PERFORMANCE EVALUATION OF NEUTRAL POINT CLAMPED ACTIVE RECTIFIER

A DISSERTATION

Submitted in partial fulfillment of the requirements for the award of the degree of

MASTER OF TECHNOLOGY

in

ELECTRICAL ENGINEERING

(With Specialization in Electric Drives and Power Electronics)

By

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CANDIDATE'S DECLARATION

I hereby declare that the work that is being presented in this dissertation entitled **"PERFORMANCE EVALUATION OF NEUTRAL POINT CLAMPED ACTIVE RECTIFIER"** in partial fulfillment of the requirements for the award of the degree of **Master of Technology** in **Electrical Engineering** with specialization in **"Electric Drives and Power Electronics"** submitted to the **Department of Electrical Engineering, Indian Institute of Technology, Roorkee, INDIA** is an authentic record of my own work carried under the guidance of **Dr. Sharmili Das**, Assistant Professor **& Dr. Pramod Agarwal**, Professor, Department of Electrical Engineering, Indian Institute of Technology, Roorkee.

The matter embodied in this dissertation has not been submitted for the award of any other degree or diploma.

Date: 30/06/2011

Ashokp.
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This is to certify that the above statement made by the candidate is true to the best of my knowledge.

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ABSTRACT

The AC-DC converters, also known as rectifiers, are developed using diodes and thyristors to provide uncontrolled and controlled, unidirectional and bidirectional dc power. However, these rectifiers can pollute AC supply with significant levels of low frequency harmonics, pulsating input current (electromagnetic interference (EMI)), and excessive VAR. with tough regulations and severe economic restraints, the design of Active rectifier which draws nearly sinusoidal current with unity power factor is very important from the point of view of energy saving and also to satisfy harmonic standards such as IEEE 1000-3-2.

In response to these problems, a significant amount of research has been devoted to the area of switch-mode rectifiers (SMRs), power-factor correctors (PFCs), pulse width-modulation (PWM) rectifiers and multilevel rectifiers. Current research has been focusing recently on decreasing the number of power switches to simplify the circuit, complexity of control circuit and increase its reliability.

In the present work, a four switch Single-phase neutral-point diode-clamped active rectifier (reduced switch topology) is considered. Detailed power circuit analysis for the undertaken topology is presented. Two high performance control strategies (two level PWM and three level PWM) are discussed and verified through simulations. These control schemes for single-phase diode-clamped active rectifier is proposed to achieve a unity power factor, balanced neutral-point voltage and constant DC-bus voltage. The application of considered active rectifier topology is to improvement of power quality is investigated. The considered rectifier can also be used for harmonic current filtering. Finally experimental prototype of the considered four switch single-phase diode-clamped rectifier is developed and tested.

Theoretical and practical results of the system show that the developed system can eliminate the harmonics and achieve unity power factor with minimum complexity.

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CHAPTER 1

INTRODUCTION AND LITERATURE REVIEW

1. 1 Introduction

The most familiar loads on electrical power system were the constant power, constant impedance and constant current loads or a linear combination of thereof. In these cases, the voltage and current wave shapes are nearly pure sinusoidal. But this is no longer the case with modern electric power system. Massive use of the nonlinear and time varying devices has led to distortion of voltage and current waveforms. As a consequence, recently the issue of power quality has become important. Both electric utility and end users of electric power are becoming increasingly concerned about the quality of electric power. The term "power quality" has been used to describe the variation of the voltage, current and frequency on the power system beyond a limit.

The equipment connected to an electricity distribution network usually needs some kind of power conditioning, typically rectification, which produces a non sinusoidal line current due to the nonlinear input characteristic. The most significant examples of nonlinear loads are AC-DC converters. These AC-DC Power Converters are extensively used in various applications like power supplies, dc motor drives and front-end converters in adjustable-speed ac drives, HVDC transmission, switched-mode power supplies, and utility interfacing with conventional energy sources and so on. Traditionally, ac-dc power conversion has been dominated by diode or phase controlled rectifiers which act as non-linear loads on the power systems. These Conventional Converter system demands reactive power from the supply lines for proper commutation of the devices used in the system. Therefore conventional converter system has low overall power factor and draw input currents which are rich in harmonics .These harmonics lead to additional power losses in electrical equipment. This creates the power quality problem for the power distribution network and for other electrical systems in the vicinity of rectifier. This is why power factor correction (PFC) on the device side has become an important part of the final design for so many products. Hence present day's technology is heading towards achieving

sinusoidal current in phase with the supply voltage especially while using power electronic equipment.

In electric equipments, PFC technology can increase power factor, reduce harmonic pollution on grid and improve power utilization. The PFC techniques reduce the input current harmonics and improved power factor operation of converters is important from the energy saving point of view and also to satisfy the standards like IEC-1000-3-2, IEC-555 or IEEE-519. For improving the quality of power some techniques are developed. The techniques for improving power factor and to reduce current harmonics are classifies as follows:

- Passive filters.
- Active filters.
- Hybrid filters
- New circuits and control techniques.

Because of severity of power quality problems passive filters, active filters (AFs), and hybrid filters along with conventional rectifiers, have been extensively developed especially in high power rating and already existing installations. However, these filters are quite costly, heavy, and bulky and have reasonable losses which reduce overall efficiency of the complete system. Even in some cases the rating of converter used in AF is almost close to the rating of the load. Under these observations, it is considered better option to include new circuits and control techniques as an inherent part of the system of ac–dc conversion. Under this a new breed of rectifiers has been developed using new solid state self commutating devices those are switch-mode rectifiers (SMRs), power-factor correctors (PFCs), pulse width-modulation (PWM) rectifiers and multilevel rectifiers.

Multilevel rectifiers have been developed now at a reasonably matured level for ac–dc conversion with reduced harmonic currents, high power factor, low electromagnetic interference (EMI) and low radio frequency interference (RFI) at input ac mains and well-regulated and good quality dc output to feed loads ranging from fraction of Watt to several hundred kilowatts (Kw) power ratings in large number of applications. These have the advantages of low stresses on the devices, low losses and thus, high efficiency, and are suitable for high-power applications. It has a stepped voltage waveform instead of PWM and has reduced high-frequency currents. The switching frequency of high power semiconductor switches is usually limited by the maximum

power loss. According to the voltage level of the power semiconductor, there are two-level and multilevel pulse-width modulation (PWM). The voltage stress of power switches can be reduced significantly if the voltage levels are increasing, but the circuit complexity, voltage balance problem and control scheme become more difficult. Recently, much literature has paid attention to multilevel converters for high power or high voltage applications. Multilevel converters take advantage of series connection of low voltage power switches (such as IGBT or IGCT) to handle high voltage stress, operation at higher switching frequency which allows a reduction in the size of passive components, and low harmonic distortion in comparison with two-level converters.

1.2 Literature review

The reason for harmonics in the systems is because of undesirable ac line current harmonics, and low power factors, of conventional rectifiers. These effects include: unsafe neutral current magnitudes in three-phase systems, heating and reduction of life in transformers and Induction Motors, degradation of system voltage waveforms, unsafe currents in power-factor-correction capacitors, and malfunctioning of certain power system protection elements are explained by Anibal T. De Almeida [1], [2].

Multilevel converters-a new breed of converters by J.S Lai and F .Z. Peng [4], [5] has described the multilevel voltage source converters are emerging as a new breed of power converter options for high-power applications. Three main topologies and their operating principle, features, constraints, and potential applications of these converters will be discussed. This paper also explains the application of multilevel converters in reactive power compensation and filtering current harmonics. In these topologies main drawbacks like voltage unbalance between levels and the complexity of control schemes are explained.

The papers [6], [7] by B. R. Lin explained the use of multilevel converters and their use for high power medium voltage applications for AC drive using front end multilevel rectifier as AC/DC/AC converters for AC drive applications. Single phase three level PWM converters [8], [9], [10] for reducing current harmonics are discussed.

The papers related to author B. R. Lin with different fellow scientists has done research on multilevel converters of various topologies and reducing the complexity of power circuit and control circuit by reducing the no. of power switches that are used in the converter. Here he discussed various control schemes [11] for multilevel converters. He discussed drawbacks of

conventional diode/thyristor rectifiers related to power factor decrement and increasing harmonics in the input current. He also given the advantages of three level converters [12], [13] and various control techniques and controllers (PI & Hysteresis current controller for capacitor voltage balancing with reference current generated from supply voltage template) which can be implemented to get better power quality and better eliminating current harmonics [14], [15].He has discussed different topologies and PWM schemes in various papers.

The papers [16], [17], [18] discuss single phase neutral-point diode clamped converter for getting high power factor with balancing output voltage. The practical problems regarding balancing DC-link voltage in multilevel converter is explained by Mario Marchesoni and Pierluigi Tenca [24]. The redundancy in switching states of power devices in diode clamped topology is to avoid capacitor voltage imbalance [16]. In this technique we don't require extra circuitry and is easy to implement. The capacitor clamped topology [19] for high power factor also discussed.

Hysteresis controller is one of the good control strategies for AC-DC converters. It can be applied to single phase rectifiers and three phase rectifiers. Green Boys [21] have explained the principle of HCC for AC-DC converters. But in HCC switching frequency does not remain constant.

Some papers [22], [23], [25] also discuss the most important information about the operation of multilevel PWM converters. N. Schibli and A. Rufer[28] in this paper the use single phase three level traction applications are discussed.

In [31], Mohan N has briefly presented different power converters, their control techniques and applications. B. K. Bose has explained control techniques in detail.

1.3 Dissertation organization

The dissertation is organized into seven chapters and the work included in each chapter is briefly outlined as follows:

The Present **Chapter 1** describes an overview of the use of conventional AC-DC converters and their adverse effects on system are of low overall power factor and draw input currents which are rich in harmonics. Brief literature review on power factor circuits (PFC), Switch Mode Rectifiers (SMRs) and multilevel converters for improving power quality by harmonics mitigation and also conclusions.

The **Chapter 2** deals the harmonics definition and the effect of harmonics in the system. Also deals with different types of linear and non linear loads, harmonic producing equipment and standard regulating line current harmonics. The causes of low power factor, how does it affect the system, different disadvantages of low power factor and the need of power factor correction are discussed.

The **Chapter 3** deals with the adverse effects of conventional rectifier's on the system and classification of rectifiers. The use of improved power quality converters and there classification is discussed. Multilevel converter topologies their advantages are discussed. Single phase three level converter topologies are discussed for eliminating current harmonics. Simulation models are developed using MATLAB/SIMULINK. Elaborate simulation study was done to check the performance of converters under varying load conditions and conclusions.

The **Chapter 4** describes the circuit topology of reduced switch single phase neutral point diode clamped rectifier for high power factor is described. The modes of operation of power circuits are explained. The control strategies for the operation of rectifier are discussed.

The **Chapter 5** deals simulation models of active rectifier using MATLAB/SIMULINK. Elaborating simulation study was done to check the performance of rectifier under varying load condition with two control schemes that are proposed to rectifier. It also gives details about the dynamic performance of converter under sudden changes in load, reference and supply voltage. The harmonic analysis for source current, THD of source current is observed. And the comparative analysis has done for various converters.

The **Chapter 6** gives the hardware implementation of single phase neutral point diode clamped rectifier for experimental validation. The fabrication of power circuit and control circuit is briefly discussed.

The **Chapter 7** presents the recorded experimental results is displayed.

The **Chapter 8** highlights the main conclusions drawn from the work done. Future scope for the improvements to get better performance is presented.

CHAPTER 2

HARMONICS AND POWER FACTOR

Introduction

The equipment connected to an electricity distribution network usually needs some kind of power conditioning, typically rectification, which produces a non sinusoidal line current due to the nonlinear input characteristics. Line-frequency diode rectifiers convert AC input voltage into DC output voltage in an uncontrolled manner. Single-phase diode rectifiers are needed in relatively low power equipment that need some kind of power conditioning, such as electronic equipment (e.g. TVs, office equipment, battery chargers, electronic ballasts) and household appliances. For higher power, three-phase diode rectifiers are used, e.g. in variable-speed drives and industrial equipment. In both single-phase and three-phase rectifiers, a large filtering capacitor is connected across the rectifier output to obtain DC output voltage with low ripple. As a consequence, the line current is non sinusoidal i.e it consists of harmonics.

In most of these cases, the amplitude of odd harmonics of the line current is considerable with respect to the fundamental. The normalized amplitudes of the 3rd, 5th, 7th and 9th harmonics are significant. While the effect of a single low power nonlinear load on the network can be considered negligible, the cumulative effect of several nonlinear loads is important. Line current harmonics have a number of undesirable effects on both the distribution network and consumers.

2.1 Harmonics

A harmonic is defined as steady state voltage or currents having frequencies that are an integer multiple of the system fundamental frequency. Electricity generation is normally produced at constant frequencies of 50 Hz or 60 Hz and the generators e.m.f can be considered practically sinusoidal. However, when a source of sinusoidal voltage is applied to a nonlinear device or load, the resulting current is not perfectly sinusoidal. In the presence of system impedance this current causes a non-sinusoidal voltage drop and, therefore, produces voltage distortion at the load terminals, i.e. the latter contains harmonics.

A sinusoidal voltage or current function that is dependent on time t may be represented by the following expressions:

Voltage function, (2.1)

Current function, (2.2)

Where $\omega=2\times\pi\times f$ is known as the angular frequency of the periodic waveform and is the difference in phase angle between the voltage and the current waveforms referred to as a common axis. The sign of phase angle is positive if the current leads the voltage and negative if the current lags the voltage is shown in Fig.2.1.

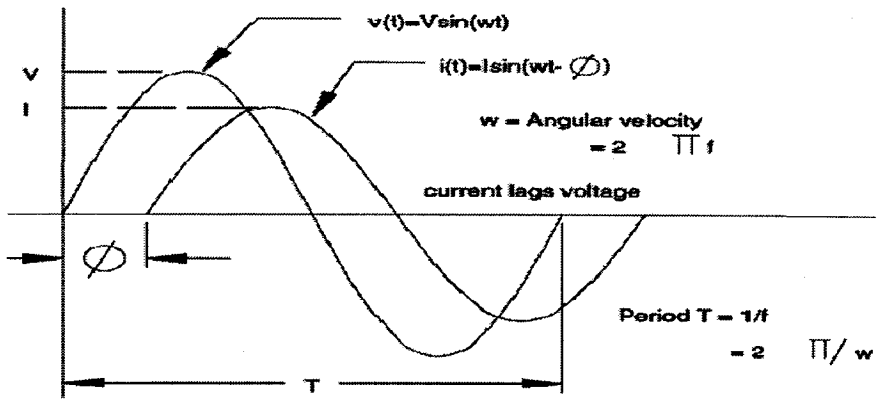


Fig.2.1 Sinusoidal voltage and current

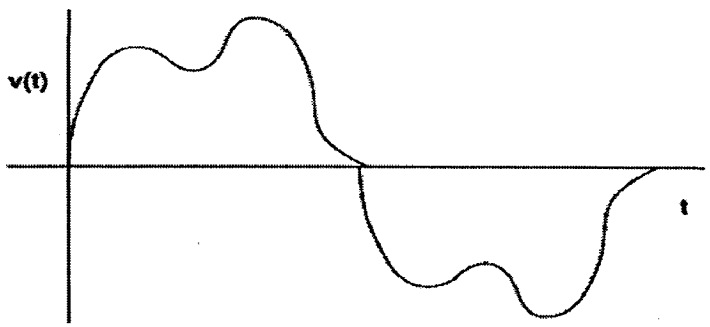


Fig.2.2 Non-sinusoidal voltage waveform

The fundamental (or first harmonic) frequency has a frequency of f_1 , the second harmonic has a frequency of $2\times f_1$, the third harmonic has a frequency of $3\times f_1$, and the n^{th} harmonic has a frequency of $n\times f_1$. If the fundamental frequency is 50 Hz, the second harmonic

frequency is 100 Hz, and the third harmonic frequency is 150 Hz etc. Fig.2.2 shows non-sinusoidal voltage waveform.

The significance of harmonic frequencies can be seen in Fig.2.3 the second harmonic undergoes two complete cycles during one cycle of the fundamental frequency, and the third harmonic traverses three complete cycles during one cycle of the fundamental frequency. V_1, V_2, and V_3 are the peak values of the harmonic components that comprise the composite waveform, which also has a frequency of f. For a periodic voltage wave with fundamental frequency of $\omega = 2\pi f$. The Fig. 2.4 gives sum of two harmonic frequency i.e. fundamental and third harmonic frequencies.

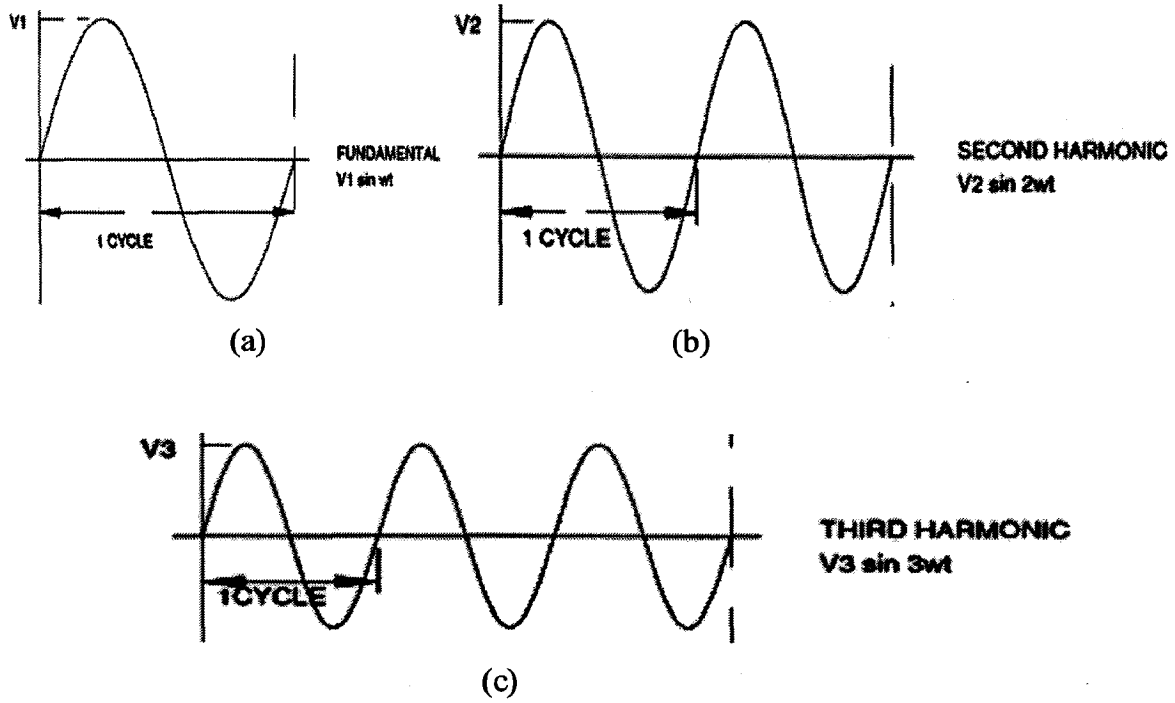


Fig.2.3 (a) Fundamental voltage, (b) second harmonics two cycles in half cycle of fundamental and (c) third harmonics three cycles in half cycle of fundamental

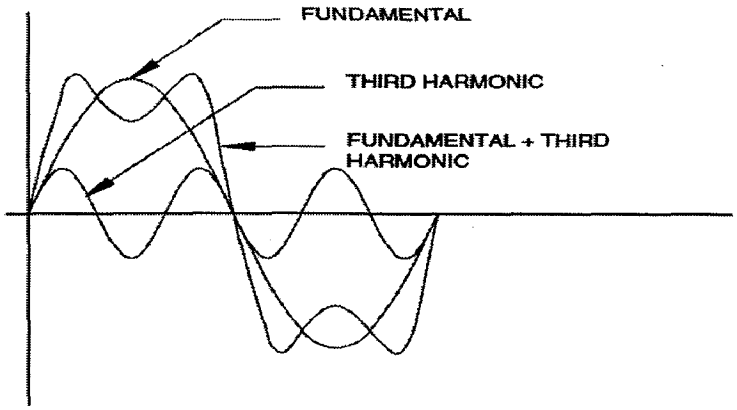


Fig.2.4 Nonlinear waveform by adding the fundamental and third harmonic frequency waveforms

2. 2 Linear and Non-Linear Loads

2. 2.1 Linear loads

Linear loads are those in which voltage and current signals follow one another very closely, such as the voltage drop that develops across a constant resistance, which varies as a direct function of the current that passes through it. This relation is better known as Ohm's law and states that the current through a resistance fed by a varying voltage source is equal to the relation between the voltage and the resistance, as described below. Fig.2.5 shows the voltage and current profile linear.

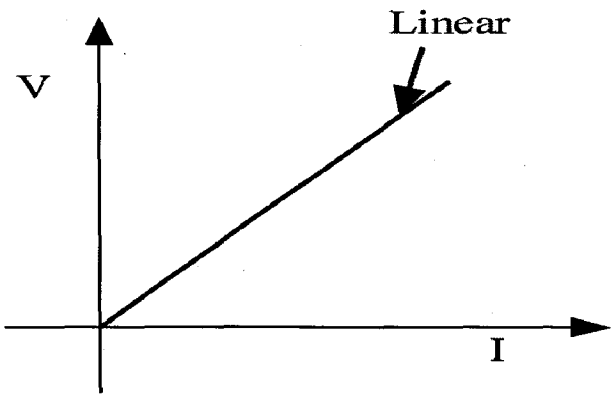


Fig.2.5 Voltage and current profile is linear

$$I(t) = \frac{V(t)}{R} \tag{2.3}$$

Linear loads, such as electrical motors driving fans, water pumps, oil pumps, cranes, elevators, etc., not supplied through power conversion devices like variable frequency drives or any other form or rectification/inversion of current will incorporate magnetic core losses that depend on iron and copper physical characteristics. Table 2.1 describes a list of linear loads [20].

Table 2.1: Examples of linear loads

Resistive elements	**Inductive elements**	**Capacitive elements**
• Incandescent lighting • Electric heaters	• Induction motors • Current limiting reactors • Induction generators (Wind mills) • Damping reactors used to attenuate harmonics • Tuning reactors in harmonic filters	• Power factor correction capacitor banks • Underground cables • Insulated cables • Capacitor used in harmonic filters

2. 2.2 Non Linear loads

Nonlinear loads are loads in which the current waveform does not be similar to the applied voltage waveform due to a number of reasons, for example, the use of electronic switches that conduct load current only during a fraction of the power frequency period. Therefore, we can conceive non linear loads as those in which Ohm's law cannot describe the relation between V and I. Among the most common nonlinear loads in power systems are all types of rectifying devices like those found in power converters, power sources, uninterruptible power supply (UPS) units, and arc devices like electric furnaces and fluorescent lamps. Table 2.2

provides a more extensive list of various devices in this category. Fig.2.6 Shows voltage and current profile is non linear.

Nonlinear loads cause a number of disturbances like voltage waveform distortion, overheating in transformers and other power devices, over current on equipment neutral connection leads, telephone interference, and microprocessor control problems.

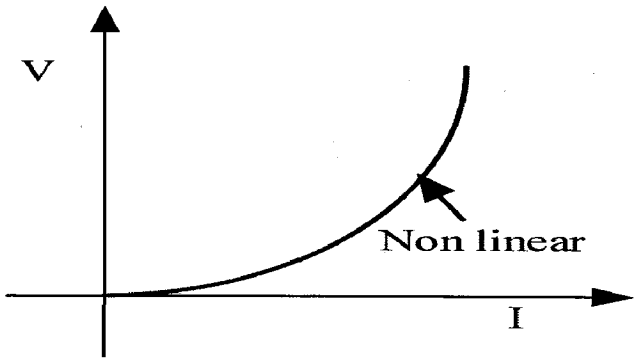


Fig.2.6 Voltage and current profile is non linear

Nonlinear loads cause a number of disturbances like voltage waveform distortion, overheating in transformers and other power devices, over current on equipment neutral connection leads, telephone interference, and microprocessor control problems.

Table 2.2: Examples of some nonlinear loads

Power electronics	Classical devices
• Power converters • Variable frequency drives • DC motor controllers • Cyclo-converters Cranes • Elevators • Steel mills • Power supplies • UPS • Battery chargers • Inverters	• Transformers • Rotating machines • Fluorescent lamps • ARC furnaces

2. 3 Sources of Harmonics

Harmonic producing equipments are found in varied locations from offices to manufacturing plants and they are becoming inevitable in daily life. Various harmonic producing equipments are [1]:

- Personal computers
- Electronic lighting ballasts
- Variable and adjustable speed drives
- Industrial process controls
- Electronic test equipment
- Solid state controls
- UPS systems
- Medical equipment
- Electronic household appliances.

Harmonic currents generated by office equipment increase power system heat losses and the power bills of end users. Generally harmonic problems in office buildings are caused by nonlinear loads causing harmonic current injection. The injected current is propagated to all distribution circuits and leads to harmonic voltage distortion on the system. Harmonic currents can cause such problems as [3]:

2.3.1 Effects of harmonics:

- Excessive current in the neutral conductor of three-phase four-wire systems, caused by odd triplen current harmonics (triplen: 3rd, 9th, 15th, etc.). This leads to overheating of the neutral conductor(over loading), tripping of the protective relay and overheating or de-rating of transformer
- Reduced power factor, hence less active power available from a wall outlet having a certain apparent power rating.
- Excessive heating of wiring and connections
- Damaging of capacitor banks
- Resonance
- Malfunction of electronic equipment & errors in metering equipments
- Communication interference & increased audio noise

- Distorted supply voltage
- Increased power losses
- Logic faults in digital devices
- Errors in power metering
- Inadvertent thermal tripping of relays, circuit breakers and protective devices
- Cogging or crawling in induction motors, mechanical oscillation in a turbine-generator combination or in a motor-load system.

2.4 Standards regulating line current harmonics

The reason for the low power factor is the undesirable ac line current harmonics, of conventional peak-detection and phase-controlled rectifiers. The previously mentioned negative effects of line current distortion have prompted a need for setting limits for the line current harmonics of equipment connected to the electricity distribution network. Standardization activities in this area have been carried out for many years. As early as 1982, the International Electro technical Committee - IEC published its standard IEC 555-2 [IEC82], which was also adopted in 1987 as European standard EN 60555-2, by the European Committee for Electro technical Standardization - CENELEC. Standard IEC 555-2 has been replaced in 1995 by standard IEC 1000-3-2 [IEC95], also adopted by CENELEC as European standard EN 61000-3-2. Standard IEC 1000-3-2 applies to equipment with a rated current up to and including 16Arms per phase which is to be connected to 50Hz or 60Hz, 220-240Vrms single-phase, or 380-415Vrms three-phase mains. Items of electrical equipment are categorized into four classes (A, B, C and D), for which specific limits are set for the harmonic content of the line current. The standard has been revised several times and a second edition was published in 2000 [IEC00] with an amendment in 2001 [IEC01]. Next, we present the current harmonic limits and the present status in equipment classification, with a discussion on the changes in the definition of Class D equipment.

