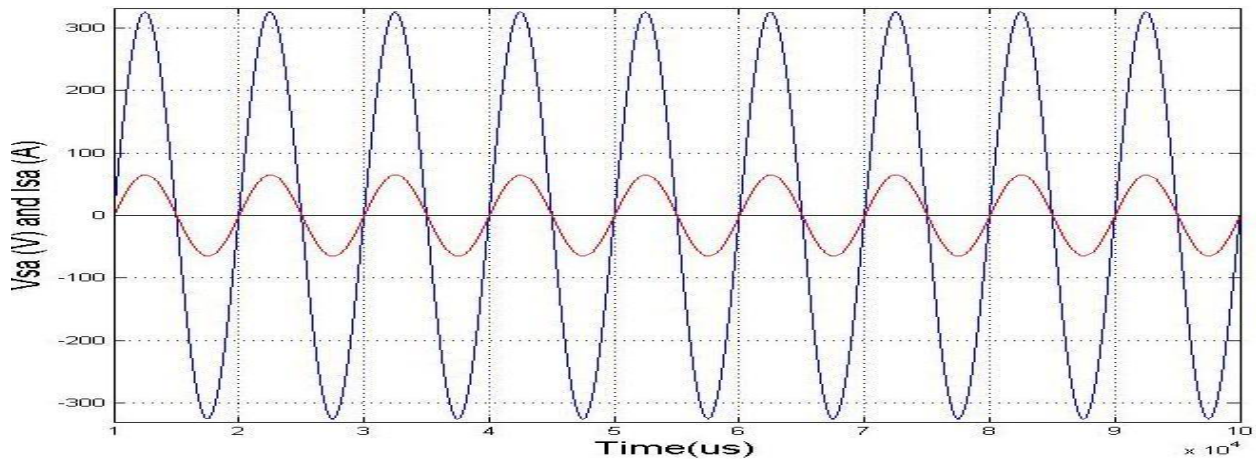


Fig.5.13 Voltage and current in phase

The above voltage and current versus the time waveform is obtained by the simulation of the model given in Fig.2, Fig.4 and Fig.9 of the appendix section. This shows that the voltage and current waveforms becomes sinusoidal and thus, the power factor improves.

The value of the power factor angle and the power factor with the FLC is given below:

Power factor angle in degree: 1.764

Power factor: 0.9995

Table 5.2 %THD level and power factor with various control schemes

S.No.	Control scheme	THD level of the source current (%)	Power factor angle (degree)	Power factor
1	With out any control scheme	30.06%	49.28	0.65
2	PI	2.11%	10.66	0.9827
3	SPWM	1.96%	8.892	0.9879
4	SVPWM	1.74%	8.208	0.9897
5	Chaos based PWM	1.12%	3.564	0.9980
6	FLC	1.04%	1.764	0.9995