Class A includes: Balanced three-phase equipment; household appliances, excluding equipment identified as Class D; tools, excluding portable tools; dimmers for incandescent lamps; and audio equipment. Equipment not specified in one of the other three classes should be considered as Class A equipment. The limits for Class A are presented.

Class B equipment includes: Portable tools; and nonprofessional arc welding equipment. The limits for this class are those shown in Table 2.3 multiplied by a factor of 1.5.

Class C includes: Lighting equipment. For an active input power greater than 25W, the harmonic currents should not exceed the limits presented in Table 2.4 (except for dimmers for incandescent lamps, which belong to Class A). Discharge lighting equipment having an active input power smaller than or equal to 25W should comply with one of the following two sets of requirements: the harmonic currents should not exceed the Class D power-related limits, shown in Table2.5.The harmonic limits for Class D are presented in Table2.5. The Class D includes equipment having an active input power less than or equal to 600W, of the following types: personal computers, personal computer monitors; and television receivers.

Table 2.3 Limits for Class A equipment in standard IEC 1000-3-2.

Harmonic order n	**Maximum permissible harmonic current** A
Odd harmonics	
3	2.30
5	1.14
7	0.77
9	0.40
11	0.33
13	0.21
$15 \le n \le 39$	$0.15 \cdot \frac{15}{n}$
Even harmonics	
2	1.08
4	0.43
6	0.30
$8 \le n \le 40$	$0.23 \cdot \frac{8}{n}$

Table 2.4 Limits for Class B equipment in standard IEC 1000-3-2.

Harmonic order n	**Maximum permissible harmonic current expressed as a percentage of the input current at the fundamental frequency** %
2	2
3	$30 \cdot PF$ *
5	10
7	7
9	5
$11 \leq n \leq 39$ (odd harmonics only)	3
PF * is the circuit power factor	

Table 2.5 Limits for Class C equipment in standard IEC 1000-3-2.

Harmonic order n	**Maximum permissible harmonic current per watt** mA/W	**Maximum permissible harmonic current** A
3	3.4	2.30
5	1.9	1.14
7	1.0	0.77
9	0.5	0.40
11	0.35	0.33
$13 \leq n \leq 39$	$\frac{3.85}{n}$	As in Class A

Standard IEEE 519-1992 [IEE92] gives recommended practices and requirements for harmonic control in electrical power systems, for both individual consumers and utilities. The limits for line current harmonics are given as a percentage of the maximum demand load current I_L(fundamental frequency component) at the Point of Common Coupling – PCC at the utility. They decrease as the ratio Isc/ I_L decreases, where Isc is the maximum short-circuit current at the PCC, meaning that the limits are lower in weaker grids. The standard covers also high voltage loads, of much higher power, which are not addressed by IEC 1000-3-2.

2.5 Power Factor

Reduction of line current harmonics is needed in order to comply with the standard. This is commonly referred to as the Power Factor Correction – PFC, which may be misleading. Therefore, some clarification is needed. The power factor PF is defined as the ratio of the active power P to the apparent power S:

$$PF=P/S$$

For purely sinusoidal voltage and current, the classical definition is obtained

$$PF=\cos\varphi \tag{2.4}$$

Where φ is the displacement angle between phase voltage and phase current. We assume the line voltage to be sinusoidal, since in most cases the total harmonic voltage distortion is quite low, e.g. the total harmonic distortion of the line voltage is THD=2%. However, the line current is non sinusoidal when the load is nonlinear. Therefore, the classical definition of the power factor does not apply. For sinusoidal voltage and non sinusoidal current can be expressed as:

$$PF = \frac{V_{rms} I_{1,rms} \cos\varphi}{V_{rms} I_{rms}} = \frac{I_{1,rms}}{I_{rms}} \cos\varphi = K_P \cos\varphi = D.F \cos\varphi \tag{2.5}$$

The factor (Distortion Factor)

$$K_P = D.F = \frac{I_{1,rms}}{I_{rms}}, K_P \in [0,1] \tag{2.6}$$

It describes the harmonic content of the current with respect to the fundamental. This factor is called distortion factor. In a classical sense, PFC means compensation of the displacement factor In this case; the power factor depends on both harmonic content and displacement factor. It appears that there is no standard term which can be used to denote the factor defined above .Some authors refer to it as the 'purity factor' while others as the 'distortion factor' We believe that 'purity factor' describes its meaning more accurately, as the factor is unity for a pure sinusoidal current, and it decreases as the harmonic content increases. Moreover, defining it as 'distortion factor' is in contradiction with the definition given by the IEEE

Standard Dictionary on Electrical and Electronics ,which considers it as a synonym for the total harmonic distortion factor, the latter being defined for the line current as:

$$THD_i = \frac{\sqrt{\sum_{n=2}^{\infty} I_{n,rms}^2}}{I_{1,rms}} \tag{2.7}$$

It is straightforward to show that the relation between *K*p and *THDi* is:

$$K_P = \frac{1}{\sqrt{1 + THD_i^2}} \tag{2.8}$$

Standard IEC 1000-3-2 sets limits on the harmonic content of the current but does not specifically regulate the purity factor *K*p or the total harmonic distortion of the line current THD_i

The values of *K*p and THD_i for which compliance with IEC 1000-3-2 is achieved depend on the power level. For low power level, even a relatively distorted line current may comply with the standard. In addition to this, it can be seen from (that the distortion factor *K*p of a waveform with a moderate THD_i is close to unity (e.g. *K*p =0.989 for THD_i =15%). Considering as well, the following statements can be made: A high power factor can be achieved even with a substantial harmonic content. The power factor *PF* is not significantly degraded by harmonics, unless their amplitude is quite large (low *K*p, very large THD_i). Low harmonic content does not guarantee high power factor (*K*p close to unity, but low cos(φ).

Some of the disadvantages of low power factor are [1]:

- Because of large current, the losses in the generators and transmission line increases and causing over heating of the system components.
- It causes poor voltage regulation at the load.
- As the load voltage increases due to poor voltage regulation the power transfer capacity is adversely affected.
- The investment in system facilities per KW of load supplied increases with decreases in supply power factor.

Improving the power factor brings three major benefits:

- Power distribution costs for the electric company are reduced, making the power company much happier. A side benefit is to reduce the tendency of the current peaks to "flatten" the tops of the input voltage sinusoidal waveform.
- More power can be drawn from a line of a given current rating, allowing more powerful equipment to be comected without having to re-wire a building, saving time and money.
- Various governmental and quasi-governmental agencies are passing laws requiring improved power factors on certain types of equipment, especially those which draw a lot of power. These laws make it illegal to sell certain types of equipment without testing and certification of a minimum power factor. To continue to sell medium to high power supplies in the future, power supply manufacturers will have to deal with power factor correction.

Because of the severity of problems due to low power factor, some options such as passive filters, active filters and hybrid filters to be used along with traditional thyristor/diode rectifiers have been extensively developed, especially in large rating and already existing installations.

2.6 Power Factor Correction

Most of the research on Power Factor Correction (PFC) for nonlinear loads actually related to the reduction of the harmonic content of the line current. There are several solutions to achieve PFC Depending on whether active switches (controllable by an external control input) are used or not, PFC solutions can be categorized as passive or active. In passive PFC, only passive elements are used in addition to the diode bridge rectifier, to improve the shape of the line current. Obviously, the output voltage is not controllable. For active PFC, active switches are used in conjunction with reactive elements in order to increase the effectiveness of the line current shaping and to obtain controllable output voltage. The switching frequency further differentiates the active PFC solutions into two classes. In low-frequency active PFC, switching takes place at low-order harmonics of the line-frequency and it is synchronized with the line

voltage. In high-frequency active PFC, the switching frequency is much higher than the line frequency. An overview of methods for PFC is presented.

2.7 Desirable features of a PFC technique

2.7.1 Input side features:

(1) Sinusoidal input current with close to unity PF operation.

(2) Reduced EMI.

(3) Insensitive to small signal perturbations in the load Output side features:

2.7.2 Output side features:

(1) Good line and load regulation.

(2) Low output voltage ripple.

(3) Fast output dynamics (i.e., high bandwidth).

(4) Multiple output voltage, levels if needed by the application.

However the filters that are used PFC are quite costly, bulky, and have reasonable losses, which reduce overall efficiency of the complete system. Even in some cases the rating of converter use in active filters is almost close to the rating of the load. Under such circumstances, it is considered better option to use such converters as an inherent part of system of AC-DC conversion, which provides reduced size, high efficiency, and well controlled and regulated DC to provide comfortable and flexible operation of the system.

CHAPTER 3

MULTILEVEL CONVERTERS

Introduction

The AC–DC conversion is used increasingly in a wide diversity of applications: power supplies for microelectronics, household electric appliances, electronic ballasts, battery charging, dc motor drives, power conversion, etc.

3.1 Classification of rectifiers

As shown in Figure 3.1 below ac–dc converters can be classified to different topologies working with low switching frequency (line commutated) and other topologies which operate with high switching frequency. The simplest line-commutated converters use diodes to transform the electrical energy from ac to dc. The use of thyristors allows for the control the power flow. The main disadvantage of these naturally commutated converters is the generation of harmonics and drawing reactive power. Harmonics have a negative effect on the operation of the electrical system and, therefore, attention is paid to their generation and control. One basic and typical method to reduce input current harmonics is the use of multi pulse connections based on transformers with multiple windings.

The main feature of the multi pulse rectifier [2] lies in its ability to reduce the line current harmonic distortion. This is achieved by the phase shifting transformer, through which some of the low-order harmonic currents generated by the six-pulse rectifiers are canceled. In general, the higher the number of rectifier pulses, the lower the line current distortion is. The rectifiers with more than 30 pulses are seldom used in practice mainly due to increased transformer costs and limited performance improvements. The multi pulse rectifier has a number of other features. It normally does not require any LC filters or power factor compensators, which leads to the elimination of possible LC resonances. The use of the phase-shifting transformer provides an effective means to block common-mode voltages generated by the rectifier and inverter in medium voltage drives, which would otherwise appear on motor terminals, leading to a premature failure of winding insulation.

Another conceptually different way of harmonics reduction is the so-called power-factor correction (PFC). In these converters, controlled power switches like insulated gate bipolar transistors (IGBTs), gate-turn-off thyristors (GTOs), or integrated gate controlled thyristors (IGCTs) are included in the power circuit of the rectifier to change actively the waveform of the input current, reducing the distortion .These circuits reduce harmonics and consequently they improve the power factor, which is the origin of their generic name of PFC. Several PFC topologies like boost and Vienna rectifiers discussed further, are suited for applications, where power is transmitted only from the ac source to the dc load. However, there are several applications where energy flow can be reversed during the operation. Examples are: locomotives, downhill conveyors, cranes, etc. In all these applications, the line-side converter must be able to deliver energy back to the power supply, which is known as power regeneration. A regenerative rectifier is a rectifier capable of power regeneration These rectifiers, also known as active front end (AFE), can be classified as voltage-source rectifiers (VSRs) and current-source rectifiers (CSRs).

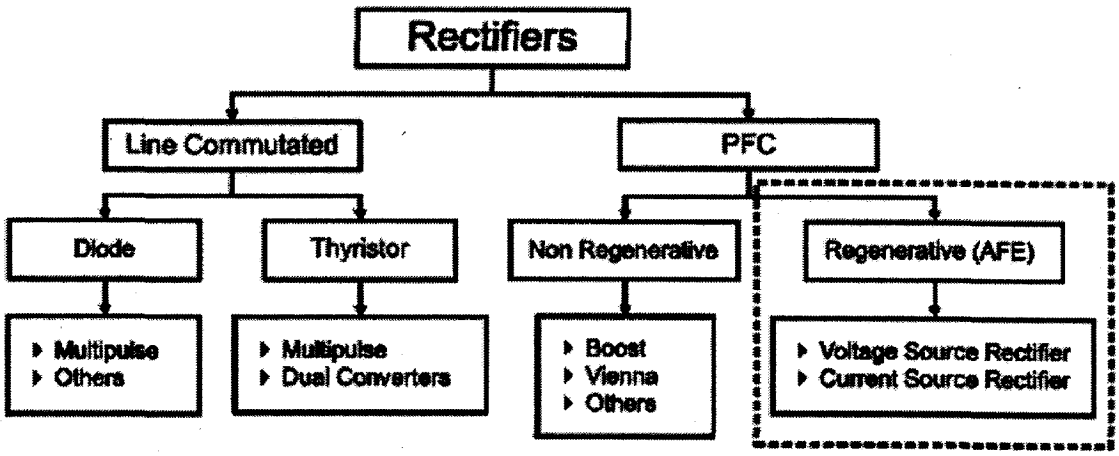


Fig.3.1 Classification of rectifiers

Though passive rectifiers are simple, these present themselves as nonlinear loads to the utility. The input currents of these rectifiers are having considerable lower order harmonics. These also cause considerable overheating in the distribution lines and the distribution transformer supplying the loads, and electromagnetic interference (EMI) with communication and control lines in the proximity. Further, a diode-bridge rectifier cannot regulate its output dc voltage against input voltage regulation. It also cannot regenerate, which is essential in the certain motor drive applications. The other associated problems of these converters include [4]:

3.1.1 Problems with Conventional Rectifiers:

i) Large reactive power drawn by the rectifiers from the power system which requires that the distribution equipment handle large power, thus increasing its volt-ampere ratings;

ii) Voltage drops at the buses;

iii) Higher input current harmonics resulting in the distorted line current which tends to distort the line voltage waveform. This often creates problems in the reliable operation of sensitive equipment operating on the same bus;

iv) Increased losses in the equipments (due to harmonics) such as transformers and motors connected to the utility;

v) Electromagnetic interference with the nearby communication lines;

vi) Blown-fuses on power factor correction capacitors due to high voltages and currents from resonance with line impedance and capacitor bank failures;

vii) Nuisance operation of protective devices including false tripping of relays;

viii) Damaging dielectric heating in cables and so on.

In order to comply with such harmonic standards, bulk input passive filters and harmonic traps have been used at the input sides of the passive rectifiers. These not only increase the volume and weight of the rectifiers, but also deteriorate the dynamic response and the overall efficiency.

With the advent of new solid state self commutating devices such as MOSFETs, insulated gate bipolar transistors (IGBTs), gate turn-off thyristors (GTOs), etc., even some of which have either not been thought or not possible to be developed earlier using diodes and thyristors. Such pieces of equipment are generally known as converters. These converters are used for power quality purpose so; these are called improved power quality converters (IPQCs):

3.2 Improved Power Quality Converters (IPQCs):

Conventional ac-dc converters have the demerits of poor power quality in terms of injected current harmonics, caused voltage distortion and poor power factor at input ac mains and slow varying rippled dc output at load end, low efficiency and large size of ac and dc filters as discussed above. In light of their increased applications, a new breed of rectifiers has been developed using new solid state self commutating devices such as MOSFETs, insulated gate

bipolar transistors (IGBTs), gate turn-off thyristors (GTOs), etc., even some of which have either not been thought or not possible to be developed earlier using diodes and thyristors. Such pieces of equpipment are generally known as converters, but specifically named as switch-mode rectifiers (SMRs), power-factor correctors (PFCs), pulse width-modulation (PWM) rectifiers and multilevel rectifiers. Because of strict requirement of power quality at input ac mains several standards have been developed and are being enforced on the consumers. Because of severity of power quality problems some other options such as passive filters, active filters (AFs), and hybrid filters along with conventional rectifiers, have been extensively developed especially in high power rating and already existing installations. However, these filters are quite costly, heavy, and bulky and have reasonable losses which reduce overall efficiency of the complete system. Even in some cases the rating of converter used in AF is almost close to the rating of the load. Under these observations, it is considered better option to include such converters as an inherent part of the system of ac–dc conversion, which provides reduced size, higher efficiency, and well controlled and regulated dc to provide comfortable and flexible operation of the system. The following are some advantages of PWM active rectifiers over passive rectifiers are:

i. Sinusoidal input current operation
ii. Adjustable input power factor which means these are used as PFC circuits
iii. well-regulated and good quality dc output voltage/current to feed loads ranging from fraction of Watt to several hundred kilowatts power ratings.
iv. Low-valued energy storage elements(inductors and capacitors)
v. Low electromagnetic interference (EMI) and radio frequency interference (RFI) at input ac mains
vi. Good dynamic response against sudden changes in input voltage and load current
vii. Higher efficiency of power conversion

Improved power quality converters (IPQCs) have been classified on the basis of the converter topology as Boost, Buck, Buck-Boost and Multilevel converters with unidirectional and bi-directional power flow and the type of converter used as unidirectional and bi-directional converters. However, for high-voltage and high-power applications, the concept of multilevel converters is developed which may avoid a low-frequency transformer and reduces the switching frequency of the devices.

The IPQC technology has been developed now at a reasonably matured level for ac–dc conversion with reduced harmonic currents, high power factor, low electromagnetic interference (EMI) and radio frequency interference (RFI) at input ac mains and well-regulated and good quality dc output to feed loads ranging from fraction of Watt to several hundred kilowatts power ratings in large number of applications. IPQCs are classified on the basis of topology and type of converter used. The topology-based classification is categorized on the basis of boost, buck, buck–boost, multilevel, unidirectional and bidirectional voltage, current, and power flow. The converter type can be step-up and step-down choppers, voltage source and current-source inverters, bridge structure, etc.

3.2.1 Topology-Based Classification

This classification of IPQC is based on the topology used in the converters. These are classified as boost, buck, buck–boost, and multilevel with unidirectional and bidirectional power flow. Fig. 3.2 shows the tree of topology-based classification of IPQCs. These converters are developed in such vastly varying configurations to fulfill the very close and exact requirement in variety.

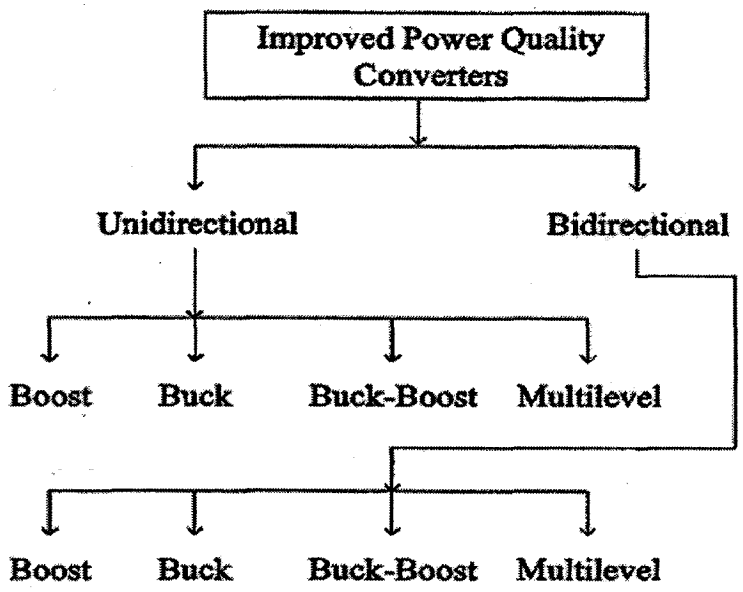


Fig.3.2 Classification of improved power quality converters

3.2.2 Converter-based classification

This type of classification is based on the converter used as shown in Fig. 3.3. These are broadly classified into two types, namely, unidirectional and bidirectional converters.

Unidirectional converters are realized using a diode bridge in conjunction with other basic power electronic converters, namely, step-down chopper, step-up chopper, step-up/down chopper, isolated, forward, fly back, push pull, half bridge, bridge, SEPIC, Cuk, Zeta, etc., and multilevel converters. Bidirectional ac–dc converters consist of basic converters normally used in inverters such as push–pull, half-bridge, voltage-source inverters, and current-source inverters employing MOSFETs for low-power, IGBTs for medium-power, and GTOs for high-power converters. These ac–dc converters are extensively employed for adjustable-speed drives used to drive active loads such as a hoist, a crane, traction, etc., line interactive UPS, and BESS. Four-quadrant ac–dc converters are normally implemented using matrix converters.

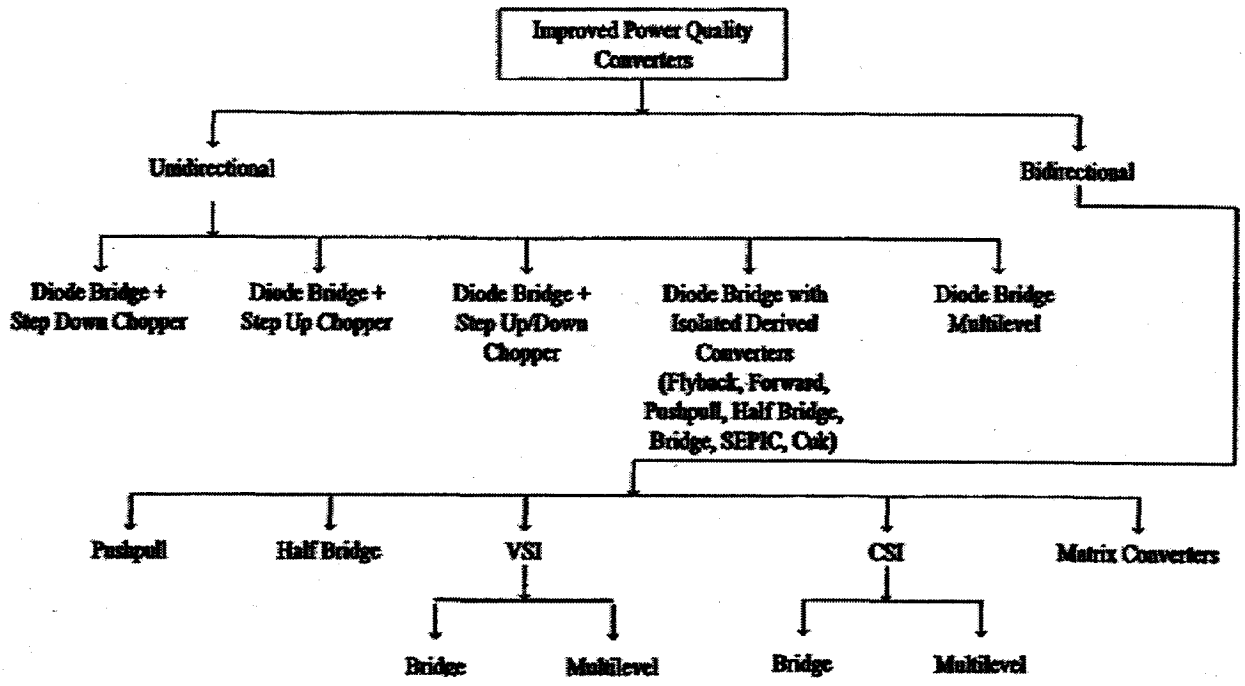


Fig.3.3 Classification based on converter used

3.3 Multilevel Converters for PFC

Multilevel converters have the advantages of low stresses on the devices, low losses and thus, high efficiency, and are suitable for high-power applications [7]. It has a stepped voltage

waveform instead of PWM and has reduced high-frequency currents. The switching frequency of high power semiconductor switches is usually limited by the maximum power loss. According to the voltage level of the power semiconductor, there are two-level and multilevel pulse-width modulation (PWM) schemes the two-level and three-level PWM pattern [4]. The voltage stress of power switches can be reduced significantly if the voltage levels are increasing, but the circuit complexity, voltage balance problem and control scheme become more difficult. . Recently, much literature has paid attention to multilevel converters for high power or high voltage applications [5]. Multilevel converters take advantage of series connection of low voltage power switches (such as IGBT or IGCT) to handle high voltage stress, operation at higher switching frequency which allows a reduction in the size of passive components, and low harmonic distortion in comparison with two-level converters.

3.3.1 Configurations:

Circuit configurations of MPCs are classified on the basis of number of phases and power flow capability as shown in Fig .3.4 the first category consists of single-phase and three-phase MPCs with unidirectional power flow. Single phase and three-phase MPCs with bi-directional power flow from the second category.

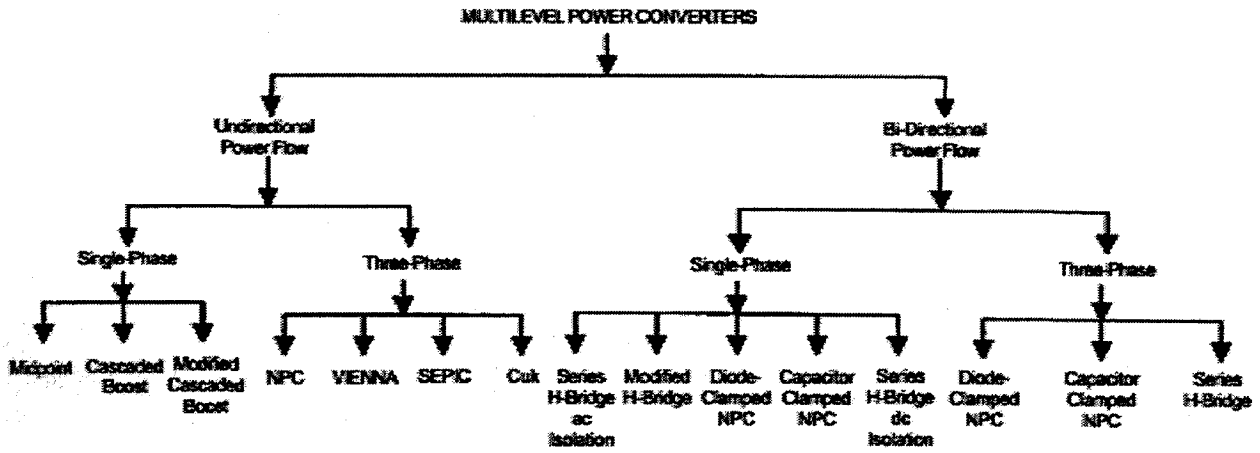


Fig.3.4 Classification of multilevel power converters

MSPC (Multilevel Static Power Conversion) technology has reached a mature level and is increasingly being applied to a number of medium and high voltage applications. Application of MPC with bi-directional power flow in electric drives forms an important area of research in MSPC. MPCs were initially proposed in ac motor drives applications due to their ability to

generate low harmonics, multi-tier waveforms. Permanent magnet brushless motor (PMSM) drives in high power three-phase industrial drive and as well as in single phase traction drives. Series H-Bridge MLI with isolated dc sources for each level has been proposed for Electric Vehicle (EV) drives applications [22]. This converter provides a modular structure, adds redundancy and is uniquely suited for the applications drawing power from independent batteries and fuel cells.

As power levels reach multiple kW in single-phase applications, multilevel techniques have been proposed in single-phase ac-dc power conversion with unidirectional power flow for two-quadrant rectifier- inverter drives and high voltage front-end power factor pre-regulators.

Use of low voltage power devices in these power factor correction (PFC) converters allows high switching frequency operation required for PFC. a number of three level topologies have been proposed for single-phase rectification [11] achieving compliance to relevant international standards albeit at more complex control strategy than two level rectifiers[12]. Three-phase MPCs with unidirectional power flow have been proposed for high performance power supplies and rectifiers in non-regenerative ac drive applications.

A number of configurations including diode clamped NPC converter, VIENNA rectifiers and series H-bridge converters have been introduced in electric drives, utility system and power supplies applications with excellent results and their widespread adaptation is certain in near future.

3.3.2 Advantages of multilevel converters:

1. Trend in development of power devices indicates a tradeoff in voltage rating and switching frequency as well as overall performance. Voltage stresses on devices in MPCs are just a fraction of overall voltage rating of the converter. This allows use of high performance devices available at low voltage rating.
2. Large changes in voltage levels at high frequency can cause common mode voltages and electromagnetic interference (EMI). Common mode voltages can cause premature bearing and insulation failure in electric motors, conducted EMI and other problems. Common mode voltages are reduced in these converters as the voltage is synthesized in smaller steps with low dv/dt.

3. Voltage handling capacity of MPCs is not restricted by voltage rating of power devices. Semiconductor devices impose a limit on voltage rating of conventional converters leading to high current design of system, which limits the power rating and increases losses.
4. Voltage and current harmonics are significantly reduced in MPCs. Multilevel PWM and step modulation methods have been proposed to synthesize voltages with high spectral quality even at low switching frequency. This is an important criterion if GTOs and other high power devices are used, as well as high efficiency is desired in converters.
5. High voltage handling capability and improved spectral performance reduce the need for step-down and multi-pulse/poly-phase transformers which are used in two level and multi-pulse converters in high voltage applications. Substantial reduction in cost, size, weight and losses are possible by reduction of transformers.

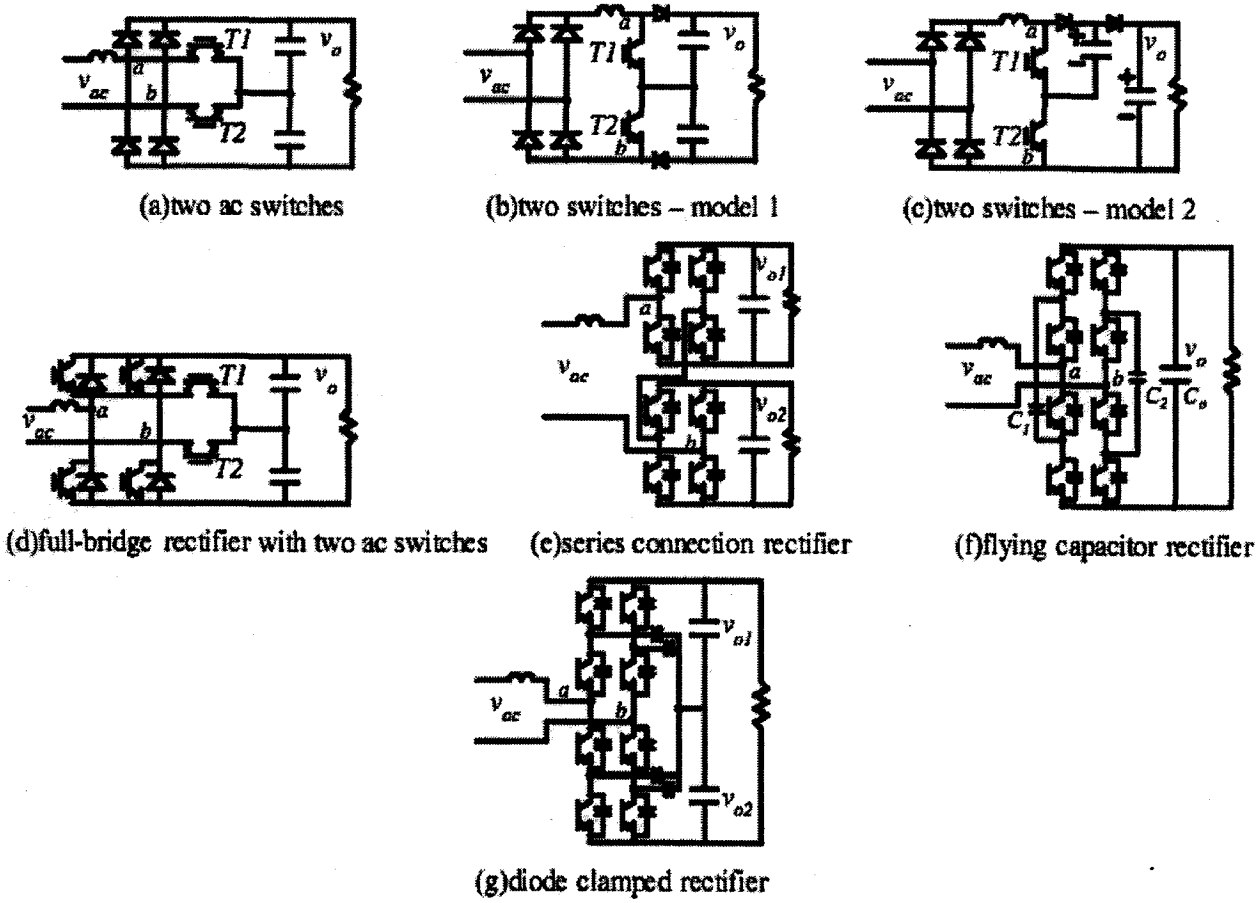
3.4 Classification of Single Phase Multilevel Converters

Converters in this category have been proposed as an alternative to conventional two level boost rectifiers for high voltage/power applications. The main advantage is increase in efficiency and performance as the current ripple is significantly reduced leading to reduction in the size and core losses of the inductor and use of power devices with low voltage ratings with better overall performance. The configurations of single phase multilevel converters [9] are shown in Fig, 3.5. The classification based on unidirectional and bidirectional power flow. First three circuits based on unidirectional power flow and for bidirectional power flow applications, four possible circuit topologies are shown for achieving a three-level voltage pattern and reducing the voltage stress on power semiconductors [13]. The circuit configuration is based on the full-bridge rectifier with two ac switches. The topology of series connection of two full-bridge rectifiers is shown. Two floating dc bus voltages are provided and the voltage stress of each switch is equal to the dc bus voltage. Increasing the connection number of full-bridge rectifiers obtains the more voltage levels but increases the control complexity. The advantage of this configuration is that it is highly modular to implement the multi-level converter.

(a) (b) (c)

Fig. 3.5 Pulse width modulation pattern: (a) two-level scheme with bipolar; (b) two-level Scheme with unipolar; (c) three-level scheme.

Its main problem is that many floating dc voltages are needed. A three-level power factor corrector based on the flying capacitor topology is shown Fig.3.6 (f) There is a flying capacitor between two nested cells. The voltage stress of output capacitor Co is twice that of flying capacitors C_1 and C_2. A three-level rectifier based on the diode clamped topology. Two neutral point clamped diodes are used in this circuit to generate a three-level voltage pattern on the ac side of the rectifier.



(a)two ac switches (b)two switches – model 1 (c)two switches – model 2

(d)full-bridge rectifier with two ac switches (e)series connection rectifier (f)flying capacitor rectifier

(g)diode clamped rectifier

Fig. 3.6 Circuit topologies for power factor correction with three-level PWM scheme.

For an n-level PWM scheme, the voltage waveform quality is improved and the voltage stress of the power semiconductors is reduced by a factor of $1/(n-1)$. For high level number applications, the control scheme of capacitor voltage balance on the dc bus becomes very difficult.

3.5 Topologies of Three Level PWM Converters

Single-phase three-level converters [9] are used to achieve high power factor and draw nearly sinusoidal line current to meet the limits of line current harmonics. The three level power factor corrector with unidirectional power flow. Two ac power switches are used here then the voltage stress of each power switch equals half of the dc bus voltage. There are three voltage levels (0; $v_0/2$ and v_0) on the ac side of rectifier. However, these converters have distinct operating modes depending on the instantaneous magnitude of the input voltage. This requires a rule-based non-linear control with large number of sense variables for current control and output voltage regulation as well as neutral point voltage balance.

In three level topologies the voltage stress of each power switch equals half of the dc bus voltage. There are three voltage levels (0; $v_0/2$ and v_0) on the ac side of rectifier. Line current is controlled on the basis of line voltage and measured supply current. There are also three voltage levels (0; $v_0/2$and v_0) on the dc-link. There are different circuit configurations for getting three level PWM operations [10]. But one of the major differences between them is the number of power switches and stresses on the switches. The conventional three-phase neutral point clamped rectifier having 12 power switches to perform three-level PWM pattern for single-phase 8 power switches needed.

For bidirectional power flow applications in single-phase, three possible circuit topologies are there for achieving a three-level voltage pattern and reducing the voltage stress on power semiconductors.

1. Diode clamped three level converter
2. Flying capacitor three level converter
3. Series H bridge three level converter

3.6 Diode Clamped Three Level Converter:

An m level diode clamped converter [17] consists of (m-1) capacitors on the dc bus and produces m levels of the phase voltage.Fig.3.7 shows a single phase full bridge three level diode clamped converter in which the dc bus consists of two capacitors C_{d1} and C_{d2}. For dc voltage V_{dc}, the voltage across each capacitor is $V_{dc}/2$ and each device voltage stress will be limited to one capacitor voltage level, $V_{dc}/2$ through clamping devices.

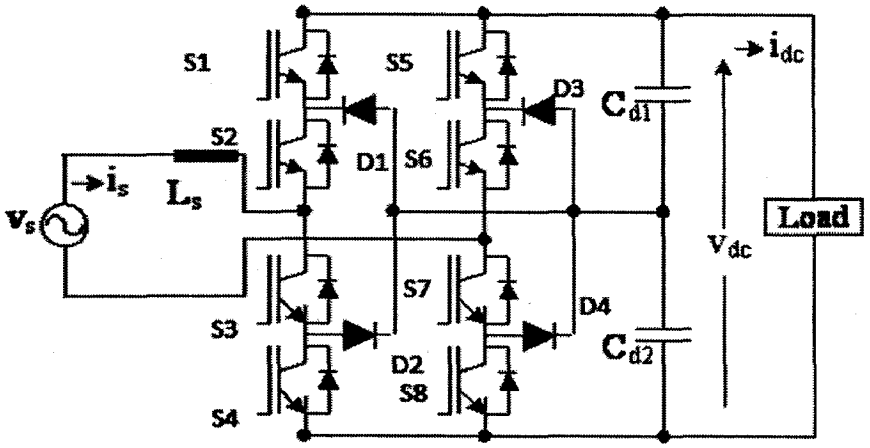


Fig.3.7 Single Phase Bidirectional Diode Clamped Three Level Converter.

Advantages:

1. When the no. of levels is high enough, the harmonic content will be low enough to avoid the need of filters.
2. Efficiency is high because all devices are switched at the fundamental frequency.
3. Reactive power flow can be controlled.
4. The adopted multilevel diode clamped rectifier can be operated in four-quadrant operation which is necessary for the shunt active power filter.

Disadvantages:

1. Excessive clamping diodes are required when no. of levels is high.
2. It is difficult to do real power flow control for the individual converter
3. There are unequal current stresses on the power devices.
4. More no. of sensing devices are required for control circuit.

3.6.1 Simulation results

The converter is simulated in MATLAB/SIMULINK to do its performance evaluation. An error signal is generated by comparing the dc voltage output with reference value and then it's passed through a PI controller to generate a reference current which is compared with actual and the error is controlled using current controller. The output of controller given to PWM (generally HCC) which gives required pulses for the operation of converter.

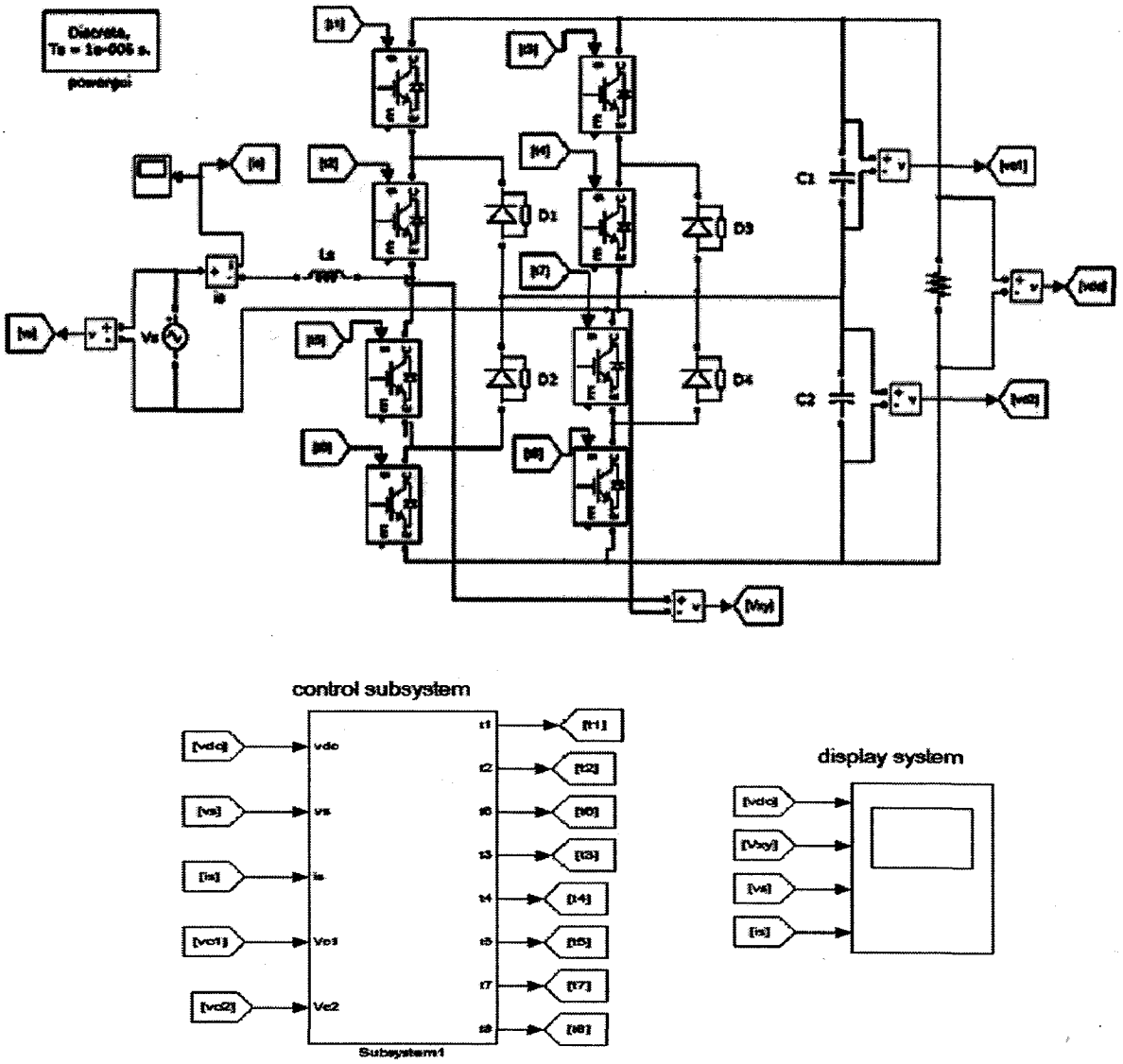


Fig.3.8 SIMULINK model of Diode clamped three level converter.

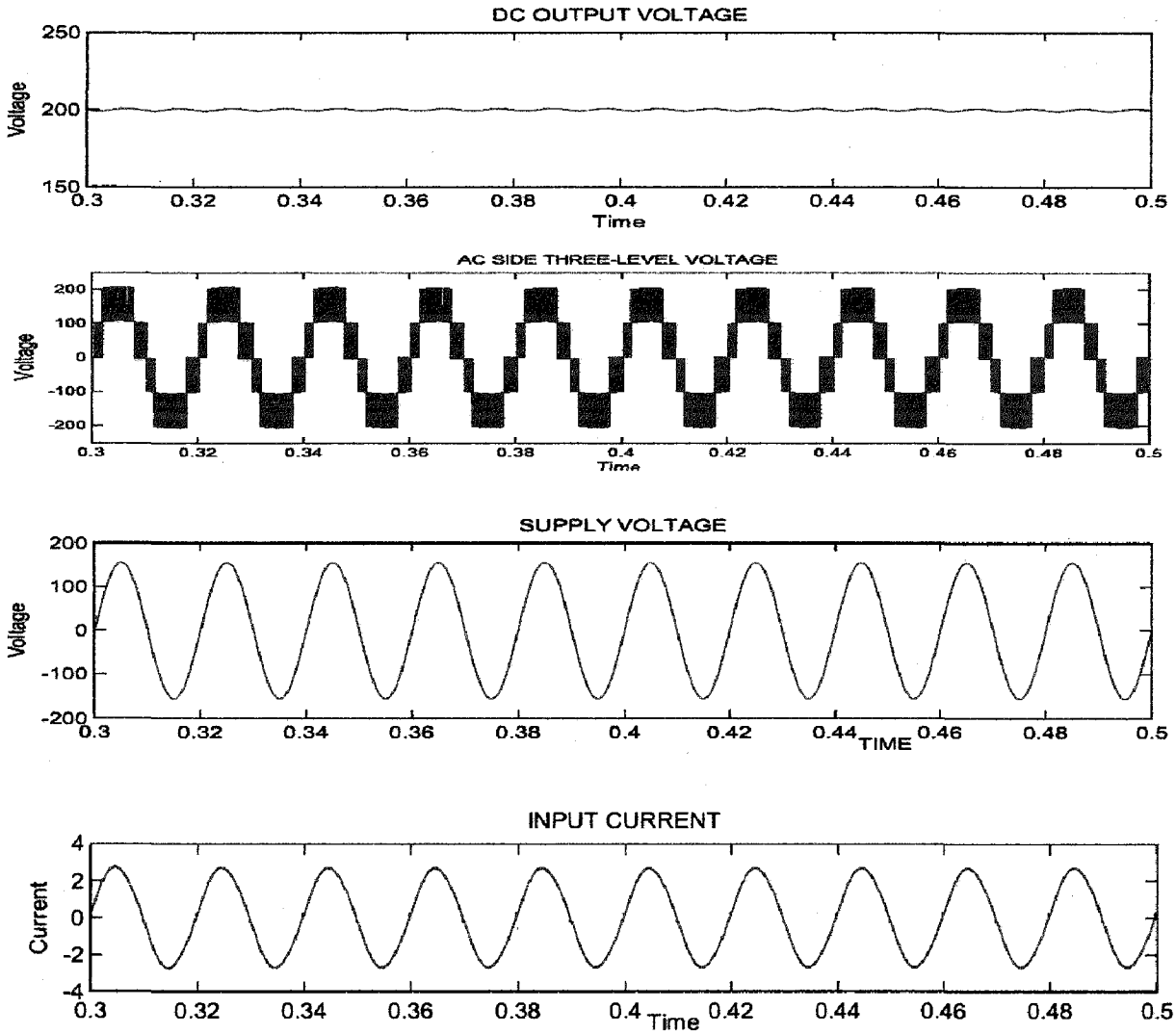


Fig.3.9 Various waveforms of Diode clamped three level converter

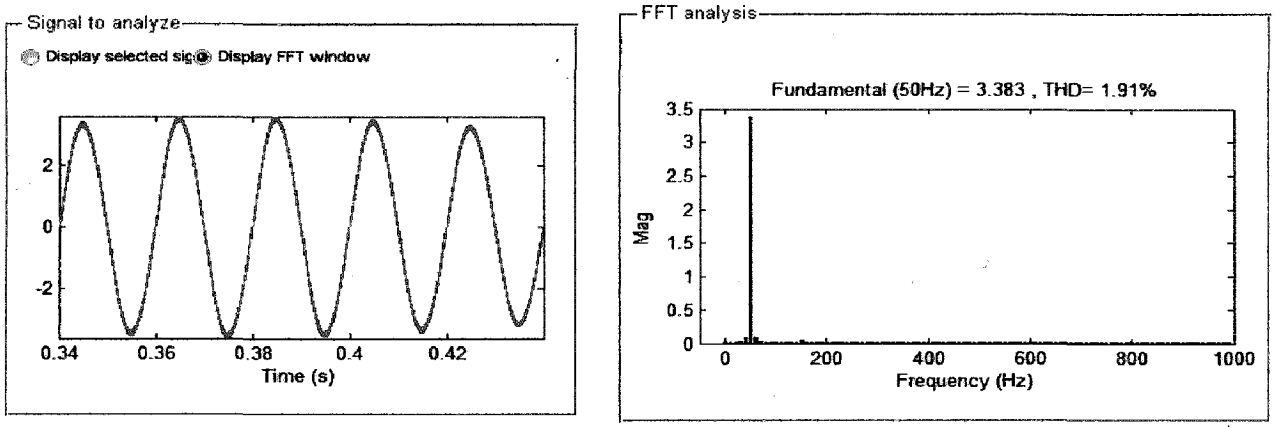


Fig.3.10 Waveform and harmonic spectrum of input current

The input current waveform and its harmonic spectrum are as shown in the figure 3.10. The supply current is having a THD of 1.91%.The output voltage settles around reference value early so response time is good and even ripple in voltage is less .The change in output voltage is less than 5V and as seen clearly from source current waveform that current is almost in phase with the voltage.THD is shown by using FFT analysis.

3.6.2 Varying load condition:

The model is simulated under various loads varying from minimum to maximum keeping input voltage constant. The input current rms value is measured directly from functional block of SIMULINK while THD from POWERGUI block. Output voltage is measured in voltage block. Power factor is found active and reactive power block while efficiency is calculated from input and output powers.

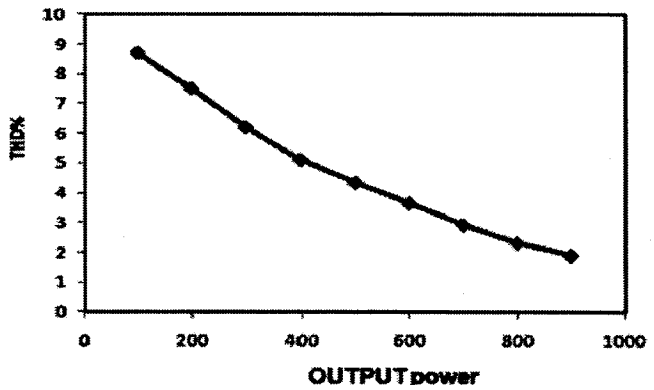


Fig.3.11 Total harmonic distortion vs output power

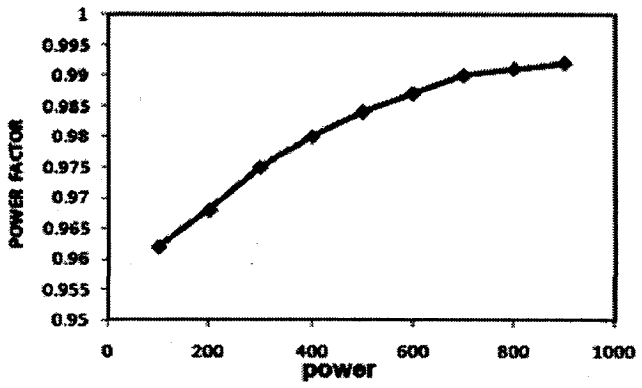


Fig.3.12 Power factor vs output power

3.7 Six Switch Diode Clamped Three Level Converter

Single phase bi-directional neutral point clamped AC-DC converter [18] with the functions of being a power factor corrector and an active filter is proposed, to reduce current harmonics and compensate for the reactive power current drawn from a nonlinear load. Due to more no. of power switches the power circuit and the control circuit is complex in nature. . Current research has been focusing recently on decreasing the number of power switches to simplify the circuit, complexity of control circuit and increase its reliability. Fig.3.13 shows the six switch Diode Clamped Three Level Converter. The main advantages of this topology as follows:

- Reduced number of switches and lower cost
- Lower overall converter switching losses and higher efficiency
- Increased reliability
- Simple power and circuit and control scheme is easy compared to conventional neutral-point clamped converter
- Four quadrant operation is also possible

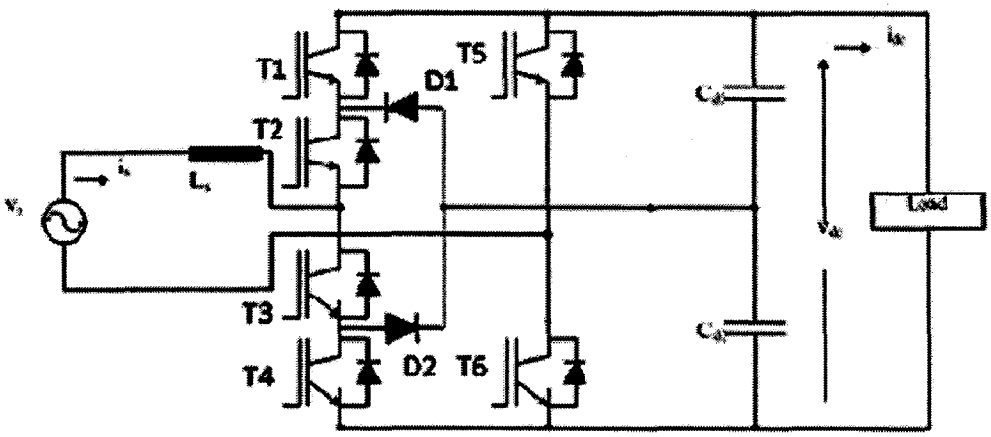


Fig.3.13 Six switch Diode Clamped Three Level Converter

3.7.1 Simulation results

The converter is simulated in MATLAB/SIMULINK to do its performance evaluation. An error signal is generated by comparing the dc voltage output with reference value and then it's passed through a PI controller to generate a reference current which is compared with actual

and the error is controlled using current controller. The output of controller given to PWM generation (generally HCC) which gives required pulses for the operation of converter. Fig 3.14 shows the simulink model of six switch neutral-point clamped converter.