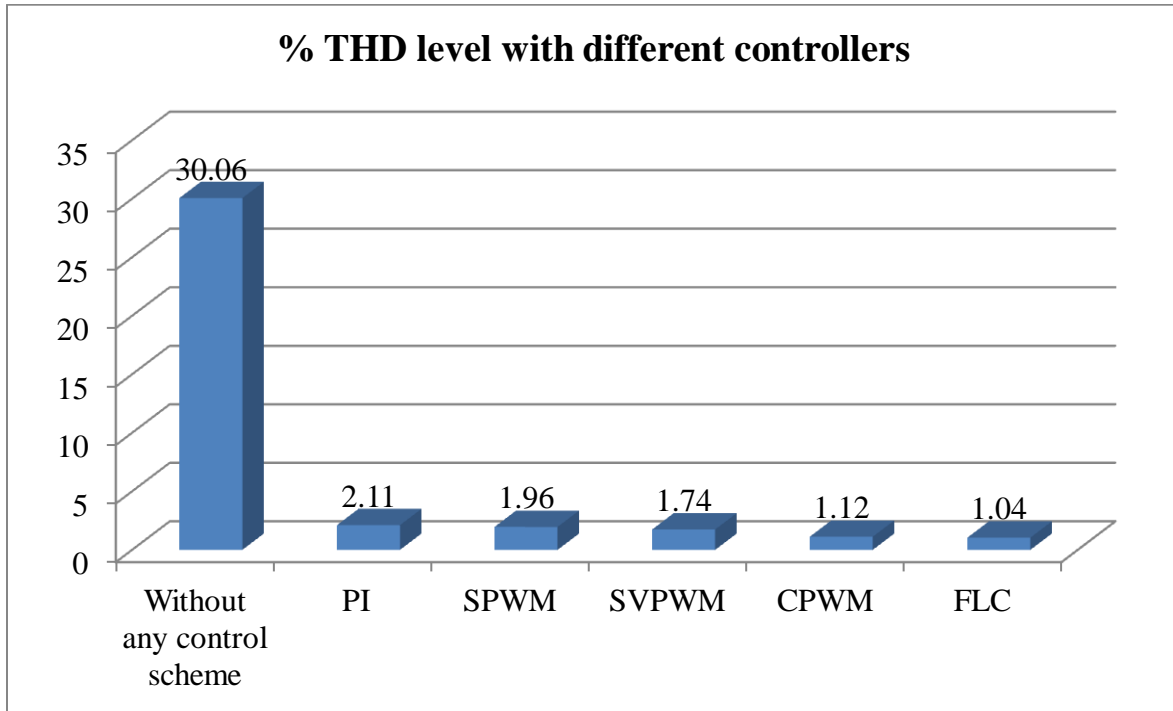


Fig.5.14 % THD with different controllers

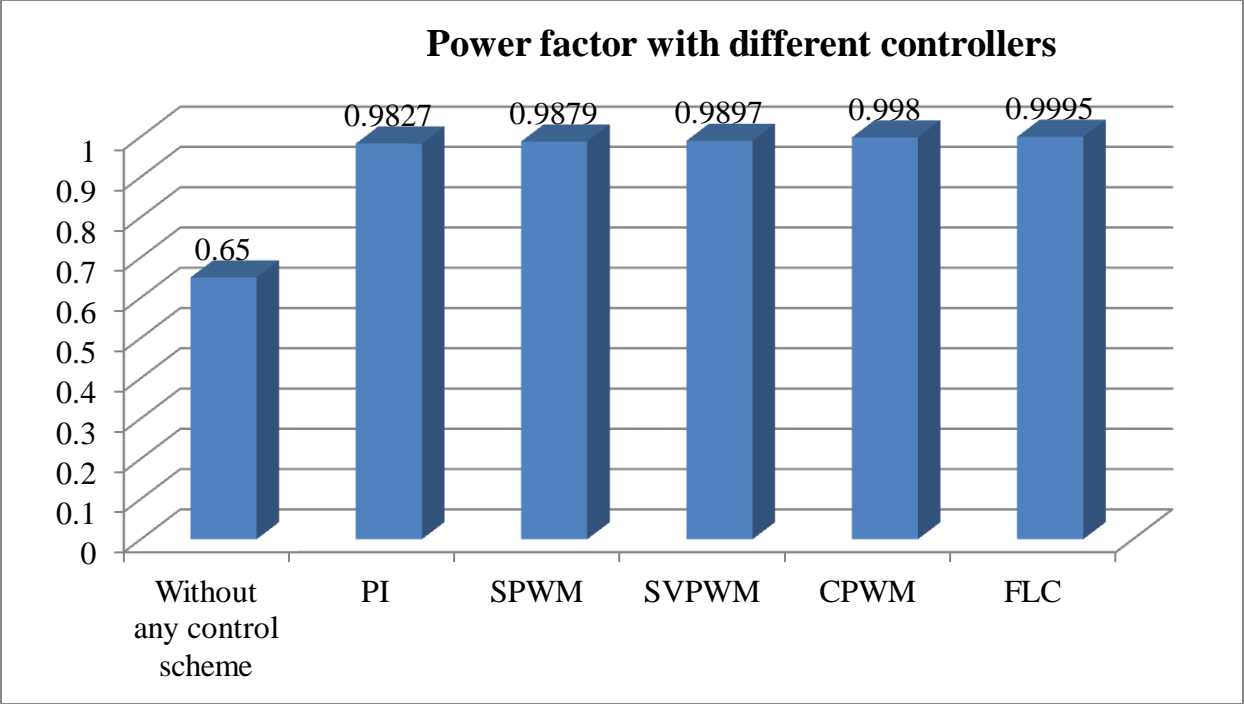


Fig.5.15 Power factor with different controllers

From all the above responses it is illustrated that the THD of the source current is reduced from 30.06 % to the level which is below 2.20 % with all the control scheme. And this attained level of THD is well in accordance with the IEEE standard, according to which THD should be less than 5%. In addition to this the power factor of the system also shows the improvement from 0.65 to 0.98 with all the control scheme.

CHAPTER 6

CONCLUSION AND THE FUTURE WORK

6.1 Conclusion

Shunt APF has been analyzed for power quality improvement. Simulation is being carried out for investigating the system performance. Five different control techniques based shunt APF is implemented for the harmonic mitigation due to the presence of non-linear load. A model is developed using the MATLAB /SIMULINK platform. It has been found that the employment of shunt APF improves the power quality by mitigating the harmonics and the reactive power demanded by the load and hence makes the current in phase with the source voltage. It has been observed that, among the various PWM techniques used CPWM shows the better result as compared to conventional PWM techniques and FLC is best among the various control techniques in terms of improving the power factor and reducing the THD level, which is well below the limit posed by the IEEE standard.

6.2 Future Work

Above analysis can also be done by developing the mathematical model for the system. In addition a prototype model in the laboratory can be developed, experimental analysis can be done on the shunt APF in order to verify the simulation result obtained with the PI, SPWM, SVPWM, CPWM and FLC control techniques.