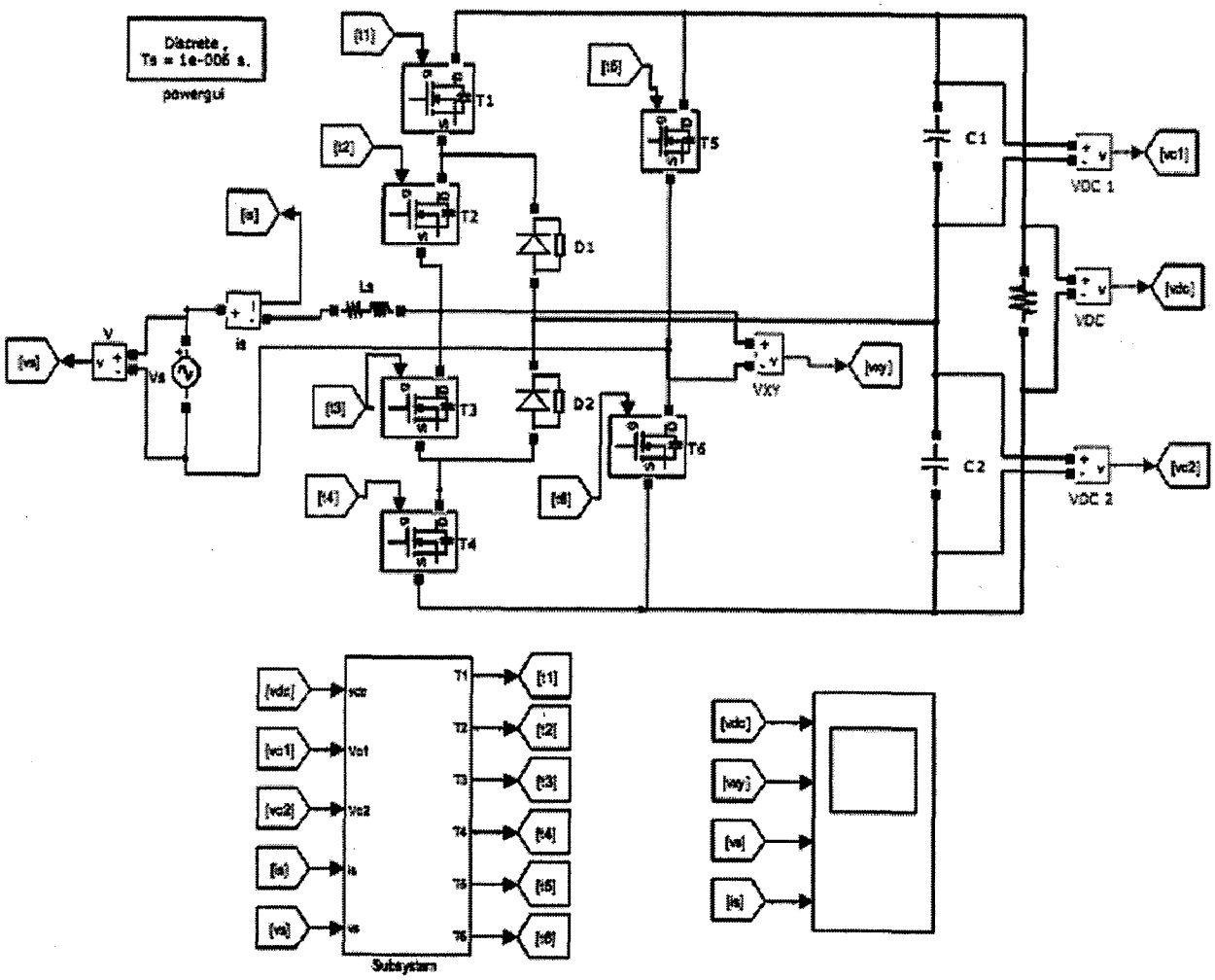


Fig. 3.14 SIMULINK model of six switch Diode clamped three level converter

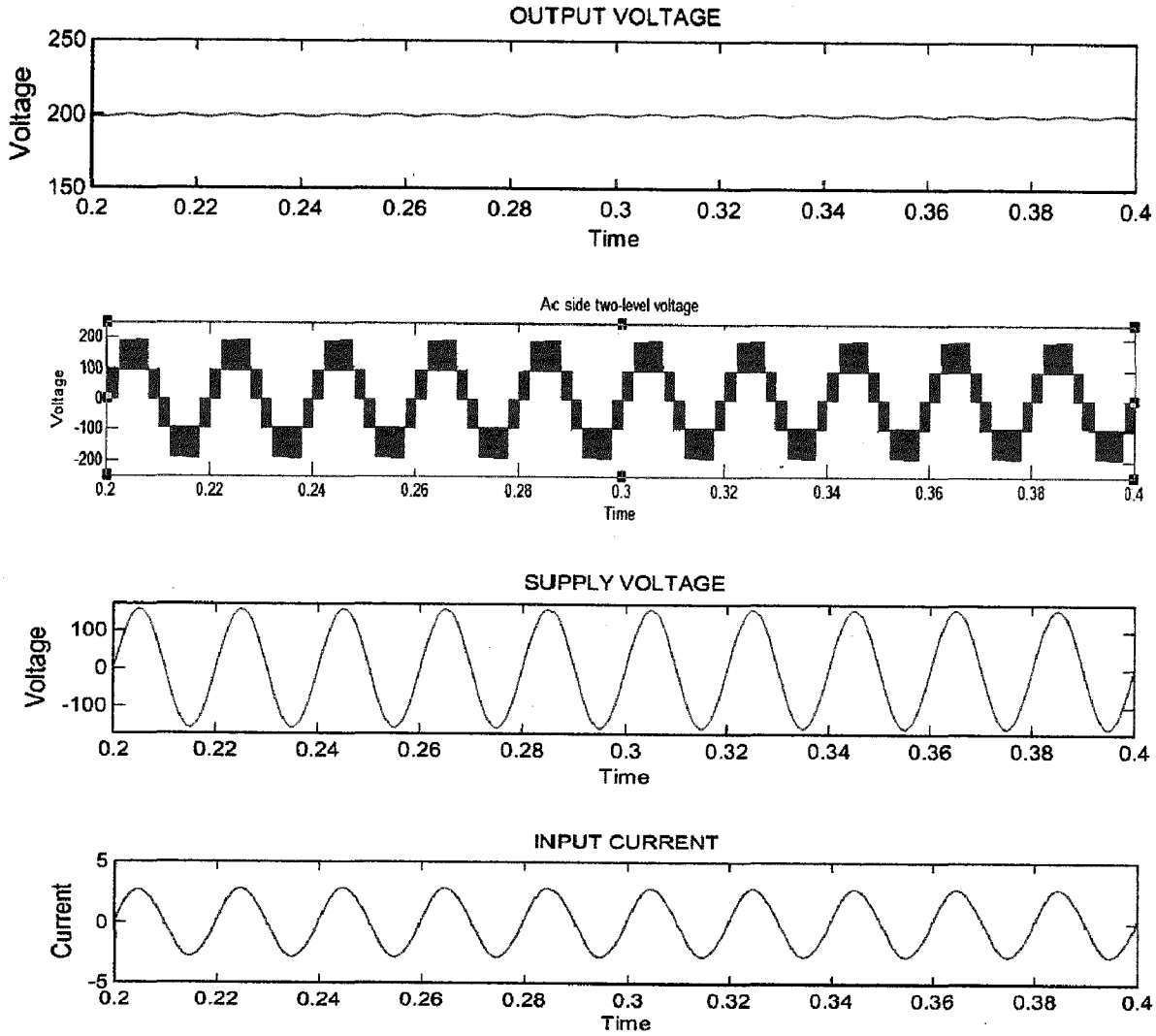


Fig.3.15 Various waveforms of six switch diode clamped converter

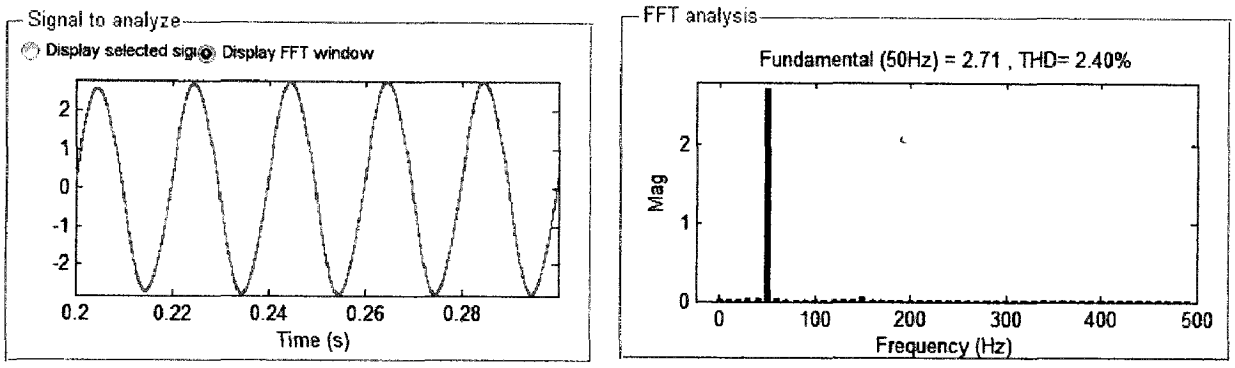


Fig.3.16 Waveform and harmonic spectrum of input current

3.8 Flying Capacitor Three Level Converter:

The Fig.3.19 shows single phase full bridge flying-capacitor based three level converter [19]. The inner loop balancing capacitors for each phase leg is independent i.e C_1 is independent of C_2. The outer capacitor C_0 is the dc link capacitor which may be a combination of two capacitors in series.

Generalizing the above circuit, that if each capacitor has same voltage rating as switching device, the dc bus needs (m-1) capacitors & each leg requires (m-1)*(m-2)/2 capacitors for m-level converter. Here size of the clamping capacitors is linearly proportional to turn off current and inversely proportional to ripple voltage and switching frequency.

Advantages:

1. Large no. of storage capacitors provides extra ride through capabilities during power outage.
2. Provides switch combination redundancy for balancing different voltage levels
3. When no. of levels is high, harmonic content will be low enough to avoid the need for filters.

Disadvantages:

1. Excessive no. of storage capacitors is required when the no. of levels is high.
2. The inverter control will be complicated and switching frequency and switching losses will be high for real power transmission.
3. Inverter rating is limited to the load current flowing through the capacitors.

The converter is simulated in MATLAB/SIMULINK to do its performance evaluation. An error signal is generated by comparing the dc voltage output with reference value and then it's passed through a PI controller to generate a reference current which is compared with actual and the error is controlled using current controller. The output of controller given to PWM generation (generally HCC) which gives required pulses for the operation of converter.

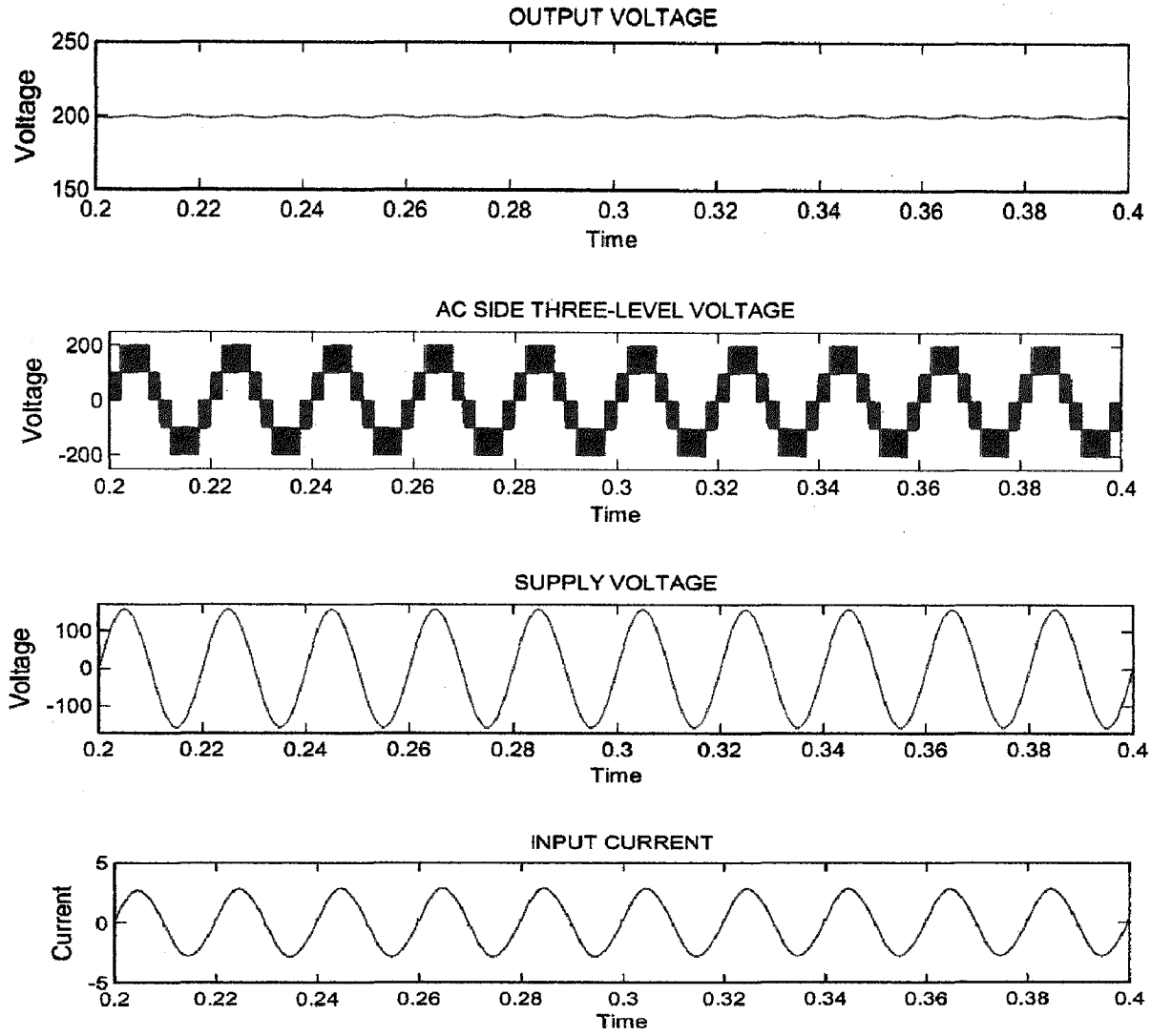


Fig.3.21 Various waveforms of Flying capacitor three level converter

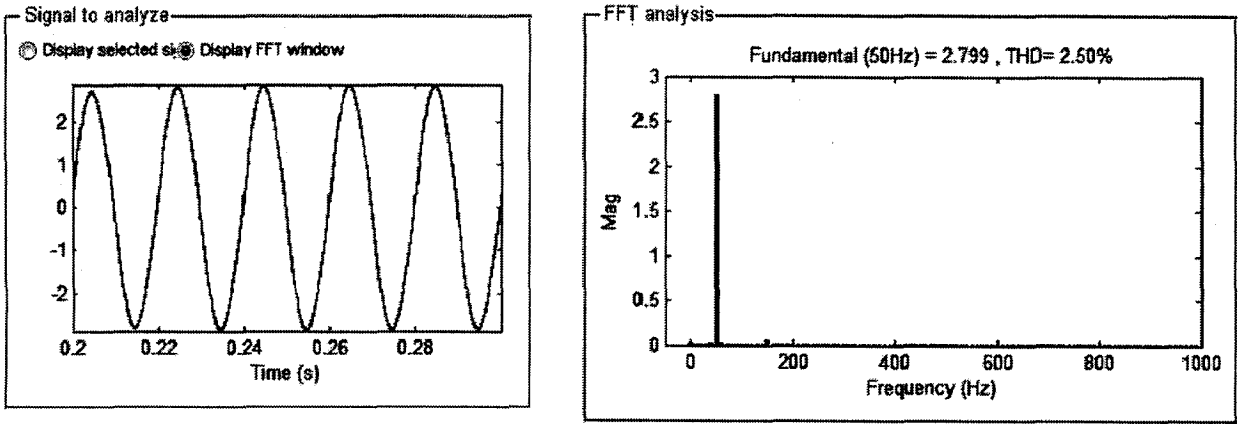


Fig3.22. Waveform and harmonic spectrum of input current

The input current waveform and its harmonic spectrum are as shown in the figure 3.22. The supply current is having a THD of 2.50%.The output voltage settles around reference value early so response time is good and even ripple in voltage is less .The change in output voltage is less than 5V and as seen clearly from source current waveform that current is almost in phase with the voltage.

3.8.2 Varying load condition:

The model is simulated under various loads varying from minimum to maximum keeping input voltage constant. The input current rms value is measured directly from functional block of SIMULINK while THD from POWERGUI block. Output voltage is measured in voltage block. Power factor is found active and reactive power block while efficiency is calculated from input and output powers.

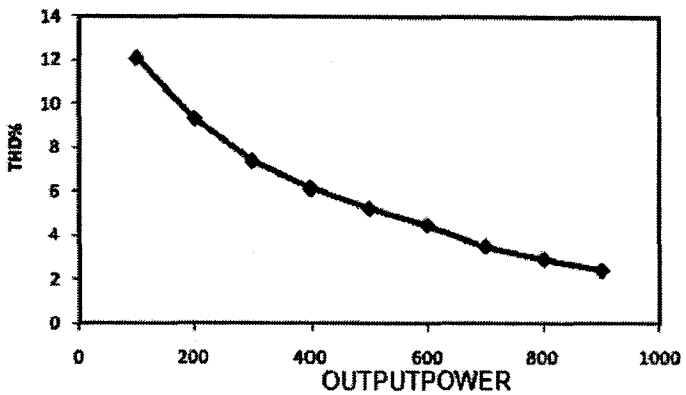


Fig.3.23Total harmonic distortion vs output power

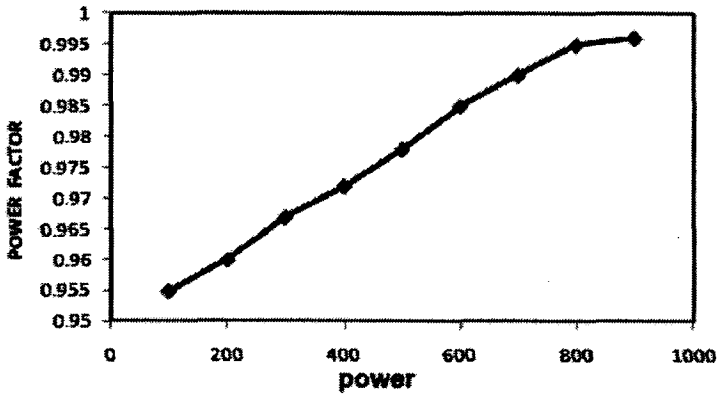


Fig.3.24 Power Factor vs output power

3.9 Conclusion:

In this chapter the classifications of conventional rectifiers are discussed. The advantages of use multilevel converters for power quality improvement purpose are discussed. Single phase neutral point clamped rectifier's simulations and their use in filtering current harmonics are discussed. Reduced switch count converters posses several desirable features such as low cost, more reliability, high efficiency and easy control circuit operation are discussed.

CHAPTER 4

SINGLE PHASE NEUTRAL POINT DIODE CLAMPED RECTIFIER

4.1 Introduction:

The single phase Neutral-point diode-clamped rectifier [16] to draw a sinusoidal line current with low harmonic content and high power factor is shown in fig.4.1. The circuit configuration consists of one boost inductor L, two DC-bus capacitors C_1 and C_2, two power diodes D_3 and D_4, two neutral-point clamped diodes D_1 and D_2, and four power switches T_1-T_4 with anti parallel diodes. The voltage stress of the power switches equals half of the DC-bus voltage. A hysteresis current controller is used in the inner control loop to track the line current command. To achieve a stable DC-link voltage, a Proportional-Integral voltage controller is employed in the outer control loop to generate line current command and balance the active power between the mains and the DC load. A capacitor voltage compensator is adopted to perform neutral-point voltage compensation. By appropriate control, five different voltage levels v_{dc}, $v_{dc}/2$, 0, $-v_{dc}$, $-v_{dc}/2$ are generated on the AC side of the adopted converter. Based on the control algorithm, the power factor of the system has been improved.

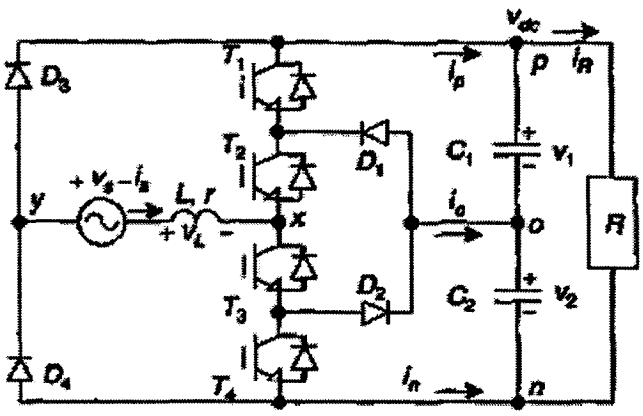


Fig.4.1 Circuit configuration of neutral-point diode-clamped rectifier

4.2 Principle of operation:

There are six operational modes of rectifier based on the line current and switching states of power switches as shown in the following;

Mode 1: Fig.4.2 (a) shows the equivalent circuit of first operational mode. In this mode no power switch is turned on and positive line current charges both capacitor voltages v_1 and v_2 to achieve voltage $v_{xy}=v_{dc}$ The line current is decreasing in this mode because $v_s< v_{dc}$. The DC-side currents are $i_p=i_s$, $i_0=0$, $i_n=-i_s$.

Mode 2: The equivalent circuit is shown in Fig.4.2 (b) Power switch T_3 and diodes D_2 and D_4 are turned on to obtain voltage $v_{xy}= v_{dc/2}$ voltage. The positive line current charges capacitor C_2. The DC load current also discharges capacitors C_1 and C_2. The boost inductor voltage equals $v_s - v_{dc}/2$. The DC-side currents $i_p=0$, $i_0= i_s$, $i_n=- i_s$.

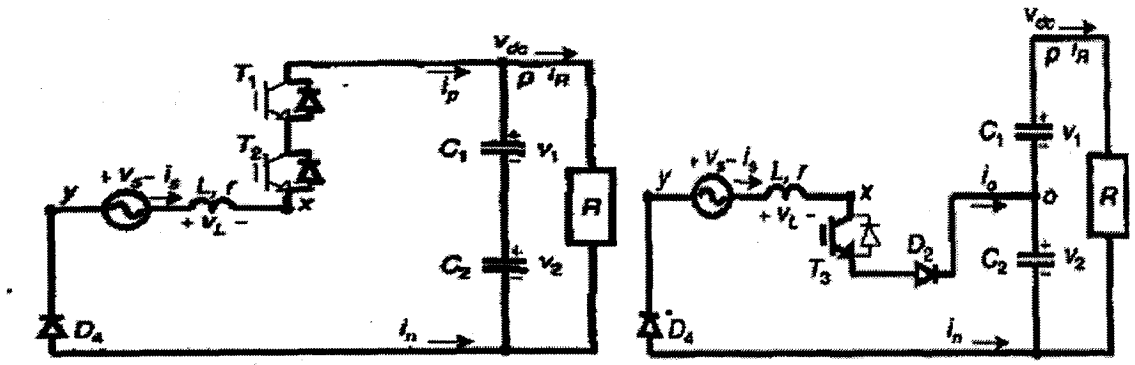


Fig.4.2 Operation in a) mode-1 & b) mode-2

Mode 3: The equivalent circuit of operation mode 3 is given in Fig.4.3 (a) Power switches T_3 and T_4 and diode D_4 are turned on to achieve voltage $v_{xy}=0$. The line current is linearly increasing because $v_L=v_s>0$ .In this mode, two capacitor voltages are decreased to supply the DC load.

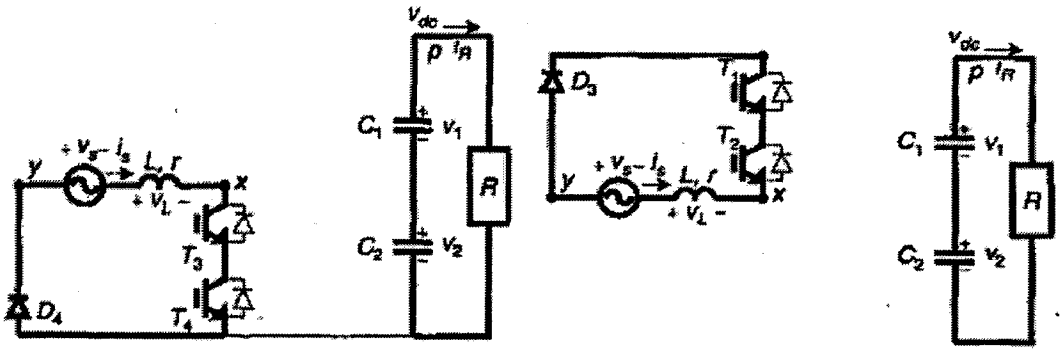


Fig.4.3 Operation in a) mode-3 & b) mode-4

Mode 4: The line voltage is short-circuited through the boost inductor in mode-4 as shown in Fig.4.3 (b) Power switches T_I and T_2 and diode D_3 are turned on to obtain voltage v_{xy}=0. The inductor current is linearly decreasing because v_L=v_s<0, The DC load current discharges capacitors C_1 and C_2,. The DC-side currents are i_p=i_0= i_n=0.

Mode 5: The equivalent circuit of mode 5 is shown in Fig. 4.4 (a) Power switch T_2, and diodes D_1 and D_3 are turned on to obtain voltage v_{xy}= -$v_{dc/2}$ The negative line current charges capacitor C_1. The boost inductor voltage equals. Capacitors C_1 and C_2 are also discharged by the DC load. The DC-side current i_p=- i_s, i_0= i_s, i_n=0.

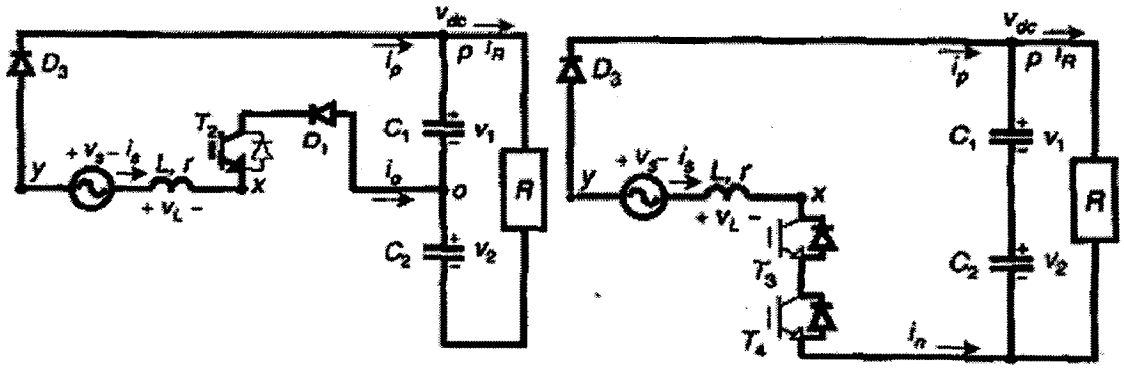


Fig.4.4 Operation in a) mode-5 & b) mode-6

Mode 6: Fig.4.4 (b) shows the equivalent circuit of operation mode 6. In this mode all power switches are turned off and negative line current charges both DC-bus capacitors to achieve voltage v_{xy}= -v_{dc} .The line current is increasing in this mode because v_s + v_{dc} >0. The DC-side currents are i_p= i_s, i_0= 0, i_n= i_s.

the six operational modes of rectifier based on the line current and switching states of power switches as shown in the Table 4.1. For positive line current, modes 1, 2 and 3 are employed in the proposed control algorithm to generate rectifier terminal voltage v_{xy}=v_{dc}, $v_{dc/2}$ and 0 respectively (assuming v_1= v_2=v_{dc}/2) Modes 4, 5 and 6 are adopted to achieve v_{xy}=0,-v_{dc}/2 and -v_{dc} respectively, in the negative line current. The following analysis of the modes of operation assumes that the power switches are ideal, the supply voltage is a constant value during one switching period, and that v_1= v_2= v_{dc}/2.

Table 4.1 switching states and modes of operation rectifier.

Mode	i_s	T_1	T_2	T_3	T_4	v_{xy}	i_p	i_o	i_n	v_1	v_2	v_L
1	+	0	0	0	0	v_{dc}	i_s	0	$-i_s$	charge	charge	v_s-v_{dc}
2	+	0	0	1	0	$v_{dc}/2$	0	i_s	$-i_s$	discharge	charge	$v_s-v_{dc}/2$
3	+	0	0	1	1	0	0	0	0	discharge	discharge	v_s
4	-	1	1	0	0	0	0	0	0	discharge	discharge	v_s
5	-	0	1	0	0	$-v_{dc}/2$	$-i_s$	i_s	0	charge	discharge	$v_s+v_{dc}/2$
6	-	0	0	0	0	$-v_{dc}$	$-i_s$	0	i_s	charge	charge	v_s+v_{dc}

According to this analysis of the six operational modes, the DC-side current i_p, does not equal zero in modes 1, 5 and 6. The neutral-point current $i_{0\,is}$ not equal to zero in modes 2 and 5. The DC-side current i_n is not equal to zero in modes 1, 2 and 6. These DC-side currents can be expressed as a function of switching states and the direction of line current.

$$i_p = T_1'T_2'T_3'T_4'\left(\frac{1+sgni_s}{2}\right)i_s - T_1'T_3'T_4'\left(\frac{1-sgni_s}{2}\right)i_s \qquad (4.1)$$

$$i_0 = T_1'T_2'T_3T_4'\left(\frac{1+sgni_s}{2}\right)i_s + T_1'T_2T_3'T_4'\left(\frac{1-sgni_s}{2}\right)i_s \qquad (4.2)$$

$$i_n = -T_1'T_2'T_4'\left(\frac{1+sgni_s}{2}\right)i_s + T_1'T_2'T_3'T_4'\left(\frac{1-sgni_s}{2}\right)i_s \qquad (4.3)$$

where $sgni_s$ = 1 (or -1) if i_s >O (or i_s <O). The AC-side voltage of the proposed rectifier v_{xy} can be expressed by the DC-bus voltage, line current and switching states of power switches.

$$v_{xn} = \left(T_1'T_2'T_3'T_4'v_1 + T_1'T_2'T_4'v_2\right)\left(\frac{1+sgni_s}{2}\right) + \left(T_1T_2T_3'T_4'v_1 + T_2T_3'T_4'v_2\right)\left(\frac{1-sgni_s}{2}\right) \quad (4.4)$$

$$v_{yn} = (v_1 + v_2)\left(\frac{1 - sgni_s}{2}\right) \quad (4.5)$$

$$v_{xn} = \left(T_1'T_2'T_3'T_4'v_1 + T_1'T_2'T_4'v_2\right)\left(\frac{1 + sgni_s}{2}\right) + \left[\left(T_1T_2T_3'T_4' - 1\right)v_1 + \left(T_2T_3'T_4' - 1\right)v_2\right]\left(\frac{1 - sgni_s}{2}\right) \quad (4.6)$$

According to the switching states of the power switches, five voltage levels v_{dc} , v_2,0, -v_1, v_{dc} and are generated on the voltage v_{xy}. To obtain a balanced neutral-point voltage, capacitor voltages v_1 and v_2 are controlled to be equal.

4.3 Control schemes

Control circuit is the heart of APFC converters. Several control techniques were reported in the literature to improve the performance of the converter for PFC operation. An ideal power factor corrector (PFC) should emulate a resistor on the supply side while maintaining a fairly regulated output voltage. In the case of sinusoidal line voltage, this means that the converter must draw a sinusoidal current from the utility; in order to do that, a suitable sinusoidal reference is generally needed and the control objective is to force the input current to follow this current reference as closely as possible. . To achieve voltage regulation and the PFC objectives simultaneously, they are generally used multi loops.

The most general control circuit for PFC operation is as shown below in Fig.4.5.The output voltage is sensed and compared with the reference voltage and the error is sent to a voltage controller. Voltage controller outputs a control effort such that the error between the set point voltage and output voltage is reduced as low as possible.

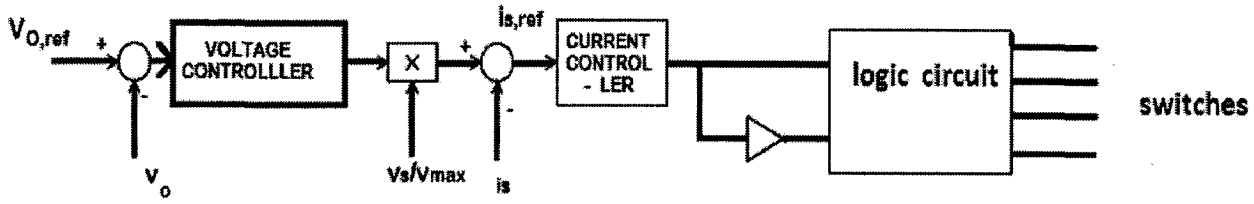


Fig.4.5 Control circuit for PFC converter system

The control effort from the voltage controller is multiplied with the unit amplitude sinusoidal signal in-phase with the supply voltage to obtain a sinusoidal reference in phase with the supply voltage. This reference signal is compared with the sensed actual current signal and the error is given to the current controller. The current controller outputs the firing pulses such that the current error is reduced. The current controller with some logic circuit will be given to the switch to control input current. Generally, the voltage controller used to reduce the voltage error is generally PI controller. However it is possible to use present day technologies such as Fuzzy controllers, neural network controllers to replace the traditional PI controllers. As in case of PI control solution, the output voltage is regulated with an outer voltage loop and sinusoidal reference template is generated by using voltage error signal. This template represents a signal which is in phase with the input voltage. The use of these advanced controllers improves the dynamic performance of the converter.

4.3.1 Two-level PWM control strategy

Based on the proposed control scheme, the proposed rectifier is controlled to draw a sinusoidal line current with almost unity power factor. For two-level unipolar PWM modulation, the switching waveforms of the proposed rectifier are shown in Fig.4.6 The rectifier terminal voltage v_{xy} equals v_{dc} (mode 1), 0 (modes 3 and 4) or $-v_{dc}$ (mode 6). In two-level unipolar PWM, the power circuit of the rectifier can be expressed as a second-order system and given as

$$v_s = ri_s + L\frac{di_s}{dt} + uv_{dc} \qquad (4.7)$$

$$ui_s = 0.5C\frac{dv_{dc}}{dt} + i_R \qquad (4.8)$$

Where $u = 1, 0$ or -1. In the positive mains voltage, modes 1 and 3 are used to control line current and to generate voltage $v_{xy} = v_{dc}$ & and 0, respectively. Modes 4 and 6 are adopted in the negative mains voltage to achieve AC-side voltage v_{xy} =0 and $-v_{dc}$ respectively. shows the relation between measured signals and the switching states of power switches based on the descriptions. A phase- locked loop circuit and a voltage controller are used to generate the line current command. A hysteresis current comparator is employed to control the line current command in phase with the mains voltage. Based on the line current error and the sign of the mains current, the corresponding switching functions of power switches can be expressed as

$$T_1 = T_2 = [1 - hys\Delta i_s]\left(\frac{1 - sgni_s}{2}\right) \quad (4.9)$$

$$T_3 = T_4 = hys\Delta i_s\left(\frac{1 + sgni_s}{2}\right) \quad (4.10)$$

The corresponding waveforms and control strategy are

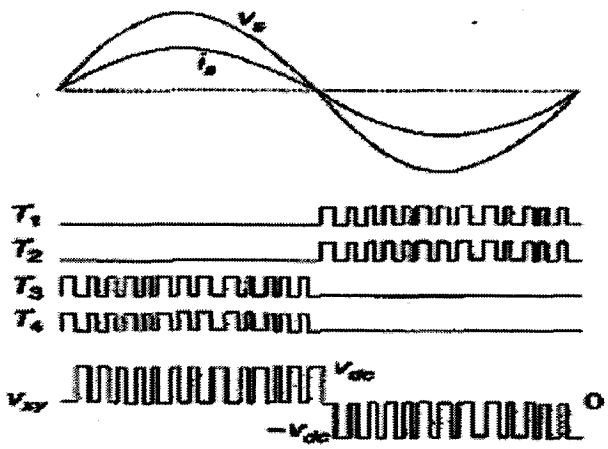


Fig. 4.6 Switching-signals and ac side voltages of two-level PWM Rectifier

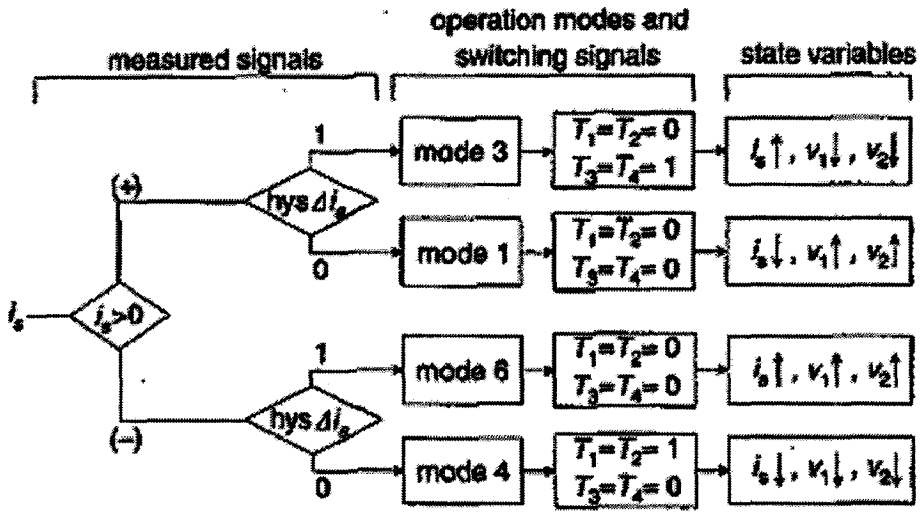


Fig.4.7 Control strategy (two-level PWM)

$$where\ \Delta i_s^* - i_s\ \ and\ \ \ hys\Delta i_s = \begin{cases} 1, & if\ \Delta i_s > h \\ 0, & if\ \Delta i_s < -h \end{cases}$$

The control block of the unipolar PWM of the proposed rectifier is shown in Fig.4.8

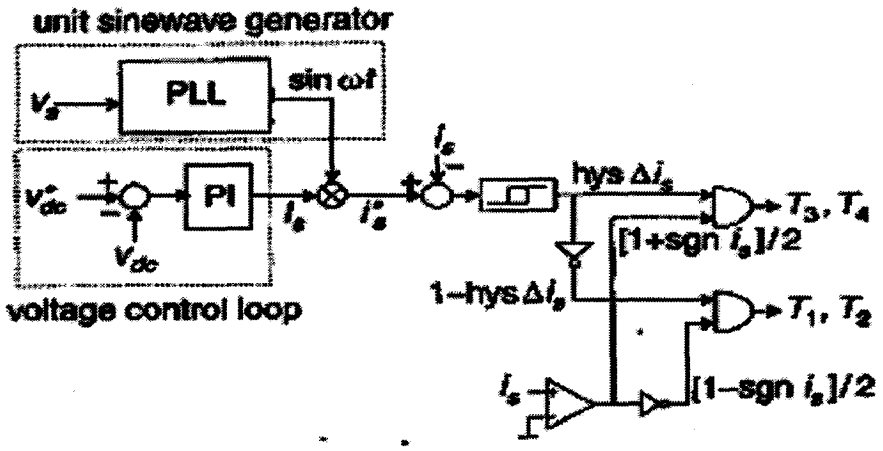


Fig.4.8 Control block diagram (two-level PWM)

4.3.2 Three-level PWM control strategy

For three-level PWM modulation, a neutral-point voltage $v_{dc/2}$ is generated to achieve a three-level voltage pattern on the rectifier AC-terminal voltage. The more voltage levels generated on the AC side of the rectifier, the less voltage harmonics are produced by the rectifier. The features of three-level PWM modulation of the proposed rectifier are drawing a clean sinusoidal line current with unity power factor, maintaining constant DC-link voltage, and keeping a balanced neutral-point voltage. To generate a three-level voltage waveform on the AC side of the rectifier, two operation regions of mains voltage during one cycle of the input line frequency are defined and shown in Fig.4.9. In the first region, the line voltage is greater than $-v_{dc/2}$ and less than $v_{dc/2}$ Voltage levels 0 and $v_{dc/2}$ (or $-v_{dc/2}$) are generated on the voltage v_{xy} in the positive (or negative) mains voltage to control the line current.

In the second region, the absolute value of the mains voltage is less than the DC-bus voltage but greater than half the DC- link voltage $v_{dc/2}$. Voltage levels v_{dc} and $v_{dc/2}$ (or $-v_{dc}$ & and $-v_{dc/2}$) are generated in the positive (or negative) half-cycle of the line voltage to track the line current. These operation regions and the corresponding PWM voltage waveforms are shown in Fig.4.8. In the positive half-cycle of mains voltage, power switchesT1 and T2 are turned off. Power device T_3 or T_4 is turned on or off to generate voltage $v_{xy} = v_{dc/2}$ or 0, respectively. Modes 2 and 3 can be employed to generate these two voltage levels. No power switch is turned on to achieve voltage $v_{xy}=v_{dc}$ in the positive line current. Three voltage levels v_{dc}(mode 1), $v_{dc/2}$ (mode 2) and 0 (mode 3) are generated on the voltage v_{xy} in the positive mains voltage because line current is controlled to have zero phase shift. The line current is controlled to increase (or decrease) in mode 3 (or mode 2) if mains voltage is less than neutral-point voltage $v_{dc/2}$ i.e. in region 1. Mode 1 or mode 2 is used to decrease or increase the mains current in the condition of $v_{dc/2} < v_s < -v_{dc}$ (region 2).

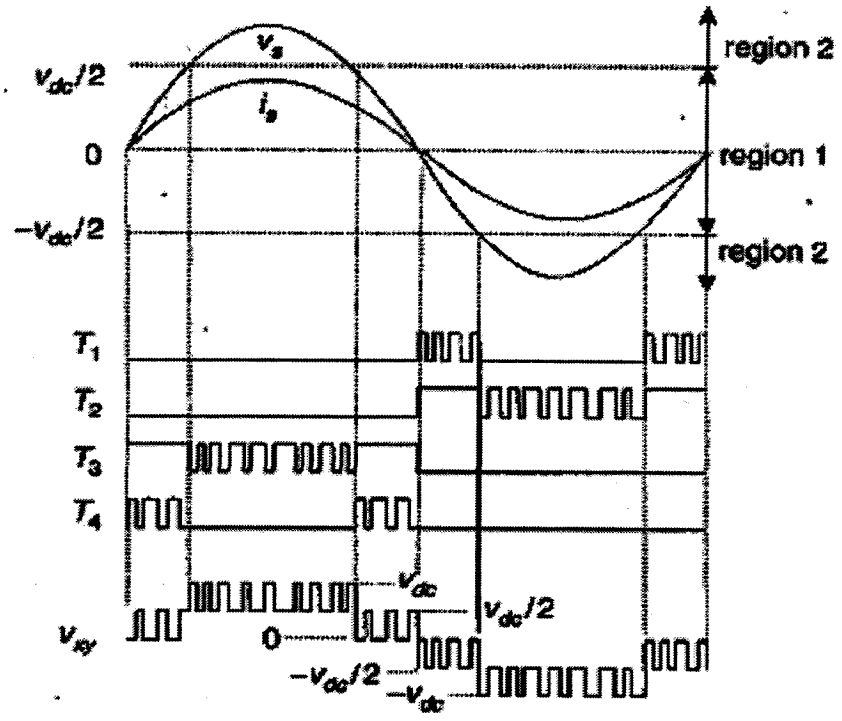


Fig.4.9 Switching signals and AC-side voltage of three-level PWM Rectifier

Based on this above analysis, the line current is controllable in the positive mains voltage by using modes 1, 2 and 3. For negative mains voltage, power switches T_3 and T_4 are turned off. Modes 4 and 5 as shown above are employed to obtain voltage v_{xy}=0 and $-v_{dc/2}$ in the first region. In mode 4 the line current is decreasing because boost inductor voltage v_L is equal to the mains voltage v_s. The line current is increasing in mode 5 because $v_L = v_s + v_{dc/2} > 0$. In the second region, modes 5 and 6 are adopted to achieve voltage levels $-v_{dc/2}$ and $-v_{dc}$ on the rectifier AC terminal voltage. The line current is controlled to increase or decrease by using mode 6 or mode 5.Three voltage levels 0 (mode 4), $-v_{dc/2}$ (mode 5) and $-v_{dc}$ (mode 6) are generated in the negative half-cycle of mains voltage.

Based on this rectifier analysis, the inductor current variation is a function of the rectified supply voltage v_s and the DC-link voltage v_{dc}. If the desired inductor current variation, DC-link voltage and rectified supply voltage are given, the proper operational mode can be chosen to control the inductor current. Fig.4.10 gives the control strategy of the proposed rectifier to perform three-level PWM. First, the sign of mains current is detected. Modes 1, 2 and 3 are used in the positive line current and modes 4, 5 and 6 are adopted in the

negative mains current. To properly control the line current a region detection of mains voltage is performed to select the appropriate mode.

$$T_1 = [1 - hys\Delta i_s]\left[1 - comp\left(v_s - \frac{v_{dc}}{2}\right)\right]\left(\frac{1 - sgni_s}{2}\right) \quad (4.11)$$

$$T_2 = \left[1 - comp\left(v_s - \frac{v_{dc}}{2}\right)\right]\left(\frac{1 - sgni_s}{2}\right) + [1 - hys\Delta i_s]\left(\frac{1 - sgni_s}{2}\right) \quad (4.12)$$

$$T_3 = \left[1 - comp\left(v_s - \frac{v_{dc}}{2}\right)\right]\left(\frac{1 + sgni_s}{2}\right) + [hys\Delta i_s]\left(\frac{1 + sgni_s}{2}\right) \quad (4.13)$$

$$T_4 = [hys\Delta i_s]\left[1 - comp\left(v_s - \frac{v_{dc}}{2}\right)\right]\left(\frac{1 + sgni_s}{2}\right) \quad (4.14)$$

$$where\ comp(x) = \begin{cases} 1, & if\ x > h \\ 0, & if\ x < -h \end{cases}$$

In region 1, operation modes 2 and 3 (or modes 4 and 5) are used in the positive (or negative) half-cycle of mains voltage. In region 2, modes 1 and 2 (or modes 5 and 6) are employed in the positive (or negative) mains voltage. A hysteresis current comparator is used to track the line current command. Based on the control strategy of three-level PWM shown in Fig.4.10 the switching functions of power switches are expressed as shown above.

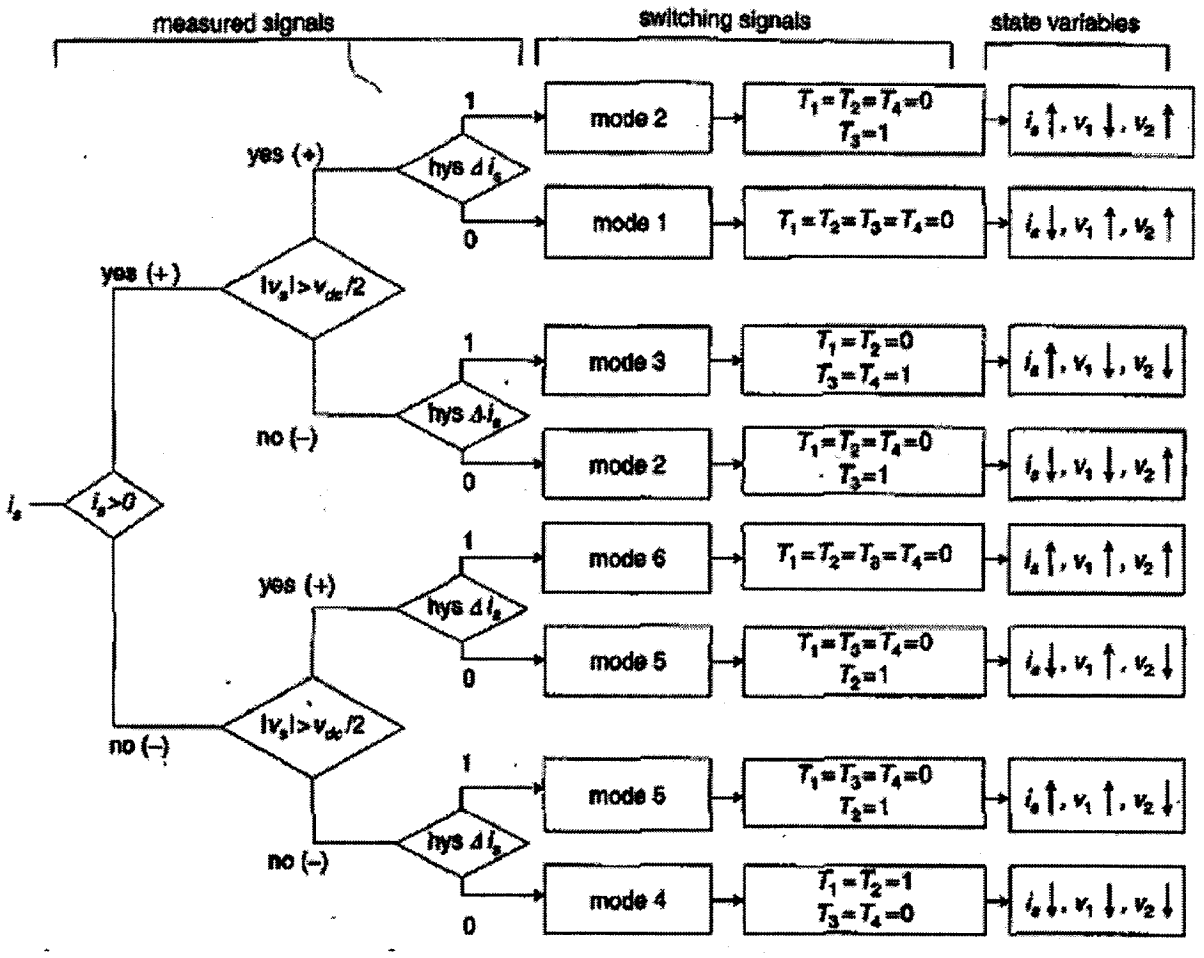


Fig. 4.10 Control strategy (three-level P WM)

Fig.4.11 shows the control block diagram of the proposed rectifier for three-level PWM. A proportional-integral voltage controller is employed in the outer loop control to maintain the constant DC-link voltage for balancing the real power between the mains and the DC load. Once the mains voltage or DC load has changed, the real power between the load and mains is not sustained. The real mains power is changed by adjusting the line current command to compensate the real power charged or discharged by the DC capacitor and to match the real power variation of the load. The line current command is derived from the output of the voltage controller and the phase-locked loop circuit. The phase-locked loop circuit generates a unit sinusoidal wave in phase with the mains voltage. To balance the neutral-point voltage, the voltage variation between two capacitors is added to the line current command. The sensed line current is compared with the line current command i_s*.An inner current loop control based on a hysteresis current comparator is used to track line current command. According to the

measured line current error and the detected mains voltage, the corresponding switching signals of the power switches based on equations are generated to obtain three-level voltage pattern on the AC side of rectifier. If the power switches in the proposed rectifier are ideal the voltage stress of each power switches equals half the DC-bus voltage.

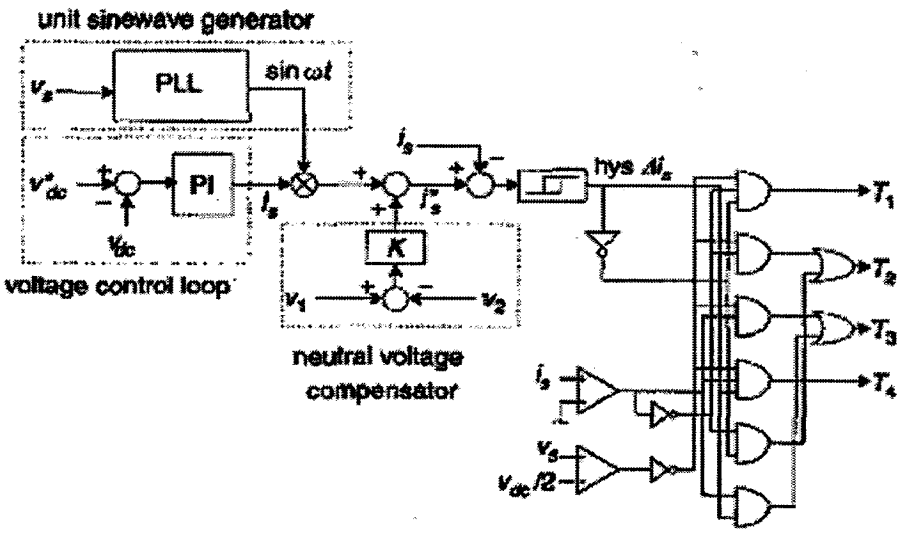


Fig.4.11 Control block diagram (three-level PWM)

The control scheme of single-phase neutral point diode clamped rectifier is to achieve a unity input power factor. Proportional-Integral (PI) voltage controller, a neutral point voltage compensator and a hysteresis current comparator are employed to perform dc-link voltage regulation, neutral point voltage balance and line current tracking respectively.

CHAPTER 5

PERFORMANCE EVALUATION OF SINGLE PHASE NEUTRAL POINT DIODE CLAMPED RECTIFIER

Introduction:

Extensive simulation is carried out to verify the validity of two PWM control schemes (two level and three level PWM) for the control of four switch of single-phase Neutral-Point diode-Clamped Rectifier. Simulation model of four switch of single-phase Neutral-Point diode-Clamped active Rectifier and the control strategies are developed using MATLAB and its SIMPOWERSYSTEMS BLOCKLIST in SIMULINK. The different components to develop the model are; single-phase voltage source, MOSFETs, diode, resistance, current measurement, voltage measurement, capacitors, inductor, multiplexers/de-multiplexers, scopes. Scopes are used to obtain the nature of current, voltage of the system at any point. These scopes have the facility of storing data which come from simulation into workspace. Various curves are plotted from scope. These curves can also be plotted from MATLAB command window after storing data variables in workspace from the scope.

The circuit parameters of the adopted of single-phase Neutral-Point diode-Clamped Rectifier in simulations are;

- Single Phase AC Voltage Source with rms voltage of 110V, 50Hz.
- Inductance(L) of 3mH, R_S=0.5 Ω
- DC Capacitances are of C1=C2=2200 μf
- Resistance load of 200Ω
- $V_{d,ref}$=200V

For the above mentioned parameters the simulation is run in the closed loop for the duration of 1 sec and waveforms are observed between 0 to 1 sec. The simulation diagram and the corresponding waveforms like the source voltage, V_s input side voltage (Vxy) and current waveform I_s, are shown in fig.5.1.

5.1 Two-level PWM control scheme

5.1.1 Steady state performance evaluation

The active rectifier is simulated in MATLAB/SIMULINK to do its performance evaluation. An error signal is generated by comparing the dc voltage output with reference value and then it's passed through a PI controller to generate a reference current which is compared with actual and the error is controlled using current controller.