APPENDIX

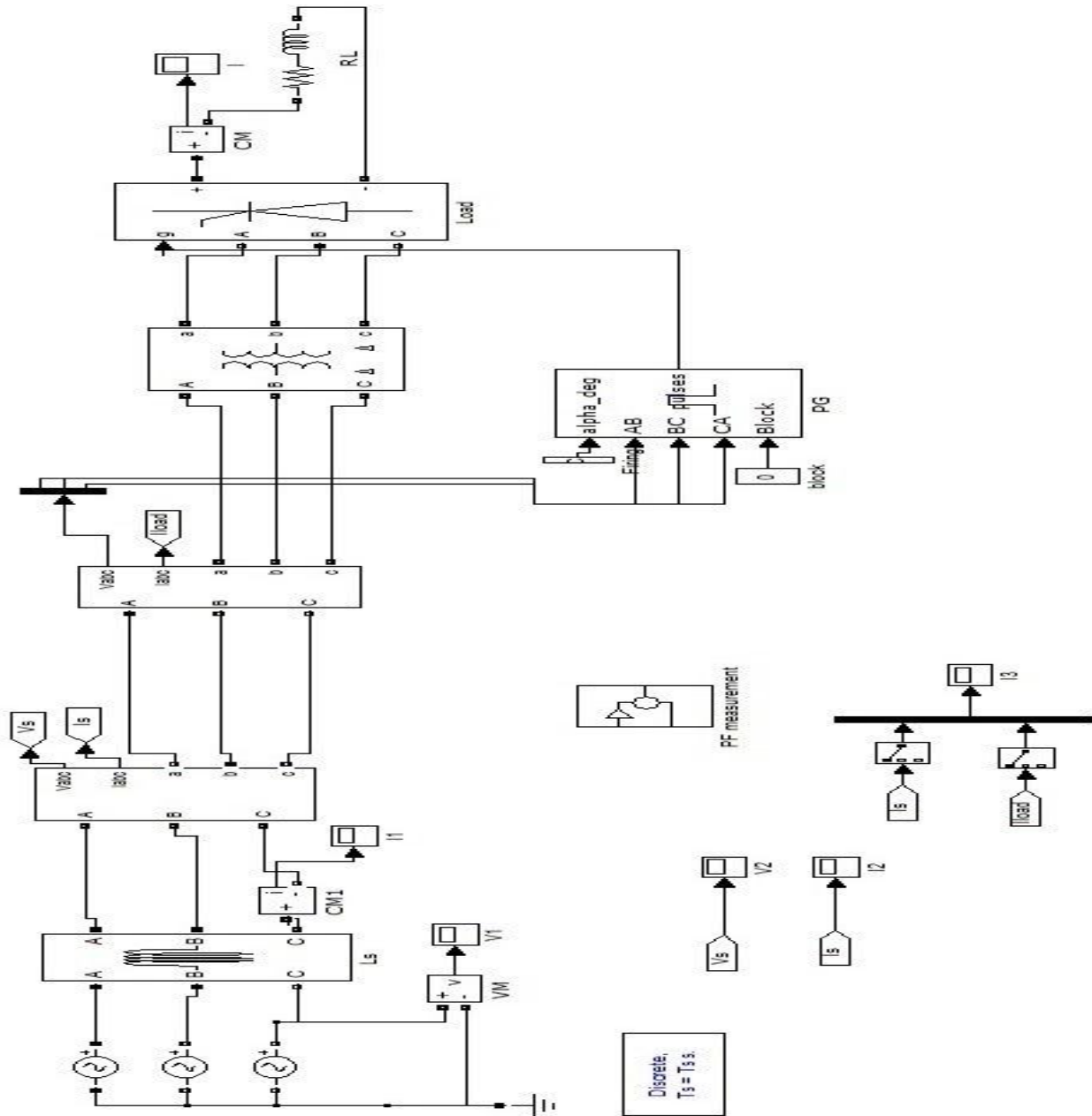


Fig.1 Simulink Model of the Three Phase Source feeding the nonlinear load without shunt APF.