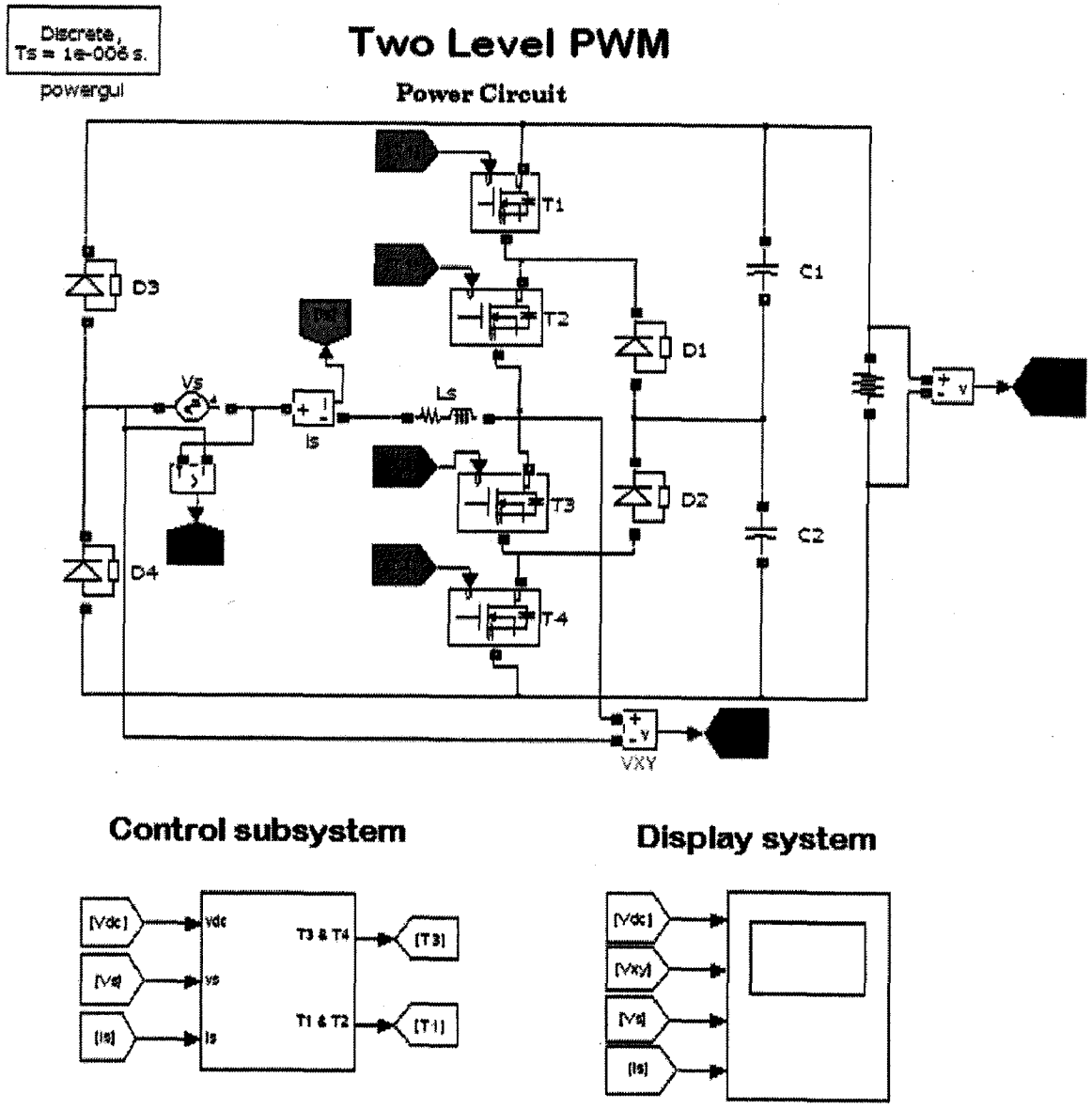


Fig. 5.1 SIMULINK model of single-phase active rectifier for Two-Level PWM

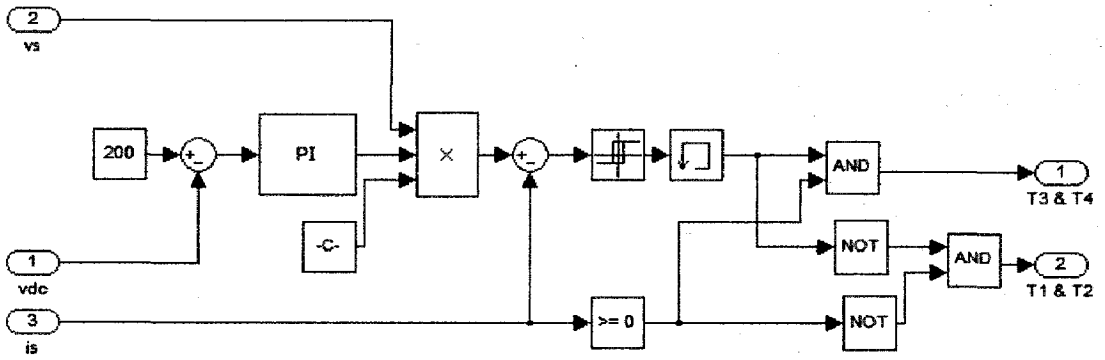


Fig. 5.2 Control block diagram for Two-Level PWM scheme

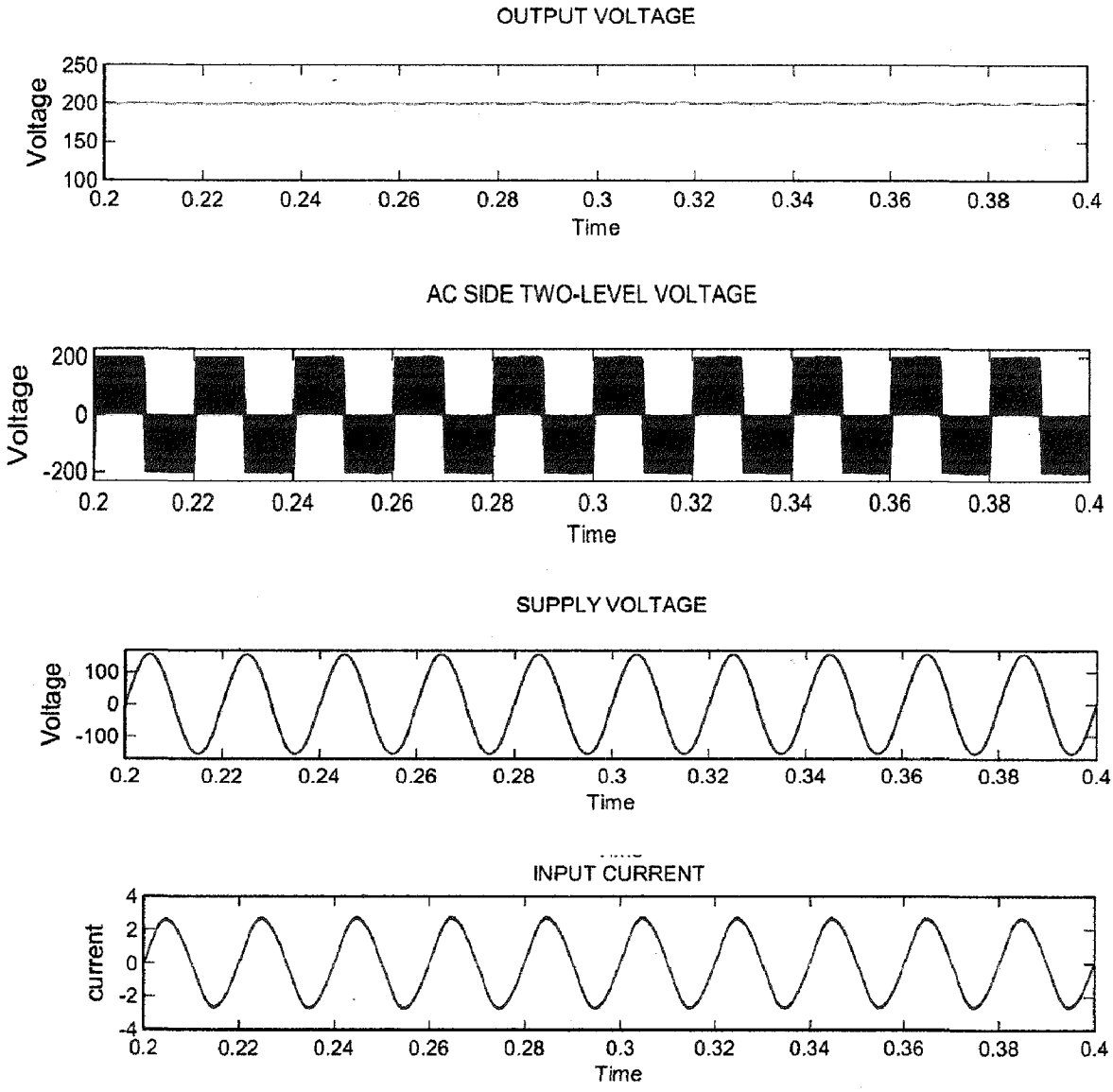


Fig. 5.3 Various simulation results

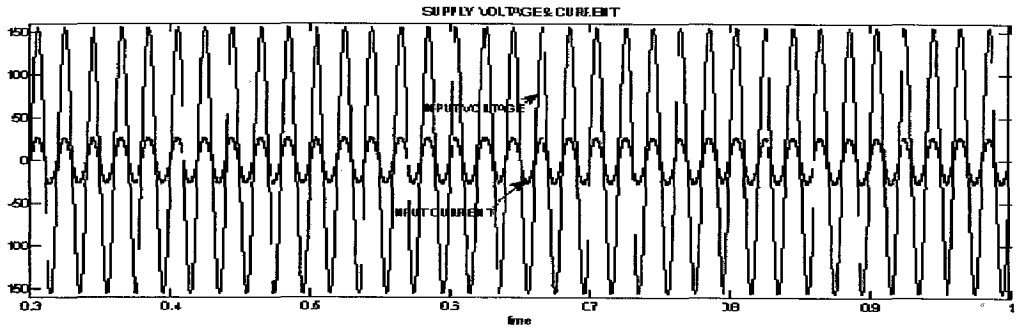


Fig. 5.4 Supply voltage & current

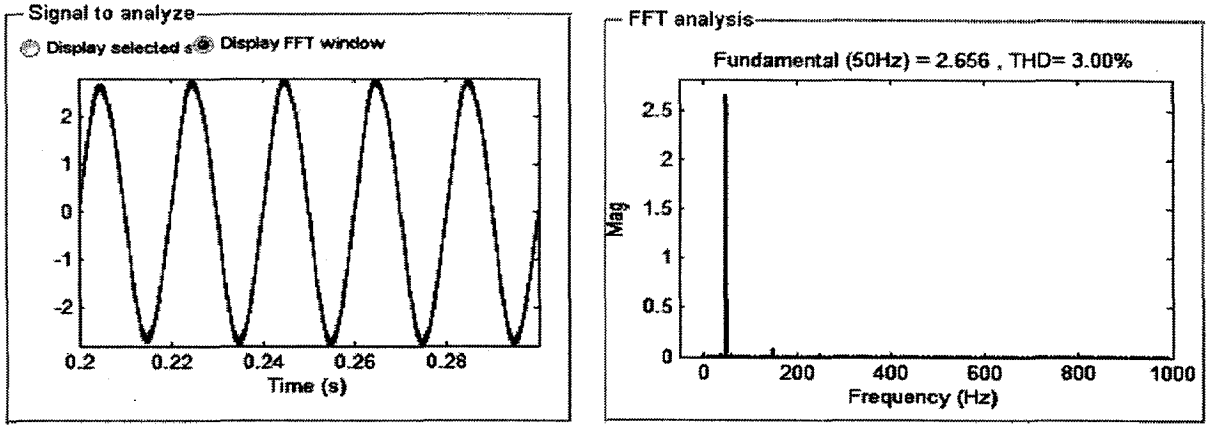


Fig.5.5 Input current waveform and harmonic spectrum

Table 5.1 Harmonic components of supply current

Harmonic number (Frequency in Hz)	I_S
Fundamental(50)	2.656
3^{rd}(150)	0.075
5^{th}(250)	0.016
7^{th}(350)	0.013
9^{th}(450)	0.01
11^{th}(550)	0.0075
THD%	3.0

The input current waveform and its harmonic spectrum are as shown in the figure 5.5. The supply current is having a THD of 3% with dominat 3^{rd},5^{th}, 7^{th}, 9^{th} and 11^{th} harmonics. The various components of the input current are as shown in the table 5.1.The output voltage settles around reference value early so response time is good and even ripple in voltage is normal with a value of 0.0065 and as seen clearly from source current waveform that current is almost in phase with the voltage.THD is shown by using FFT analysis.

5.1.2 Performance under varying load condition:

The model is simulated under various loads varying from minimum to maximum keeping input voltage constant. The input current rms value is measured directly from functional block of SIMULINK while THD from POWERGUI block. Output voltage is measured in voltage block. Power factor is found active and reactive power block while efficiency is calculated from input and output powers. The waveforms are shown in below.

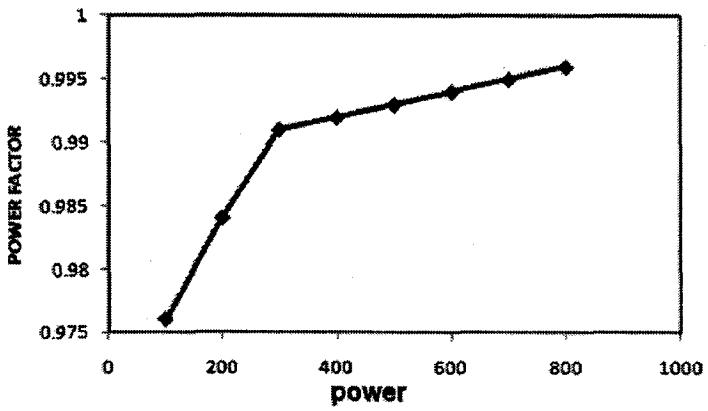


Fig.5.6 Power factor vs output power

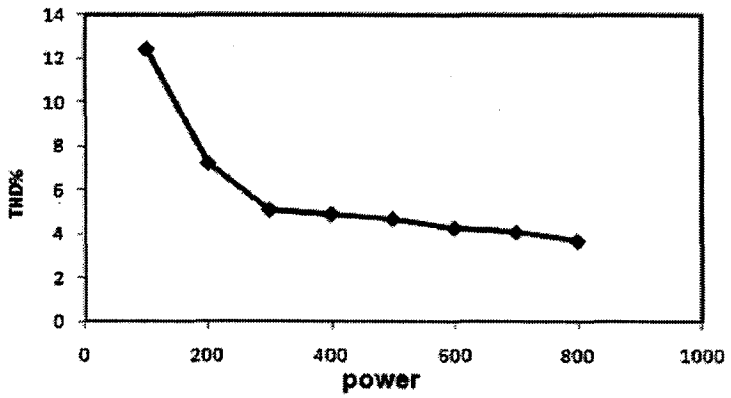


Fig.5.7 Total harmonic distortion vs output power

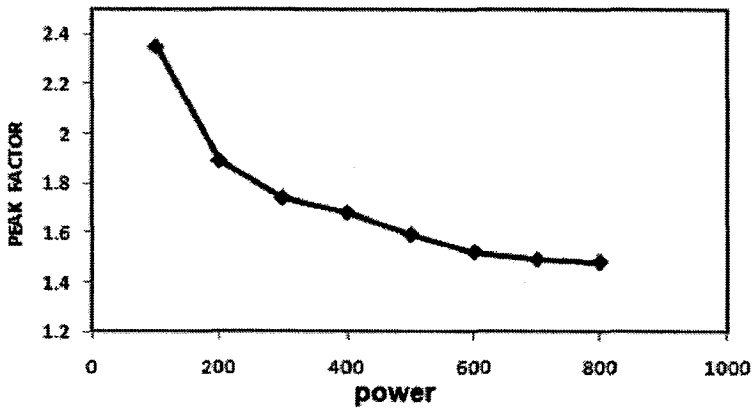


Fig.5.8 Peak factor vs output power

We conclude that single-phase Neutral-Point diode-Clamped active Rectifier provides good performance but as output power increases, the demand for input current becomes very high. And its THD is not very low. It has a good efficiency 96.52% and even power factor is almost unity at high loads. Now as per the voltage and current waveforms, output voltage first becomes more than the reference then settles down around reference and current also. Thus, it can be said that its performance is good for this non-complex control scheme.

5.1.3 Dynamic Performance Evaluation:

Dynamic performance is seen by applying sudden changes to load reference and supply voltage to see how converter reacts to transients.

a) Sudden change in load:

Here, converter is running at a load of R=200 ohm then at t=0.5s the load is changed to R=150 ohm while the reference is set to 200V in both the cases, the waveforms of output voltage and currents are observed as shown in Fig.5.9.

As the load increased the output voltage falls then as per control action increases to reach that particular load in that way voltage again settle down to reference value. Here the settling time is around .45s. The waveforms under load changing are shown

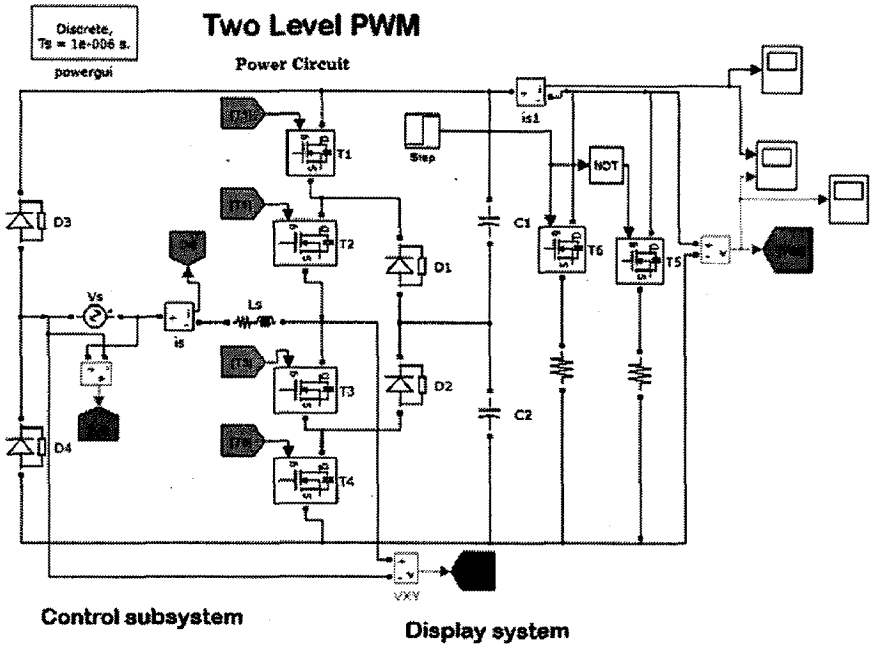


Fig.5.9 Converter with load change from 200Ω to 150Ω

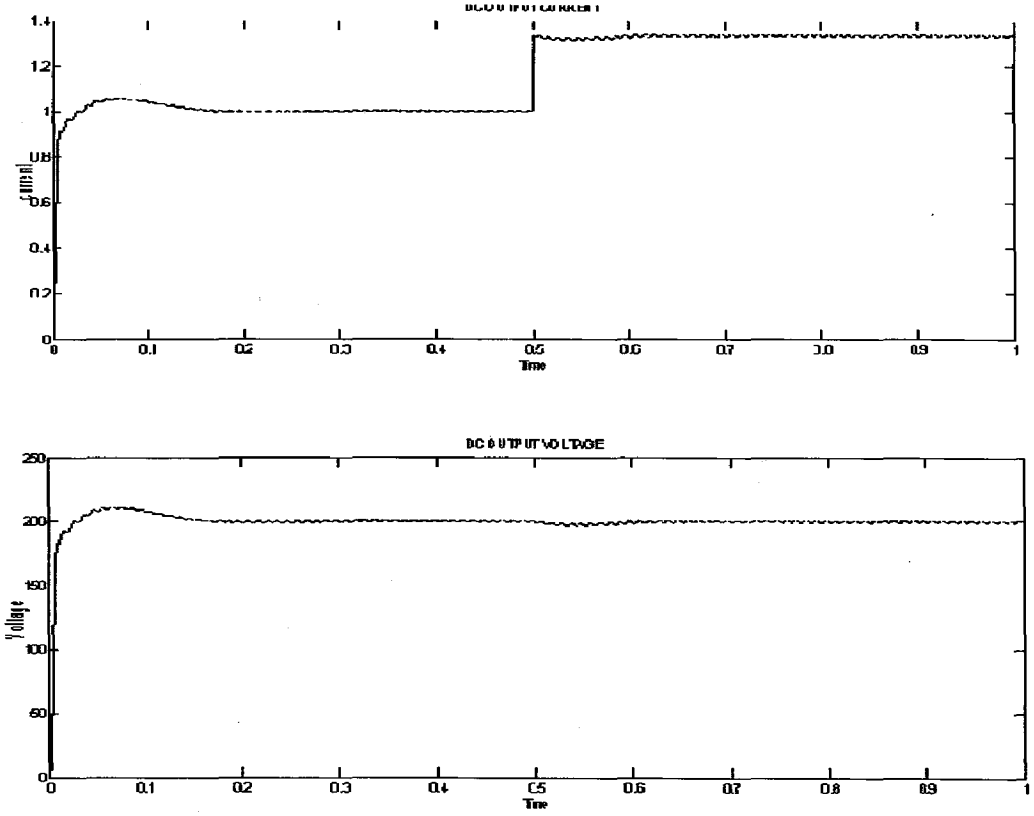


Fig.5.10 Output current (above) and voltage (below) for change in load condition

b) Variation in supply voltage:

The simulation model which is shown in Fig.5.11 can be used for this condition by usin one switch.Here the reference voltage is set at 200V and the input voltage changes from 110V to 135V at time t = 0.5sec.

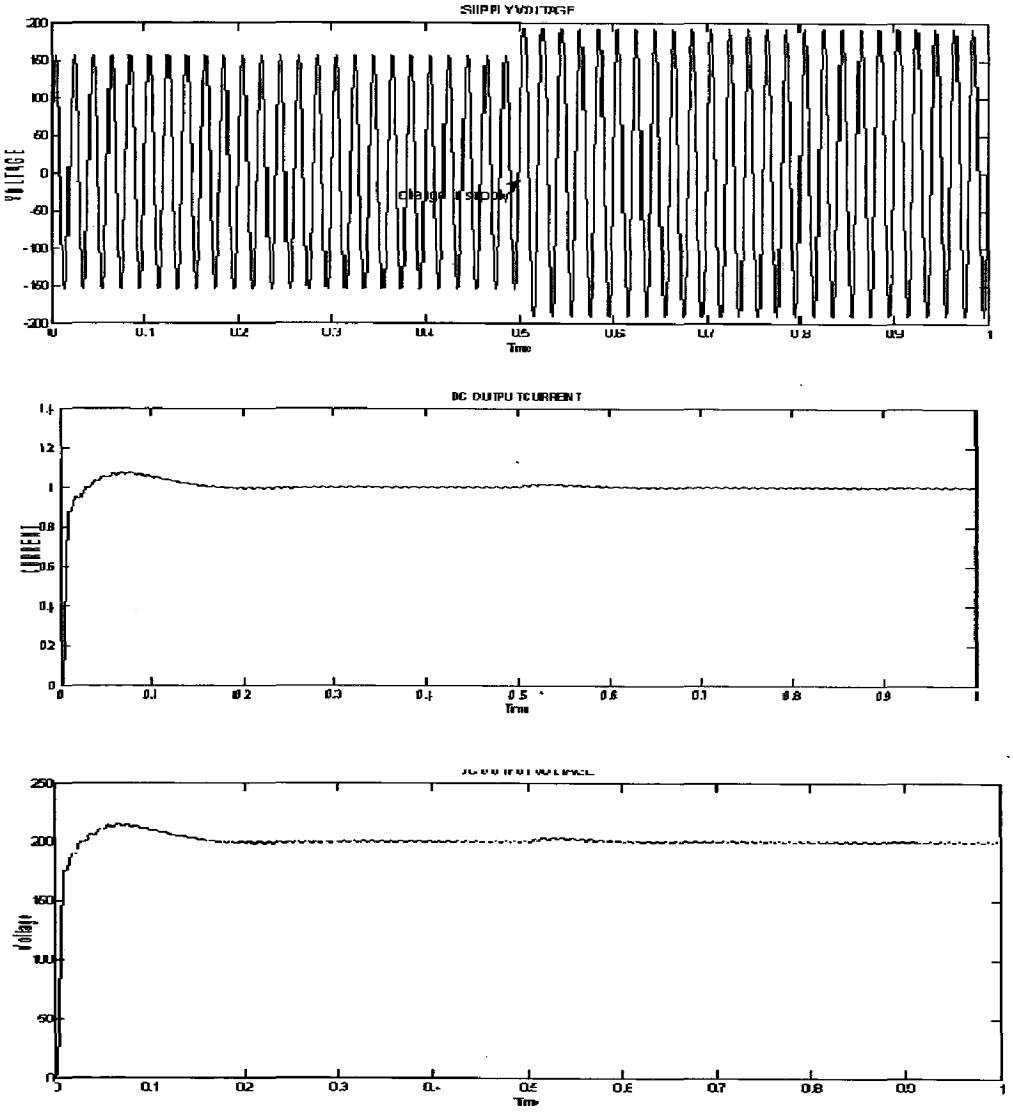


Fig5.11 Waveforms of change in supply (above), output current (middle) and output voltage (below)

simulation result for this condition is shown in Fig.5.11. The reference output voltage for the converter is set at 200V and initially converter is operating at V_{in} = 110V. At t = 0.5 sec input voltage is changed from 110V to 135V due to some disturbance in the system. Because of this the output voltage stars increasing. Now in order to decrease output voltage the PI controller

change the switching pattern such that output voltage increases. Because of controller action output voltage settles at 200V at t = 0.62 sec.

b) Sudden change in reference:

The reference has been changed to see the effect on how the voltage settles down to new value. The voltage reference has been changed from 200V to 150V at t=0.5s.the corresponding waveforms of voltage and current are shown in fig.5.12

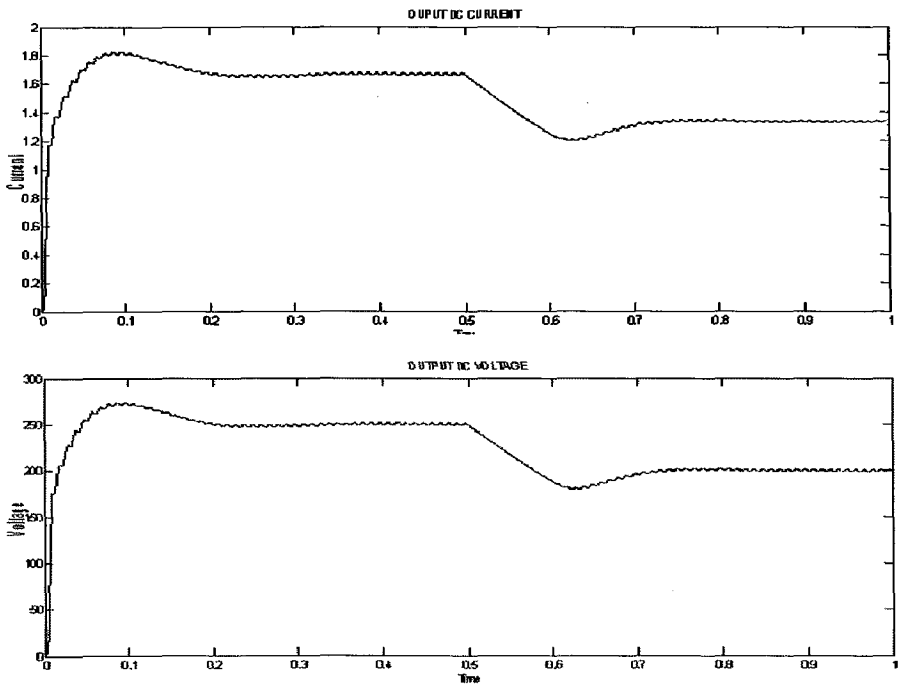


Fig5.12 Output voltage and current for change in reference

The voltage is settles down to new value after t=.21sec.

5.2 Three-level PWM control scheme

5.2.1 Steady state performance evaluation

The active rectifier is simulated in MATLAB/SIMULINK to do its performance evaluation. An error signal is generated by comparing the dc voltage output with reference value and then it's passed through a PI controller to generate a reference current which is compared with actual and the error is controlled using current controller. The simulation circuit and the corresponding waveforms are shown in Fig.5.13 & 5.14.

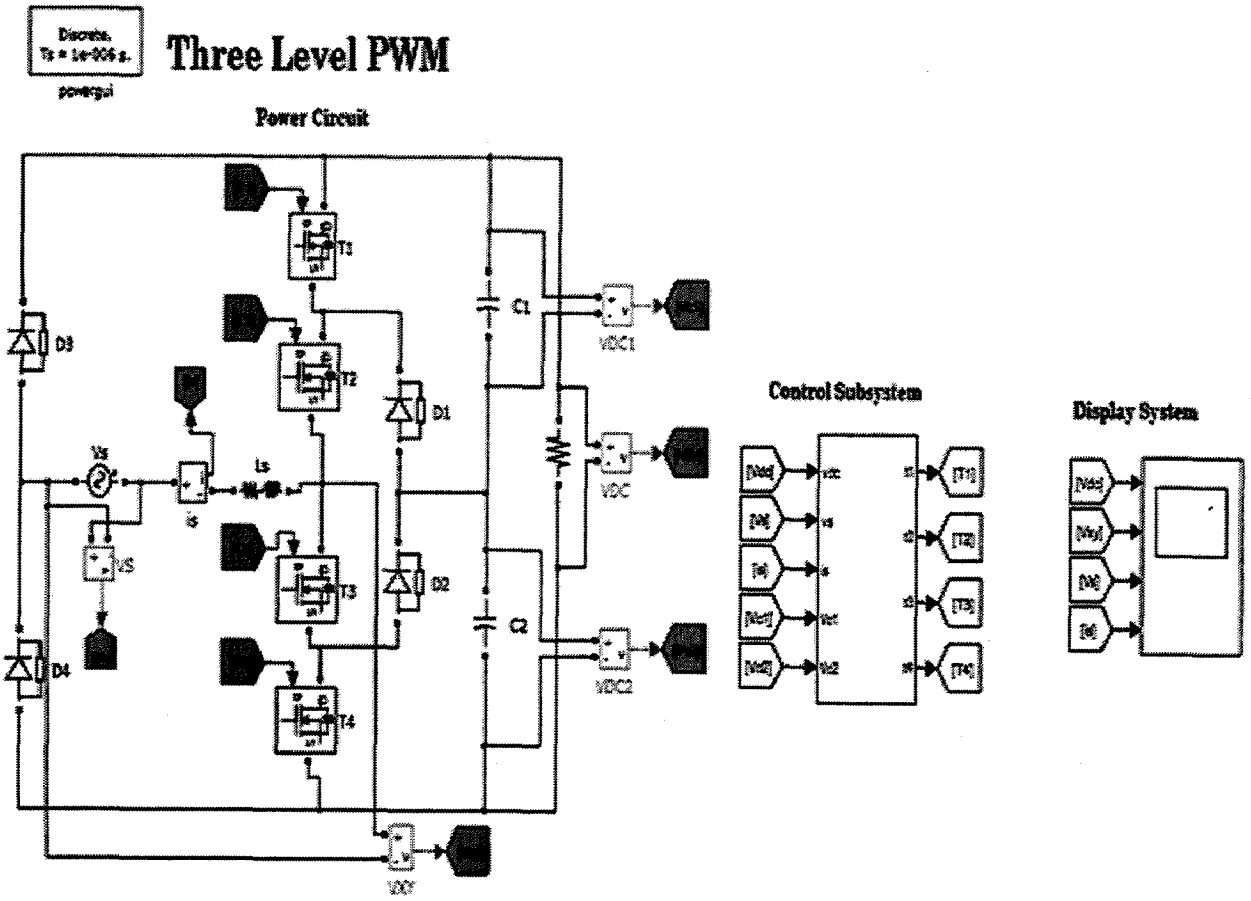


Fig.5.13 SIMULINK model of single-phase active rectifier for Three-Level PWM

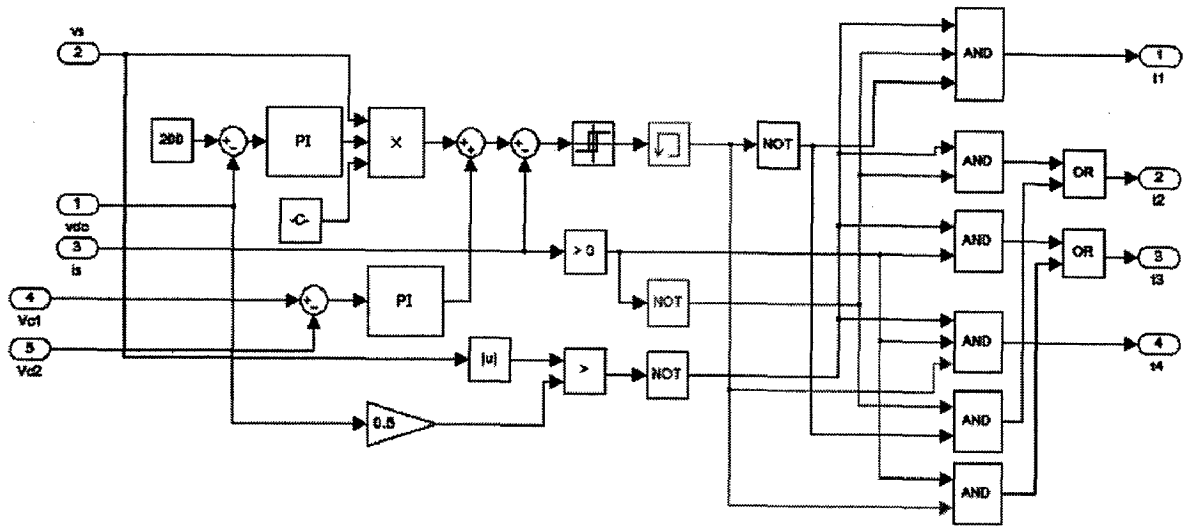


Fig .5.14Control block diagram for Three-Level PWM scheme

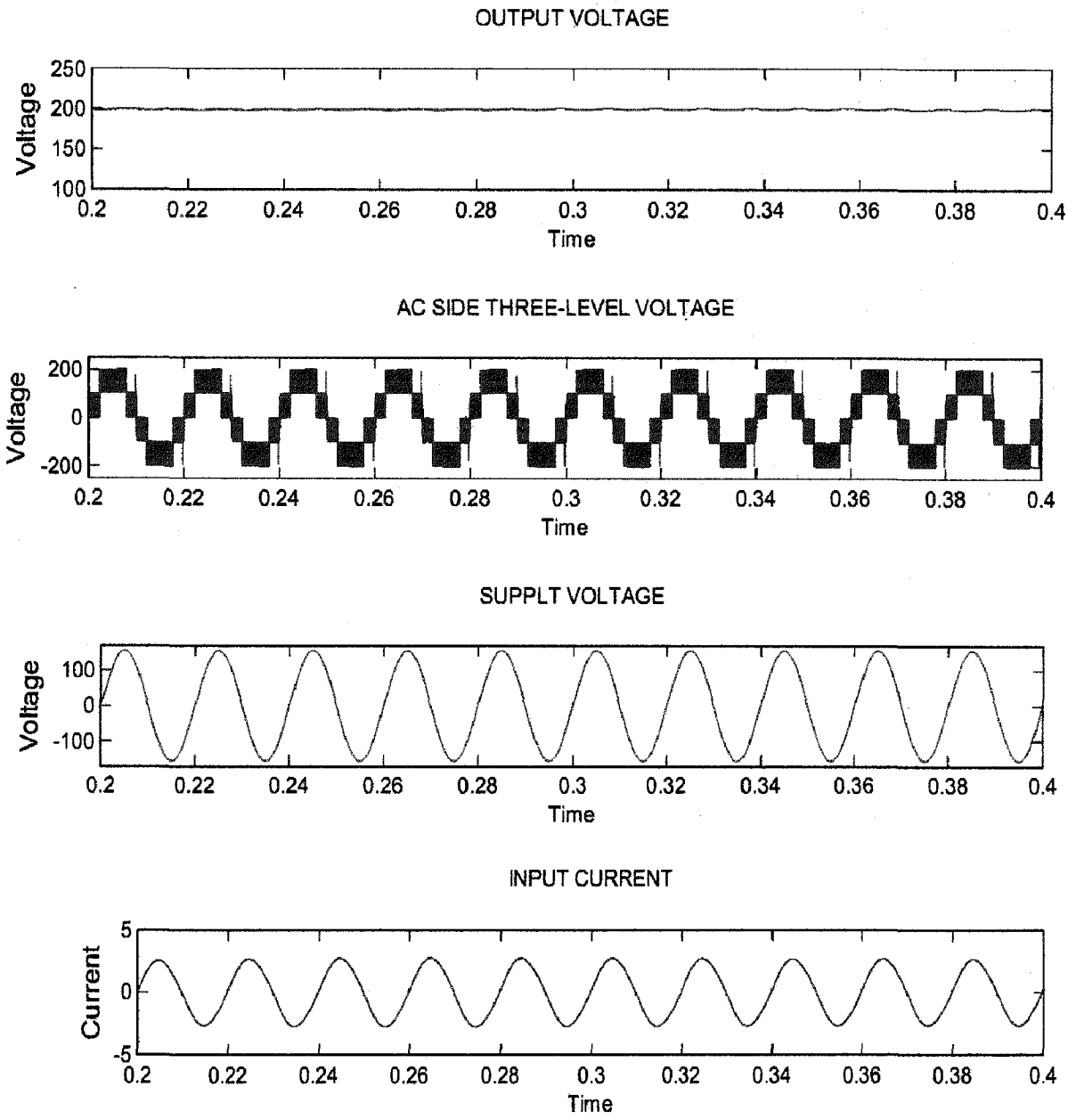


Fig.5.15 Simulation results

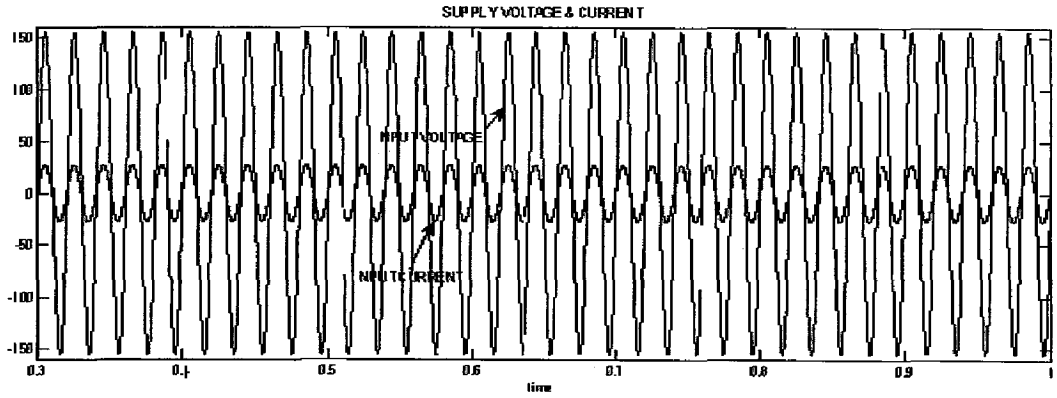


Fig.5.16 Supply voltage & current

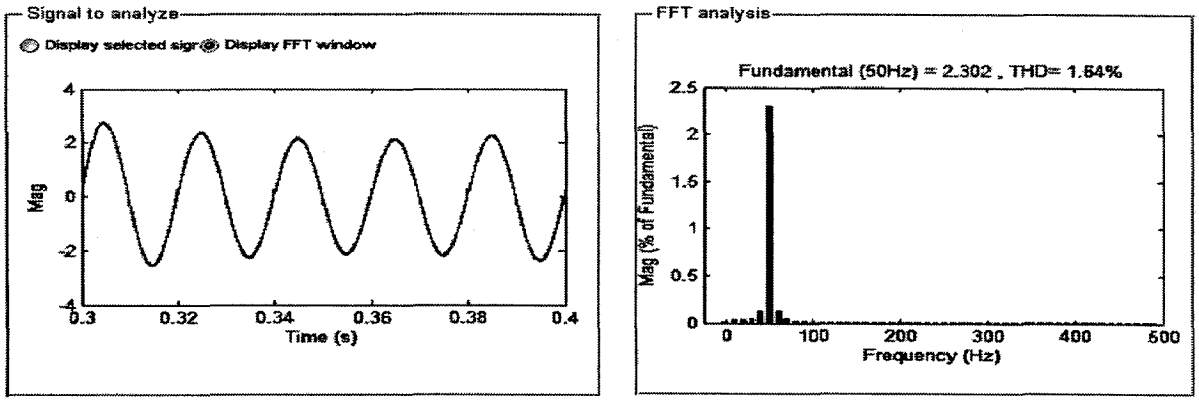


Fig.5.17 Input current waveform and harmonic spectrum

Table 5.2 Harmonic components of supply current

Harmonic number (Frequency in Hz)	I_S
Fundamental(50)	2.31
3^{rd}(150)	0.057
5^{th}(250)	0.01
7^{th}(350)	0.008
9^{th}(450)	0.018
11^{th}(550)	0.0075
THD%	1.64

The output voltage settles around reference value early so response time is good and even ripple in voltage is normal with a value of 0.0514 and as seen clearly from source current waveform that current is almost in phase with the voltage.THD is 1.64% shown by using FFT analysis in Fig.5.17

5.2.2 Performance under varying load condition:

The model is simulated under various loads varying from minimum to maximum keeping input voltage constant. The input current rms value is measured directly from functional block of SIMULONK while THD from POWERGUI block. Output voltage is measured in voltage block. Power factor is found active and reactive power block while efficiency is calculated from input and output powers.

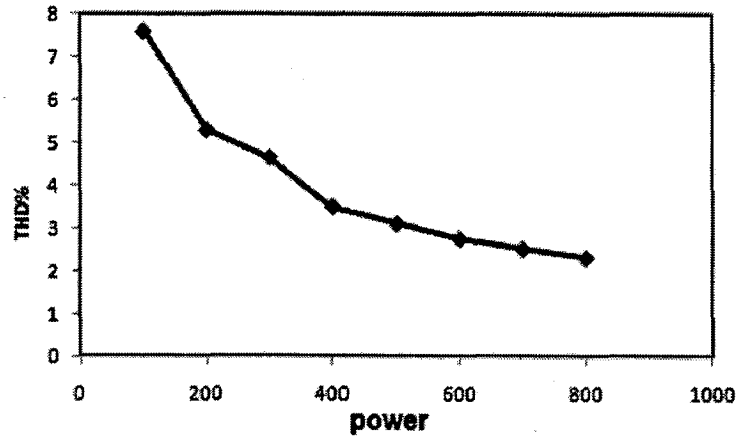


Fig.5.18 Total harmonic distortion vs output power

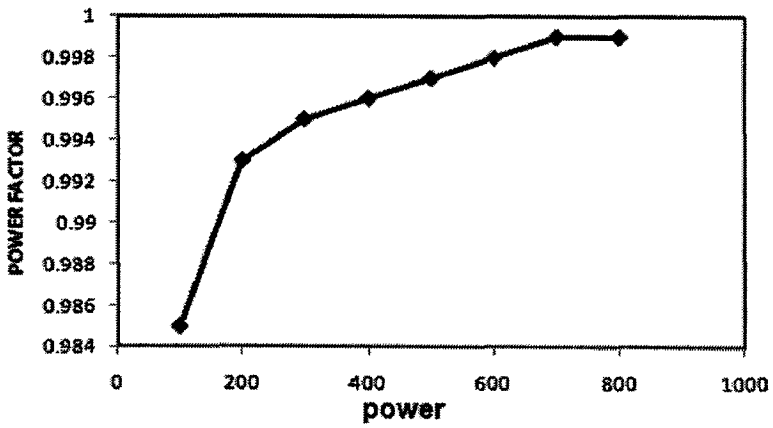


Fig.5.19 Power factor vs output power

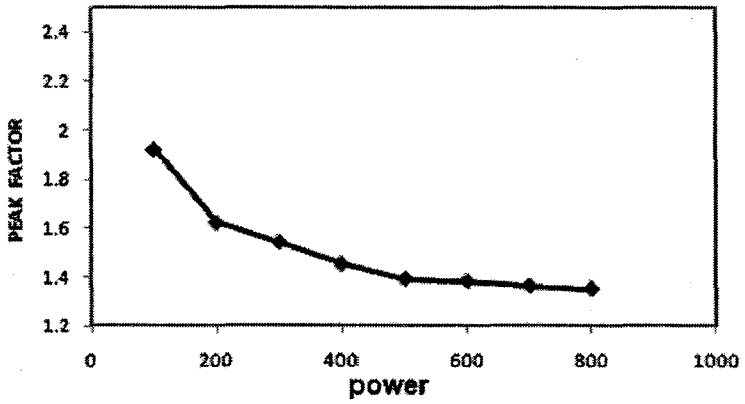


Fig.5.20 Peak factor vs output power

We conclude that single-phase Neutral-Point diode-Clamped active Rectifier provides good performance but as output power increases, the demand for input current becomes very high. And its THD is very low compared to two-level PWM scheme. It has a good efficiency 98.35% and even power factor is almost unity at high loads. The performance for various loads is observed from figures above shown.

5.2.3 Dynamic Performance Evaluation:

Dynamic performance is seen by applying sudden changes to load reference and supply voltage to see how converter reacts to transients occurs in the system. The change is applied using one switch at t=0.5 for each case and the rectifier performance is observed using simulations in every case of sudden change of to load, reference and supply voltage.

a) Sudden change in load:

Here, converter is running at a load of R=200 ohm then at t=0.5s the load is changed to R=150 ohm while the reference is set to 200V in both the cases, the waveforms of output voltage and currents are observed as shown in Fig.5.21.

As the load increased the output voltage falls then as per control action increases to reach that particular load in that way voltage again settle down to reference value. Here the settling time is around .4s. The waveforms under load changing are shown in fig.5.21

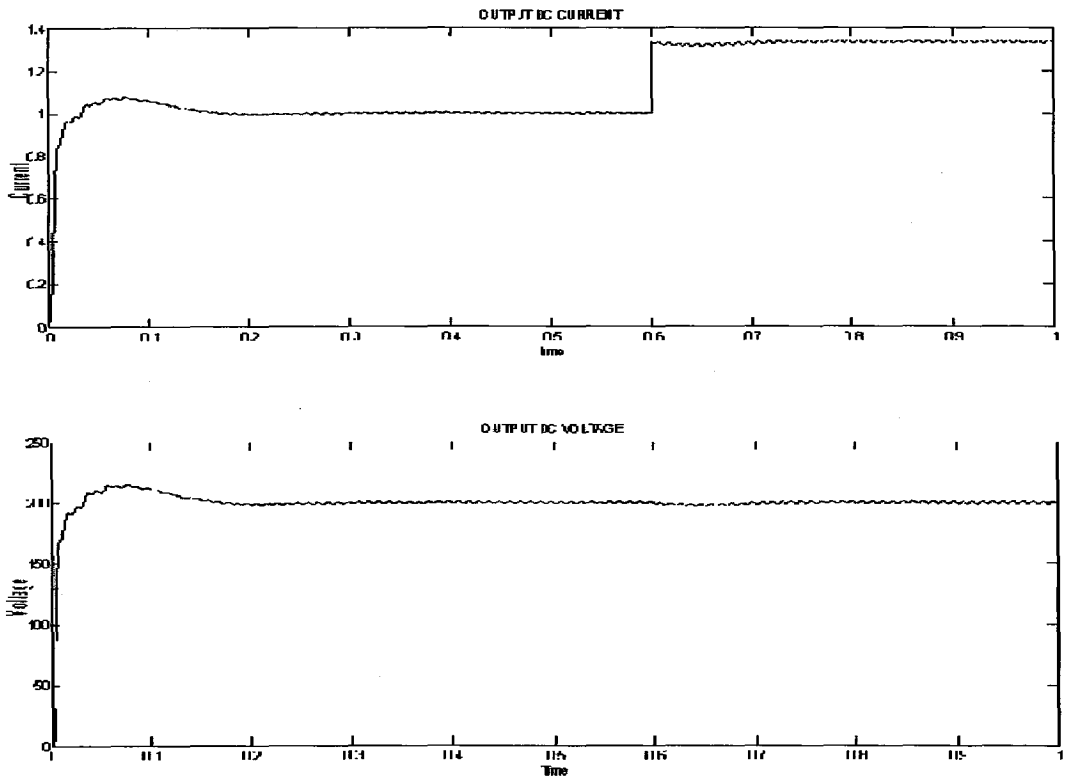


Fig.5.21 Output current (above) and voltage (below) for change in load condition

b) Sudden change in reference:

The reference has been changed to see the effect on how the voltage settles down to new value. The voltage reference has been changed from 200V to 150V at t=0.5s.

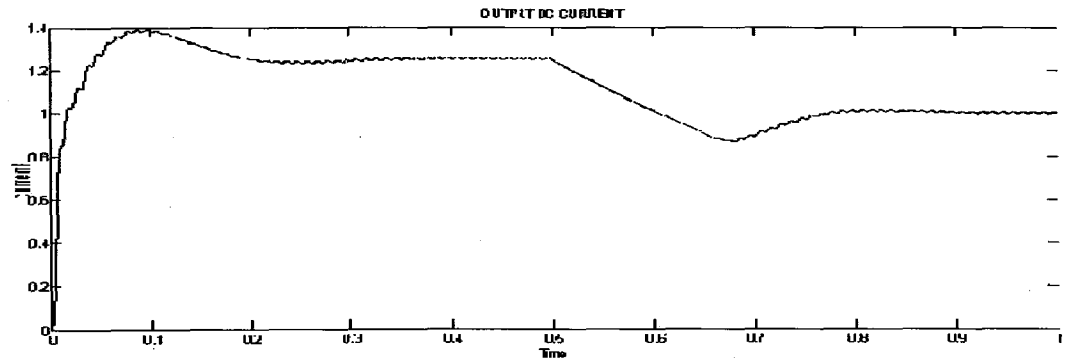


Fig.5.22 Output current for change in reference

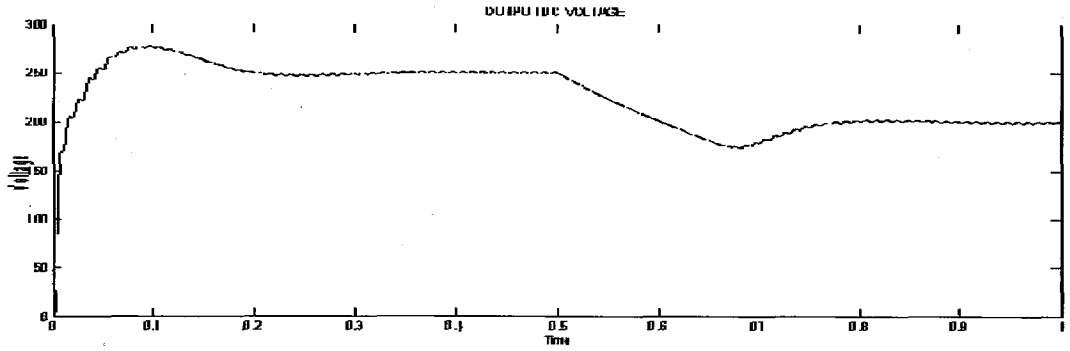


Fig5.23. Output voltage for change reference

The voltage is settles down to new value after t=.2 sec.

c) Variation in supply voltage:

The simulation model which is shown in Fig.5.24 can be used for this condition by usin one switch.Here the reference voltage is set at 200V and the input voltage changes from 110V to 135V at time t = 0.5sec.