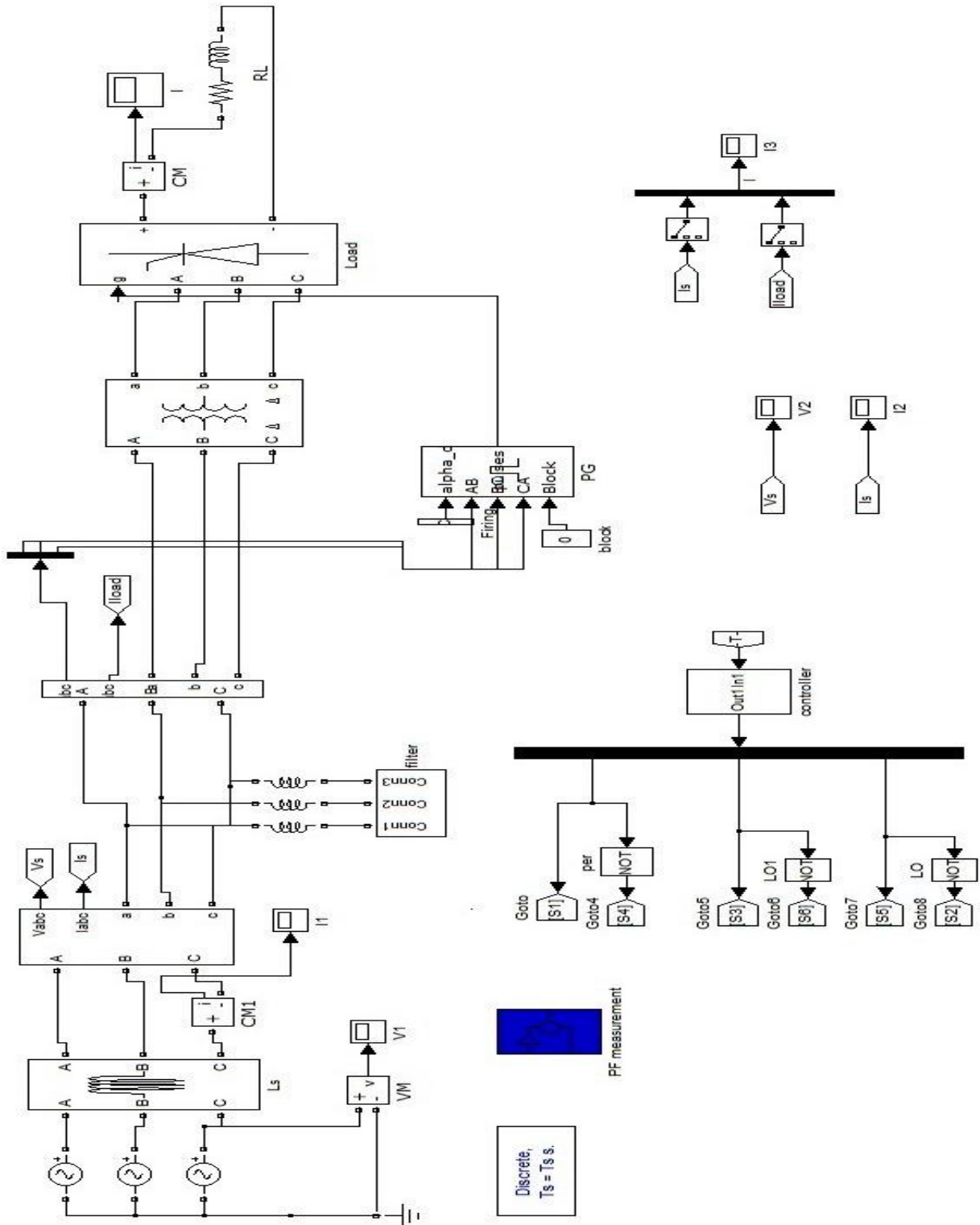


Fig.2 Simulink Model of the Three Phase Source feeding the nonlinear load with shunt APF.

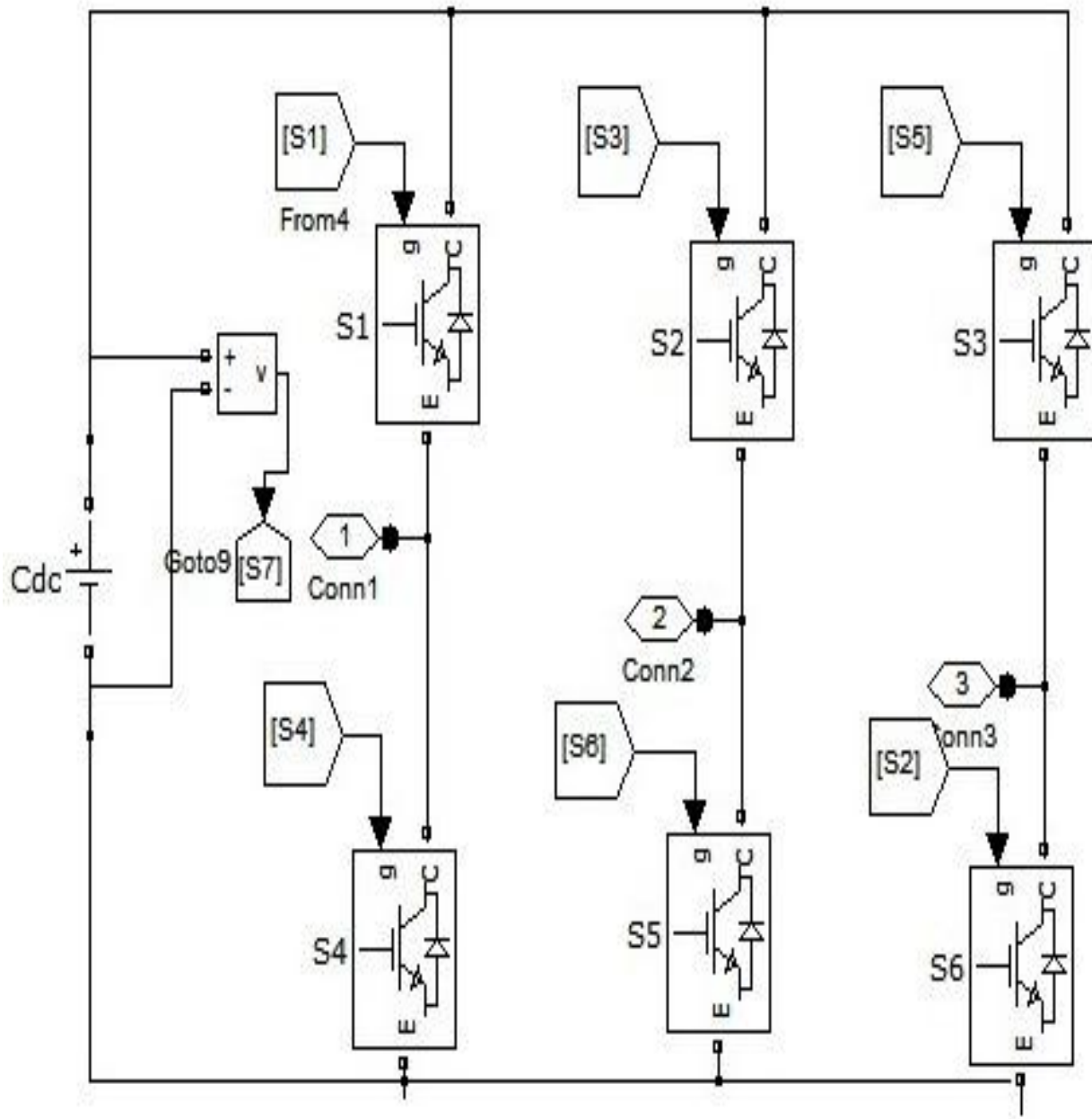


Fig.3 Simulink Model of Active Power Filter

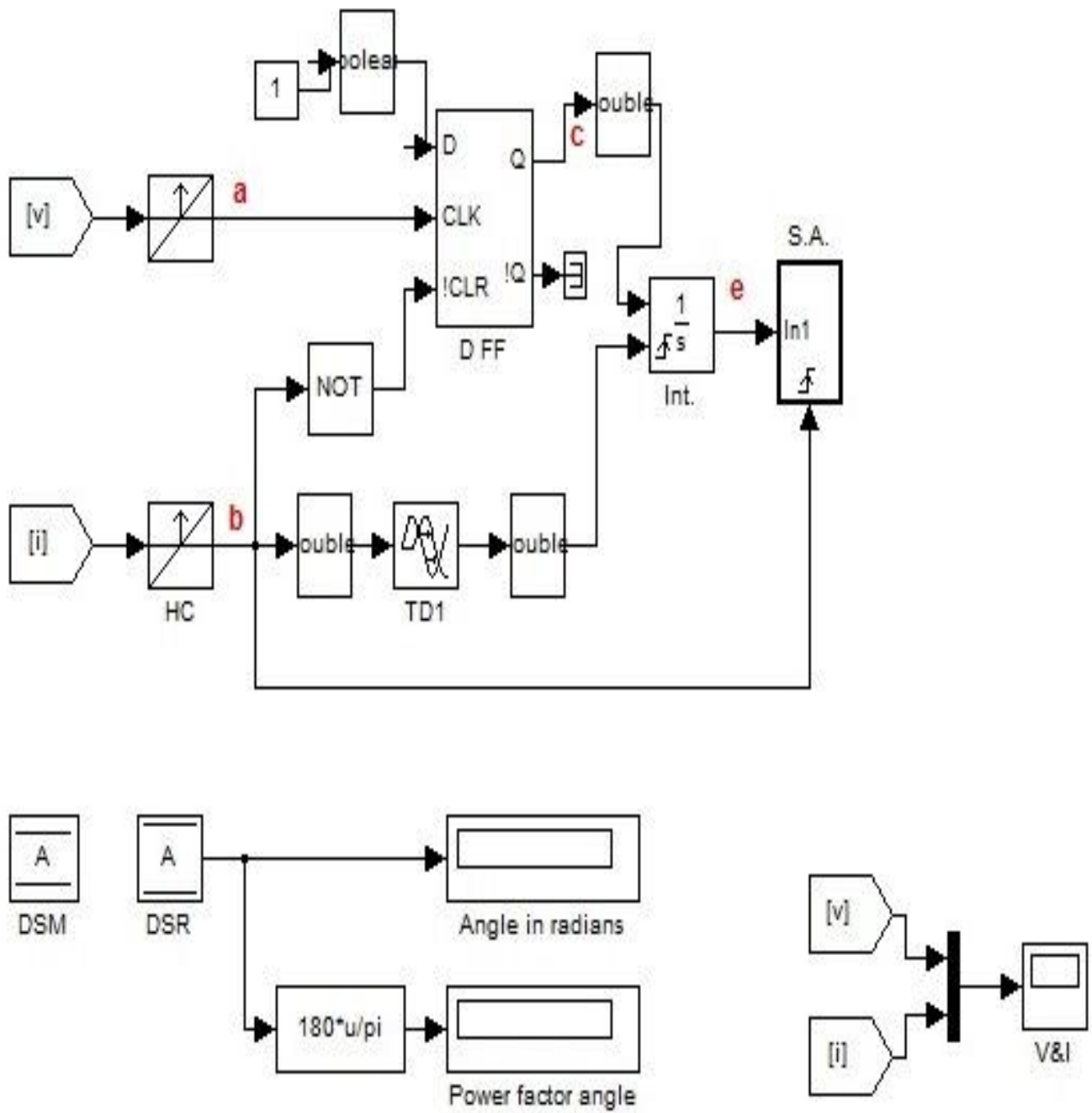


Fig.4 Simulink Model For Power Factor Measurement

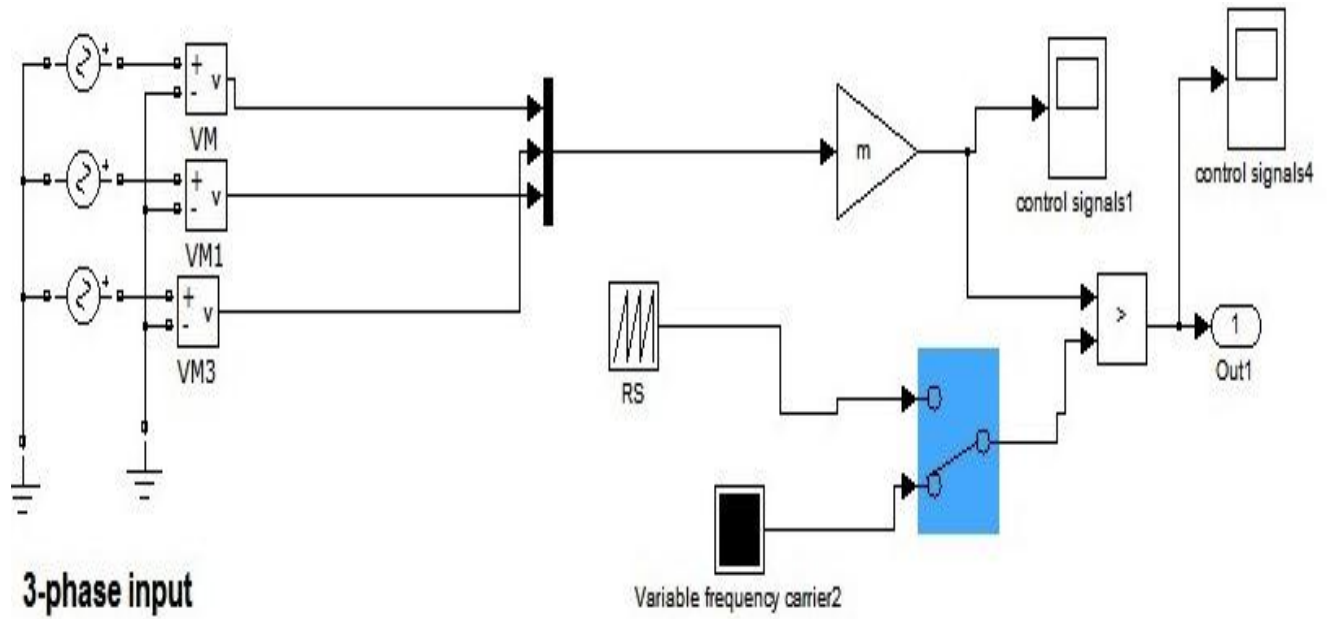


Fig.5 Simulink Model of SPWM Control Scheme

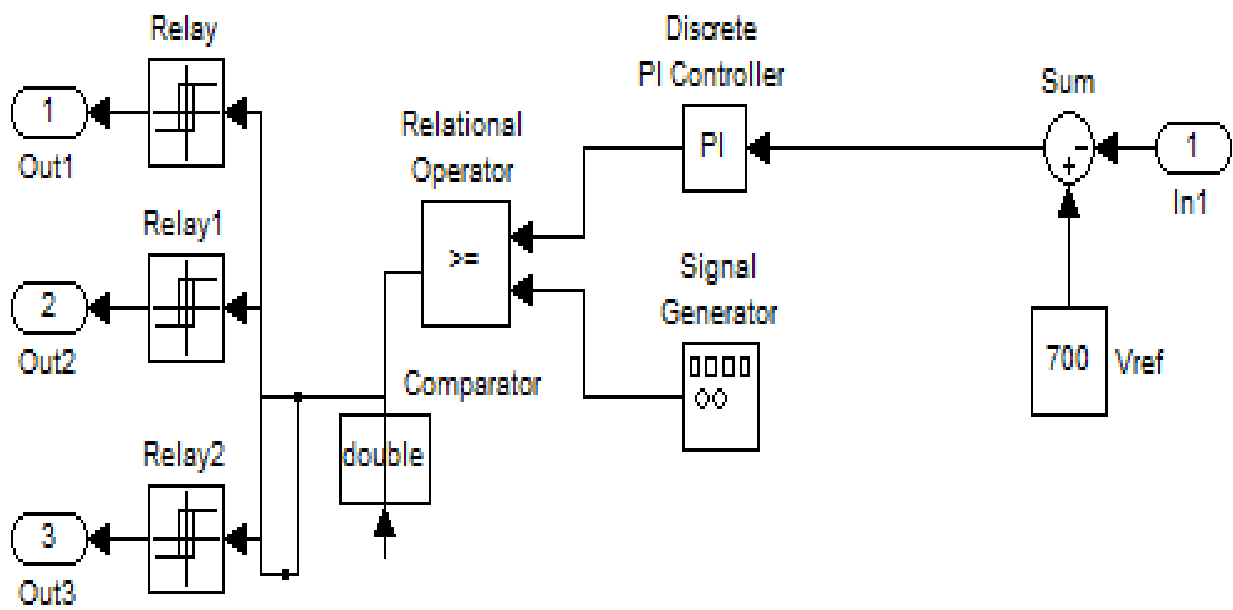


Fig.6 Simulink Model of PI Control Scheme

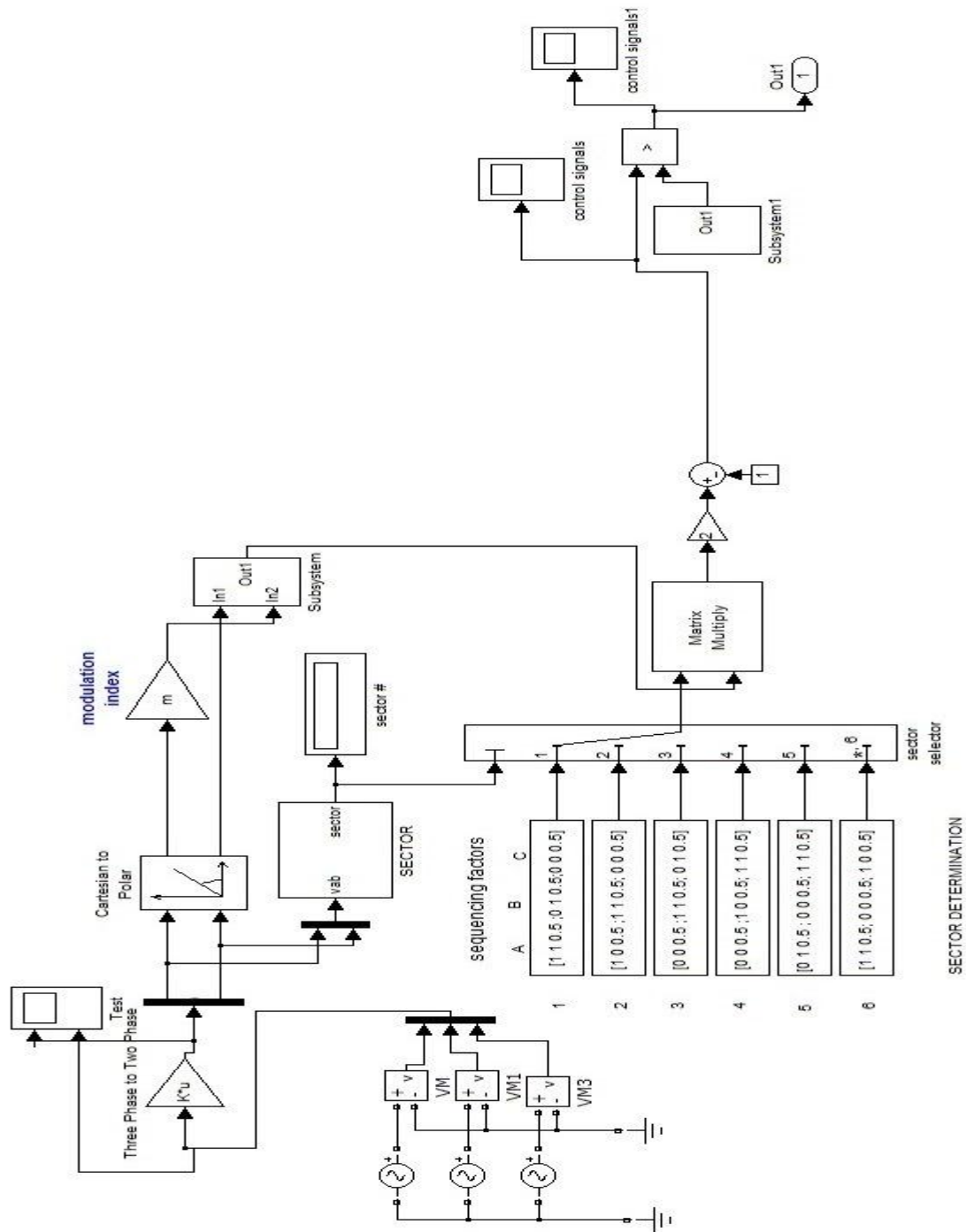


Fig.7 Simulink Model of SVPWM Control Scheme

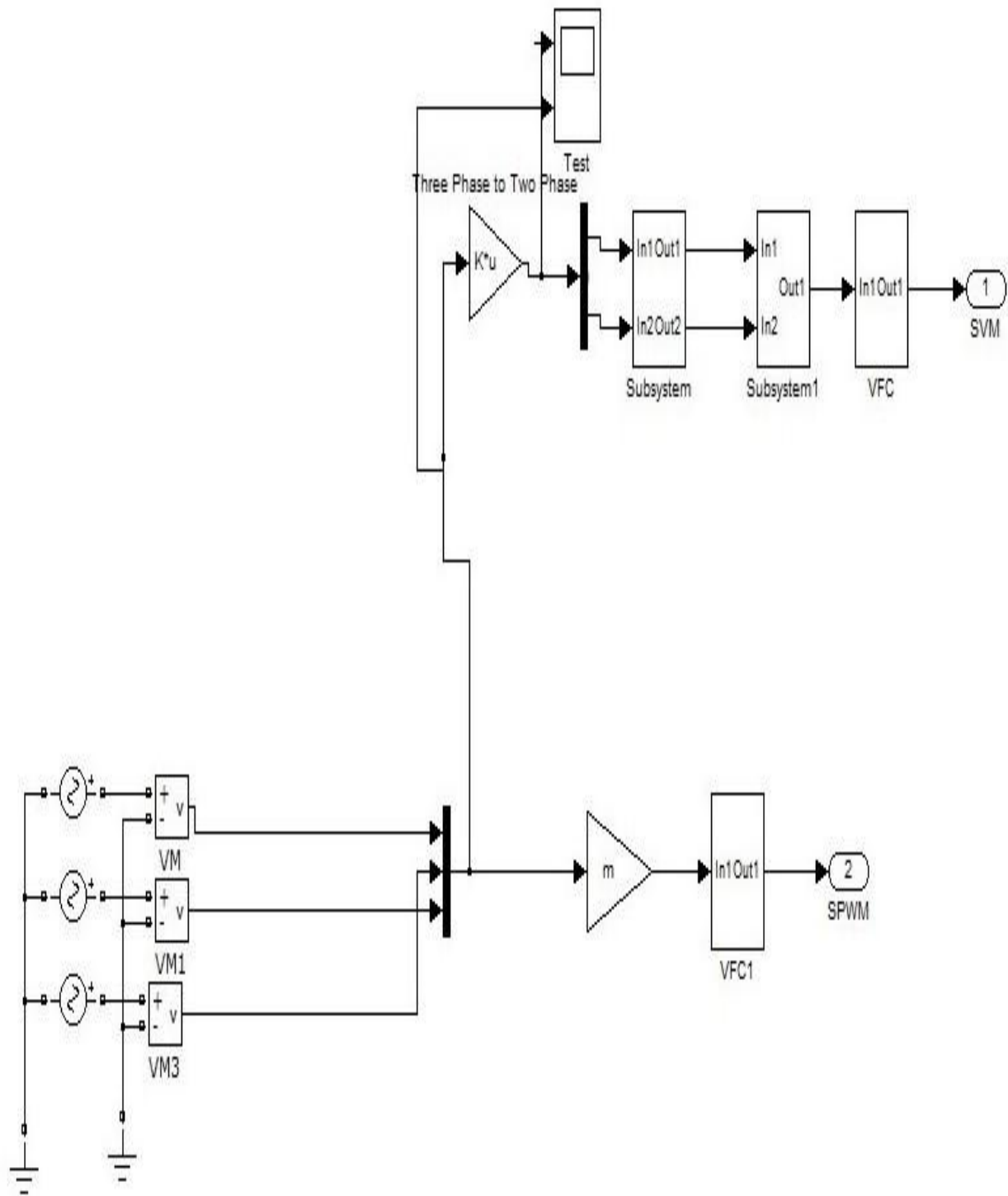


Fig.8 Simulink Model of CPWM Control Scheme.

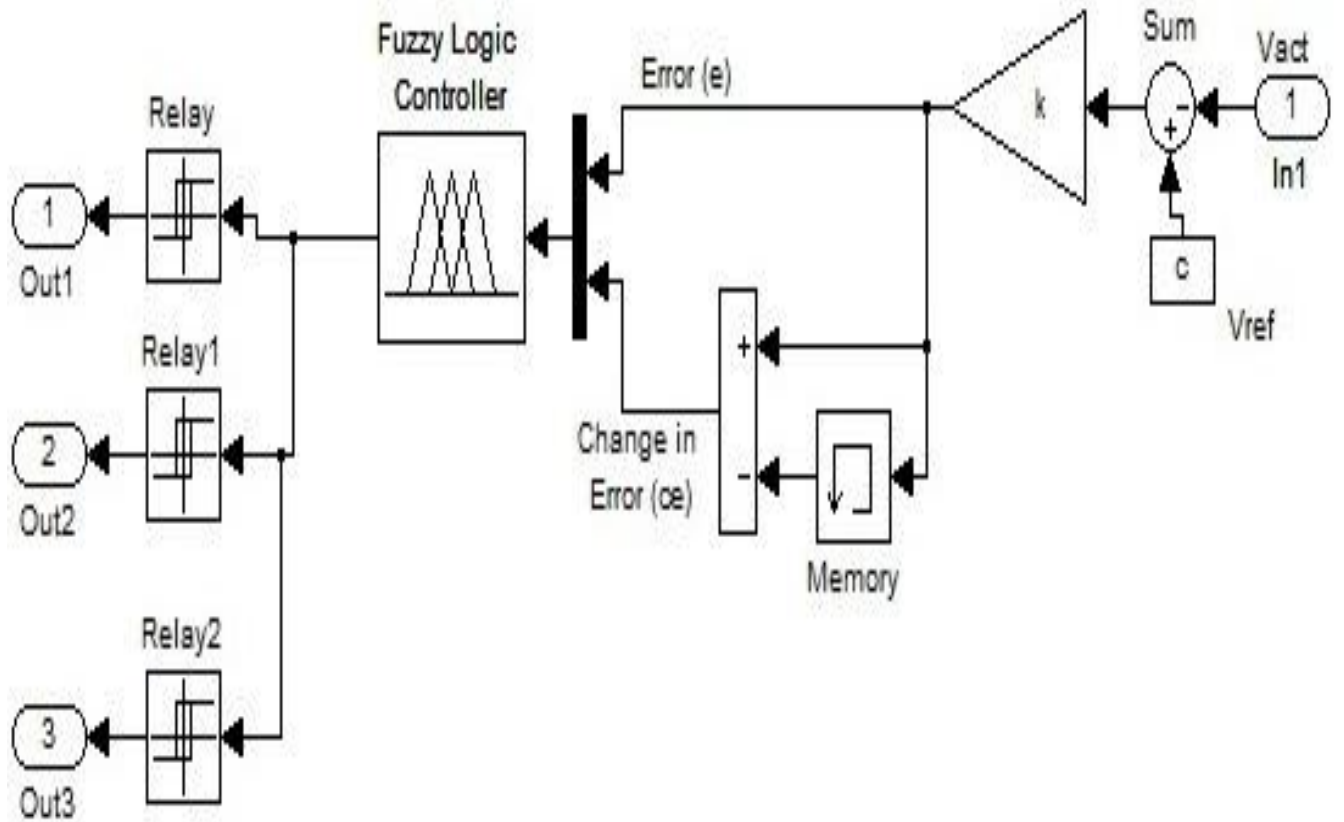


Fig.9 Simulink Model of Fuzzy Logic Control Scheme

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