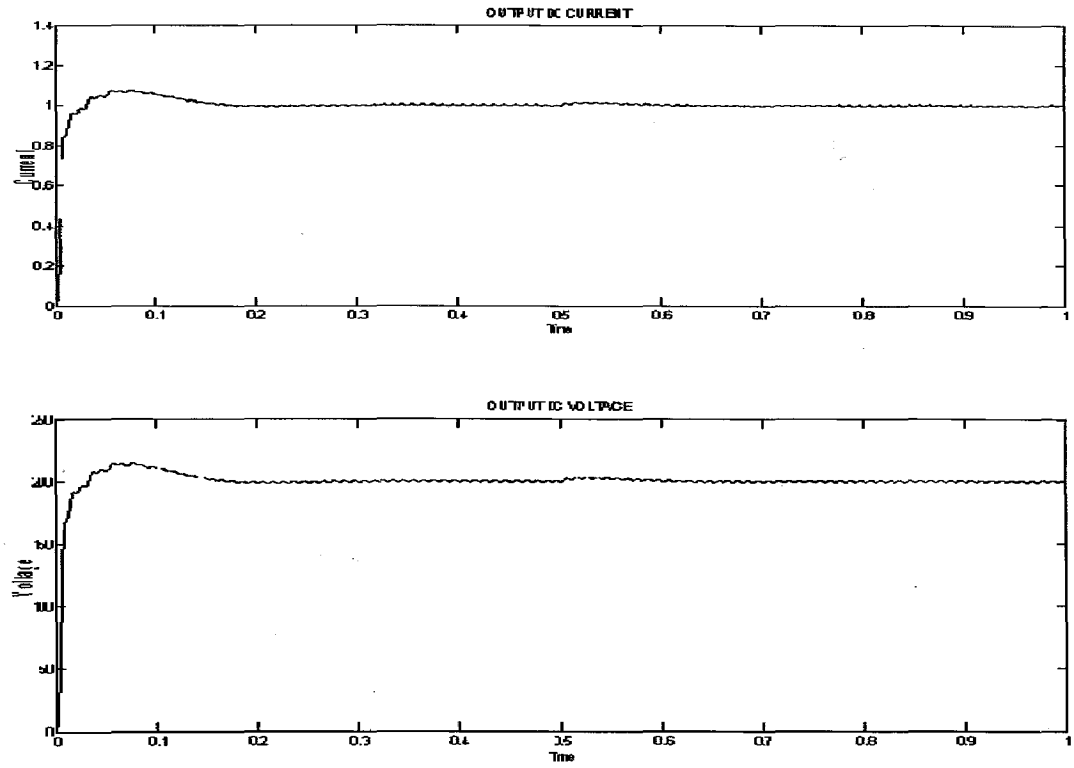


Fig.24 Output current (above), output voltage (below) for change in supply

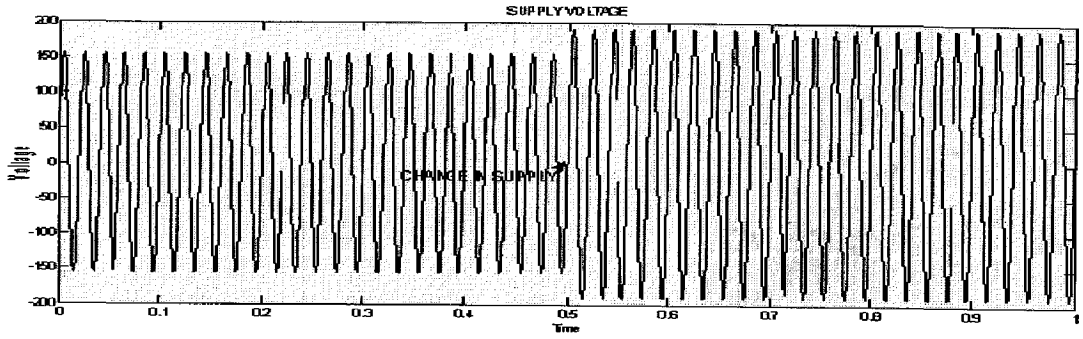


Fig.5.25 Change in supply voltage at t=0.5 sec.

5.2.4 Step in response:

The step in response is as shown in the fig. the active rectifier is connected in the line at .05seconds and the corresponding response is as shown in the figure 5.26.

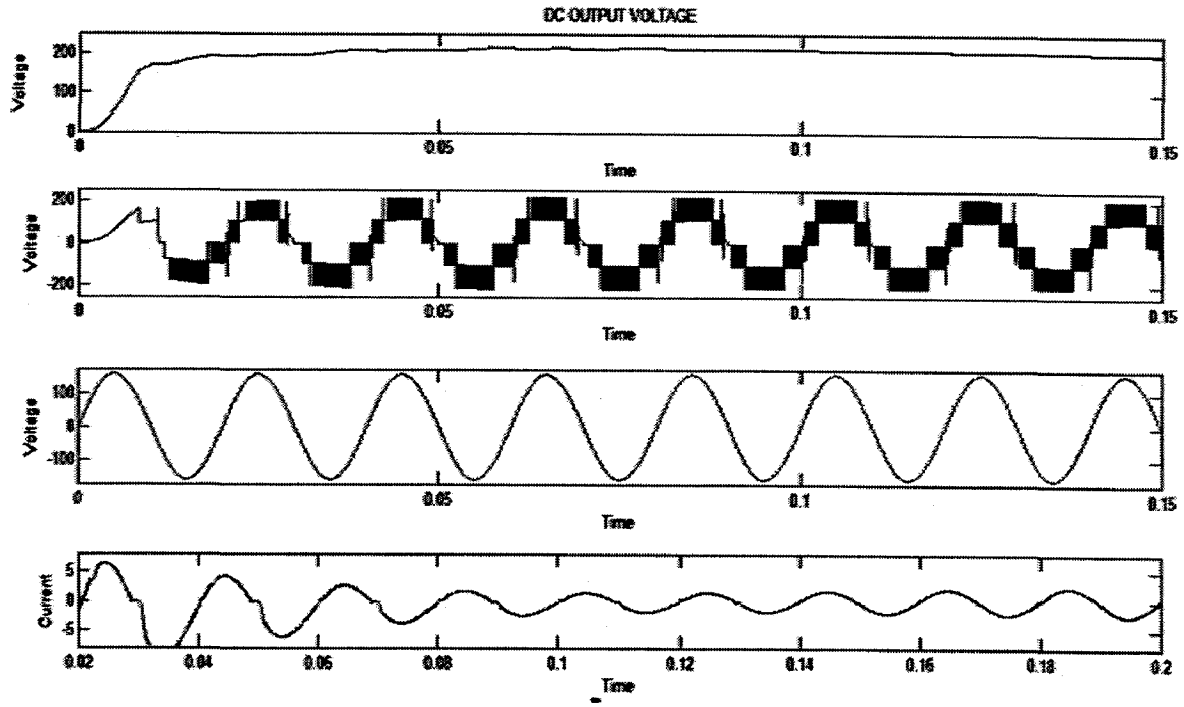


Fig.5.26 Step in response of active rectifier

5.3 Comparative analysis of converters

Here the two control strategies for the active rectifier are proposed such that the input current drawn from supply is nearly sinusoidal and unity power factor operation can also be achieved. Even though input current is controlled there is some amount of harmonics are present. So, there are some performance measures that are defined for those converters.

- Total Harmonic Distortion of input current
- Input power factor
- Peak factor
- Efficiency
- Ripple factor
- Response time

Table 5.3 Comparison of converter topologies

Topology	No. of switches/diodes/ capacitors	THD of input current (%)	Voltage ripple factor	Input power factor	Response time
Diode Clamped Three Level Converter	8/4/2	1.91	0.00245	.996	.08
Six switch Diode Clamped Three Level Converter	6/2/2	2.40	0.00452	.995	.12
Flying capacitor three level converter	8/0/4	2.50	0.00523	.996	.13
Four switch diode clamped converter (Two level PWM)	4/4/2	3.0	0.0065	0.996	0.2
Four switch diode clamped converter Three level PWM	4/4/2	1.64	0.00514	0.998	0.15

For all above tabulates various parameters with only hysteresis PWM control scheme only. From them with reducing switch converters have good performance with compared to other converter topologies.

5.3.1 Various load conditions

Here a comparative analysis of different techniques has been done by plotting parameters THD and Power Factor with varying output power for all techniques.

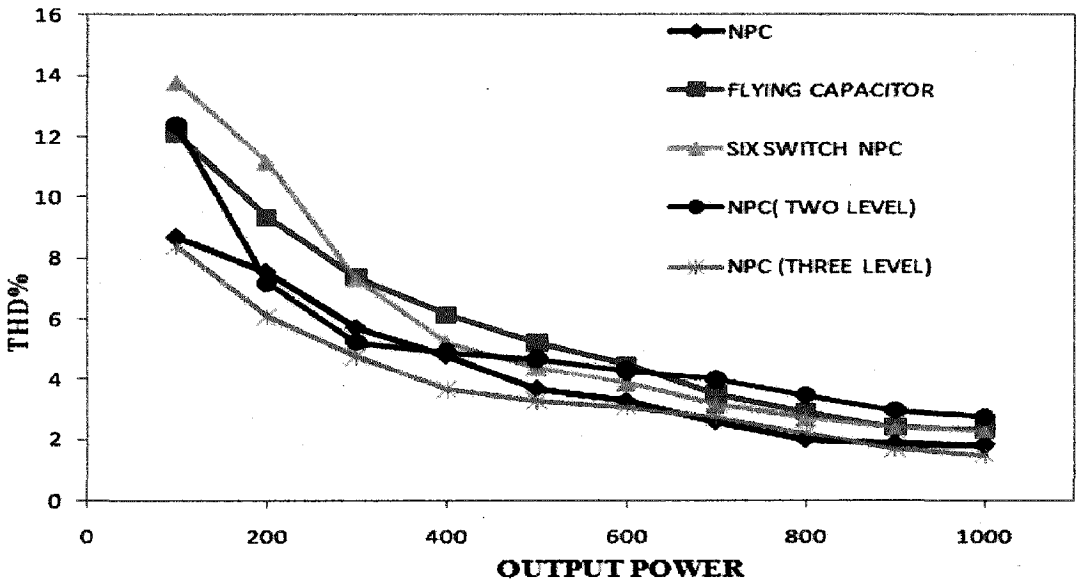


Fig.5.27 Total Harmonic Distortion vs Output power

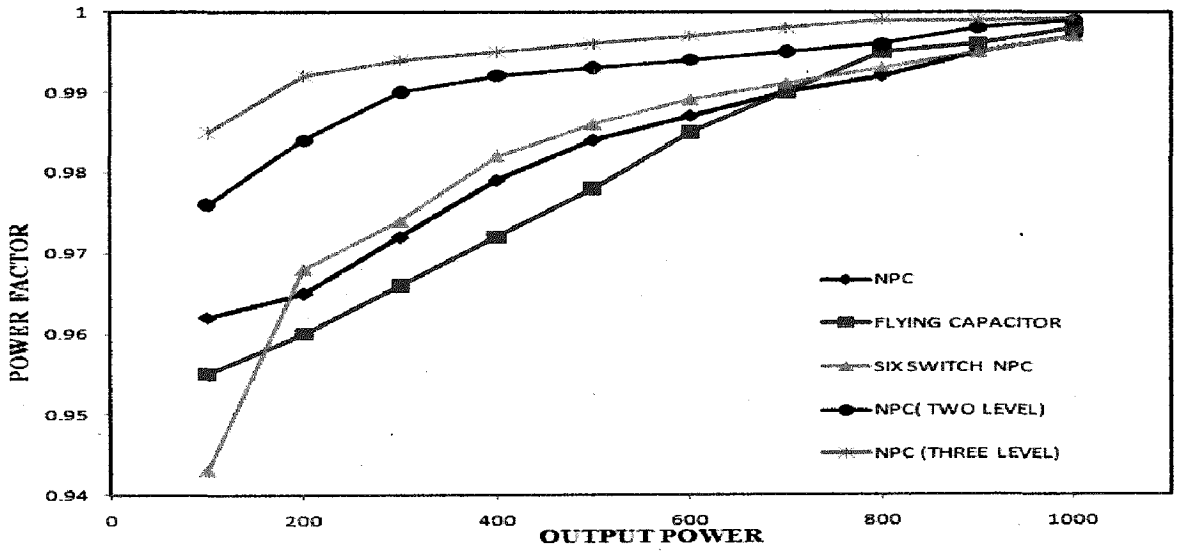


Fig.5.28 Input Power Factor Vs Output Power

From fig.5.27, we can say that four switch neutral point diode clamped converter have least THD and having unity Power factor shown in Fig.5.28.

5.4 Conclusion

All the neutral point clamping three level rectifier topologies are implemented and simulated. Their performance is investigated using results and graphs. Each topology has its own advantages and disadvantages. The selection of converter depends on the application.

CHAPTER 6

SYSTEM HARDWARE DEVELOPMENT

In this chapter the design procedure of the hardware development for the implementation of single-phase Neutral-Point diode-Clamped Active Rectifier has been described. The protection of MOSFETs has been discussed. All the hardware requirements have been described briefly. All interfacing procedures have also been discussed in details.

6.1 Hardware Development

The system has been developed for closed loop control containing the following blocks:

- Power Circuit
- Control circuit
- Power supplies

6.2 Power Circuit development

Fig 6.1 shows the power circuit of a single-phase Neutral-Point diode-Clamped Rectifier.

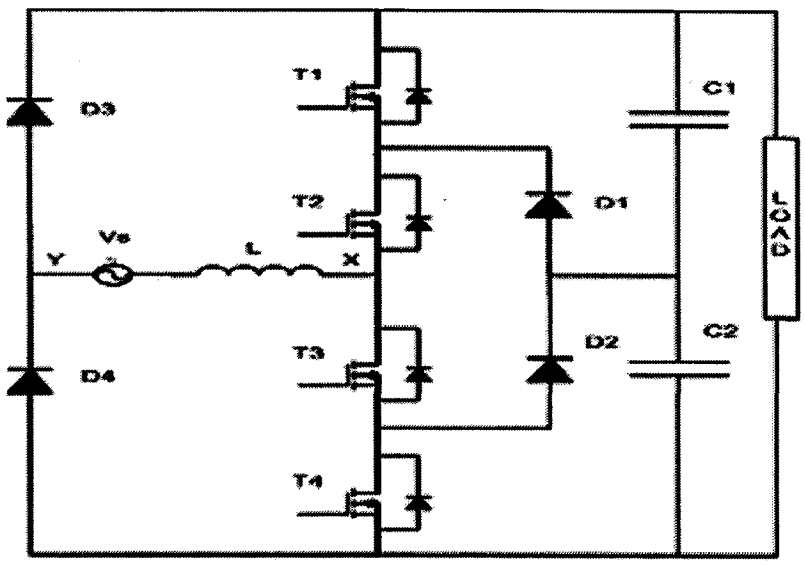


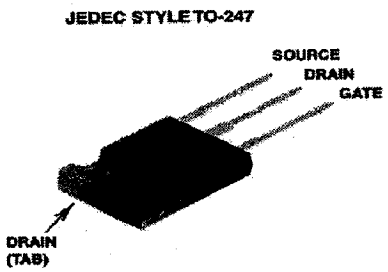
Fig.6.1 Power circuit of a single-phase Neutral-Point diode-Clamped Rectifier

This circuit requires four switches capable of blocking voltage and current in both directions. MOSFET switch used in the circuit consists of an inbuilt ant parallel freewheeling diode. No forced commutation circuits are required for the MOSFET as it is a self commutating device. These power devices are placed on heat sinks made of aluminum sheet to dissipate the excessive heat generated by switches.

6.2.1 SWITCHES;

Power circuit consists of four switches here MOSFETS Aare used. MOSFETs are widely used for switching operations in low power and high frequency applications. In these devices, there are no delays during turn-off period due to the recombination of minority carriers. Therefore these devices are suitable for high frequency operations. The gate drive requirement for MOSFET devices is almost negligible when compared with power transistors. In power circuit realization, MOSFETs IRFP460 are used.

1. MOSFET-IRFP 460 (500V, 20A): 4 nos.



2. INDUCTOR 3 mH [air core,5A]
3. CAPACITOR 2200 μf, 500v : 2 nos
4. POWER DIODES 16D40R: 4 nos
5. RESISTANCE LOAD
6. HEAT SINK & CONNECTORS.
7. CONNECTING WIRES

6.2.2 Snubber Circuit

All semiconductor devices have limited capabilities. Reliable and satisfactory operation of the device depends on ensuring that the circuit conditions imposed on them is always within their capabilities. There is a temperature rise as the device losses such as conduction and switching are inevitable. To operate the devices within their upper temperature

limit, the heat produced by the device must be dissipated sufficiently and effectively. A heat sink made up of aluminium or copper which provides large surface area for heat dissipation is generally used in MOSFET circuits to protect from the high temperature rise. Voltage transients occur in the converter circuits due to switching actions in the presence of circuit inductances. Since an RC snubber circuit has been used for protection of the main switching device. Switching high current in short time gives rise to voltage transients that could exceed the rating of the MOSFET. Snubbers are therefore needed to protect the switch from transients. Snubber circuit for MOSFET is shown in fig.6.2. The diode prevents the discharging of the capacitor via the switching device, which could damage the device due to large discharge current. An additional protective metal oxide varistor (MOV) is used across each device to protect against over voltages across the devices.

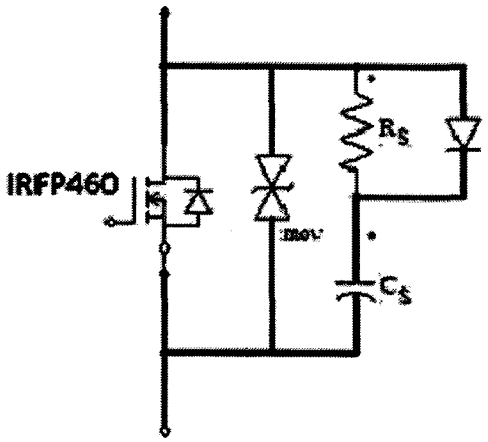


Fig.6.2 Snubber circuit for MOSFET protection

Components:

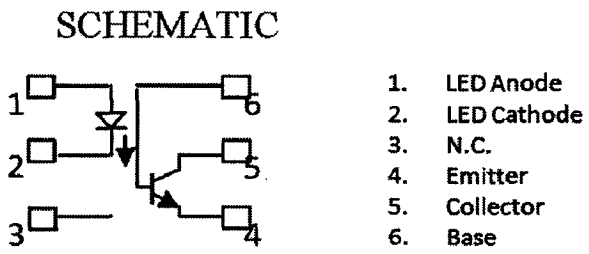
- Snubber circuits: 4 nos.
- Capacitance: 0.01μF/250V
- MOV (metal oxide varistor): 510V
- Diodes IN5408 : 4nos

6.2.3 Pulse Amplification and Isolation Circuit

The pulse amplification circuit for MOSFET is shown in fig. 6.3.this circuit is also called MOSFET driving circuit. The opto-coupler MCT-2E provides necessary isolation between the low voltage isolation circuit and high voltage power circuit. The pulse amplification is provided by the output amplifier transistor 2N2222. When the input gating is +5V level, the transistor saturates, the LED conducts and the light emitted by it falls on the base of the phototransistor, thus forming its base drive. The output transistor thus receives no base drive and remains in the cut-off state and a +12V pulse (amplified) appears at its collector terminal.

Components

- Opto-coupler MCT-2E: 4 nos.



- Output amplifier transistor (2N2222): 8 nos
- Resistance: - 10k: 8 nos., 1.2k: 4 nos., 470k: 4 nos., 3.8k: 4 nos.
- Zenner diode (+12V): 4nos.
- Copper clad sheet (4'' x 2'') for making 4 PCBs.

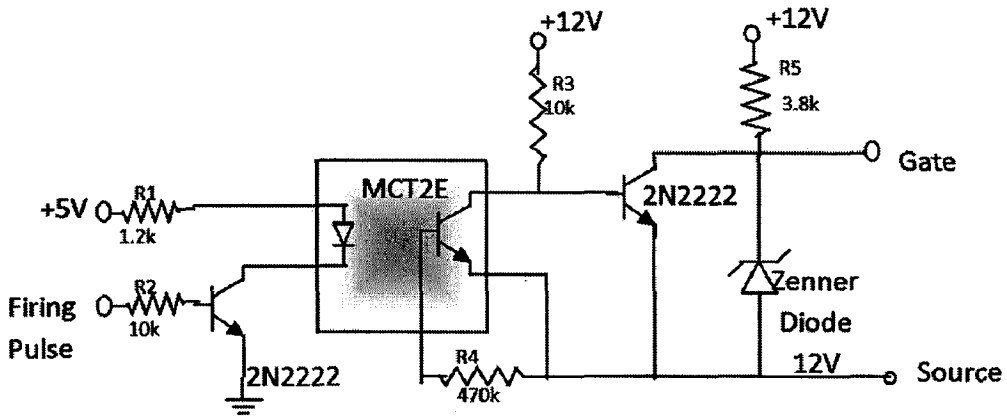


Fig. 6.3 Pulse amplification and isolation circuit diagram

When the input gating pulse reaches ground level, the input switching transistor goes to cut-off state and LED remains off, thus emitting no light and therefore the photo-transistor remains off. The output transistor receives base drive and saturates, hence the output falls to ground level. Therefore, the circuit provides proper amplification and isolation. Further, since slightest spike above 20 can damage the MOSFET; a 12V Zener diode is connected across the output isolation circuit. This clamps the triggering voltage to 12V.Further to the +12V power supply was fabricated on the same PCB using 7812 chip.

6.3 Control Circuit Realization:

Control circuit is the main part of multilevel converters. Here the hardware developed for the closed loop operation so it has sensors and PI controller. The control circuit realization is shown in Fig.6.4. As discussed in the previous chapters the control circuit consists of the following;

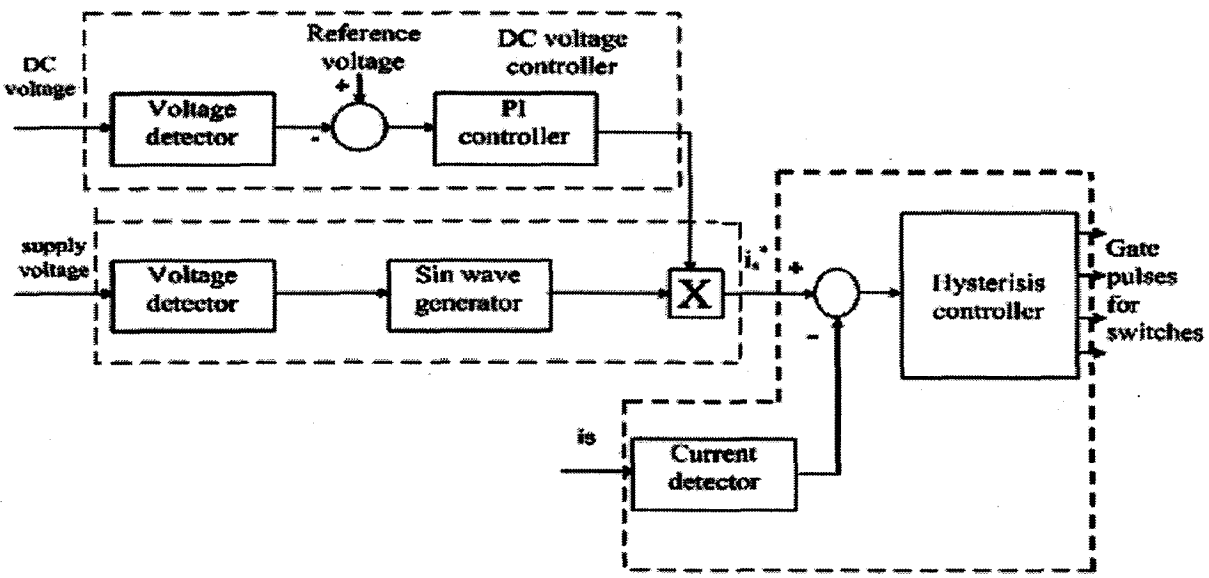


Fig.6.4 Control Scheme Realization

- AC voltage sensing circuit
- Input AC current sensing circuit
- DC voltage sensing circuit &PI controller circuit
- Multiplier circuit
- Hysteresis controller circuit

6.3.1 AC voltage sensing circuit:

This circuit sense the input voltage which in phase with the supply voltage and unity magnitude. This sensed voltage is isolated from input voltage using isolation amplifier. AD202JN isolation amplifier is used which is a transformer coupled isolation amplifier to provide isolation between the control circuit and the voltage source It is necessary that the voltage between the pins 1&2 for AD202 should not exceed +/-5V. Therefore a potential divider circuit is used which provides 1/30 time the supply voltage between pins 1&2. The connections shown for the AD202JN are for a unity gain application. Therefore the output signal (at 19th pin) is same as that provided between 1&2 with isolation. . The connection diagram which was developed is as shown in fig 6.5.

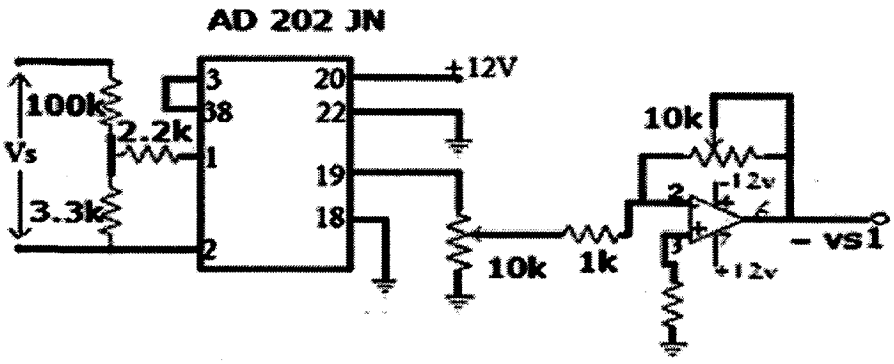


Fig.6.5 AC Voltage sensing circuit.

The signal at 19th pin is inverted using an inverting amplifier which utilizes operational amplifier LM 741. With proper scaling it is possible to obtain a unit amplitude signal. Therefore the output of the above circuit is the signal of unit amplitude which is out of phase by 180 degrees with the input voltage. The signal is inverted because in the multiplication circuit the other signal from the PI controller is inverted. Therefore the multiplication of these two signals provides a correct reference signal as desired.

6.3.2 Current Sensing Circuit:

With the advancement of Hall Effect technology, it is very easy to sense and measure the actual current in a circuit. Current sensing is done by using Hall Effect 1:1000 current sensor. The current sensing circuit is as shown in fig 6.5. The biasing voltages for the current sensor are +/-15v. But it works satisfactorily even if the bias voltage is +/-12V.

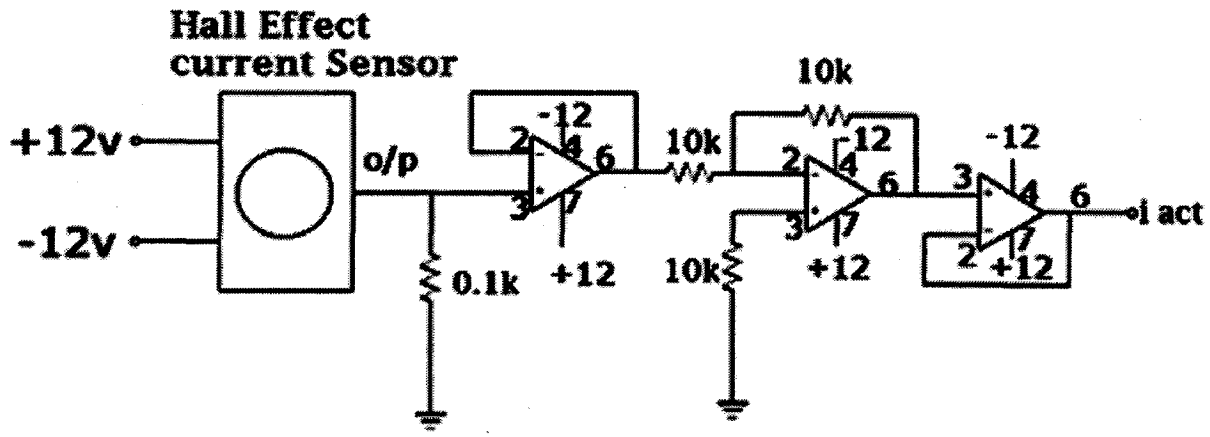


Fig 6.6 AC Current sensing circuit.

6.3.3 DC Voltage Sensing and PI controller circuit:

DC voltage sensing can be done in a similar way to the AC sensing circuit. However there are two such circuits are needed in order to sense two capacitor voltages and appropriate action can be taken along with the voltage balancing of the capacitors.

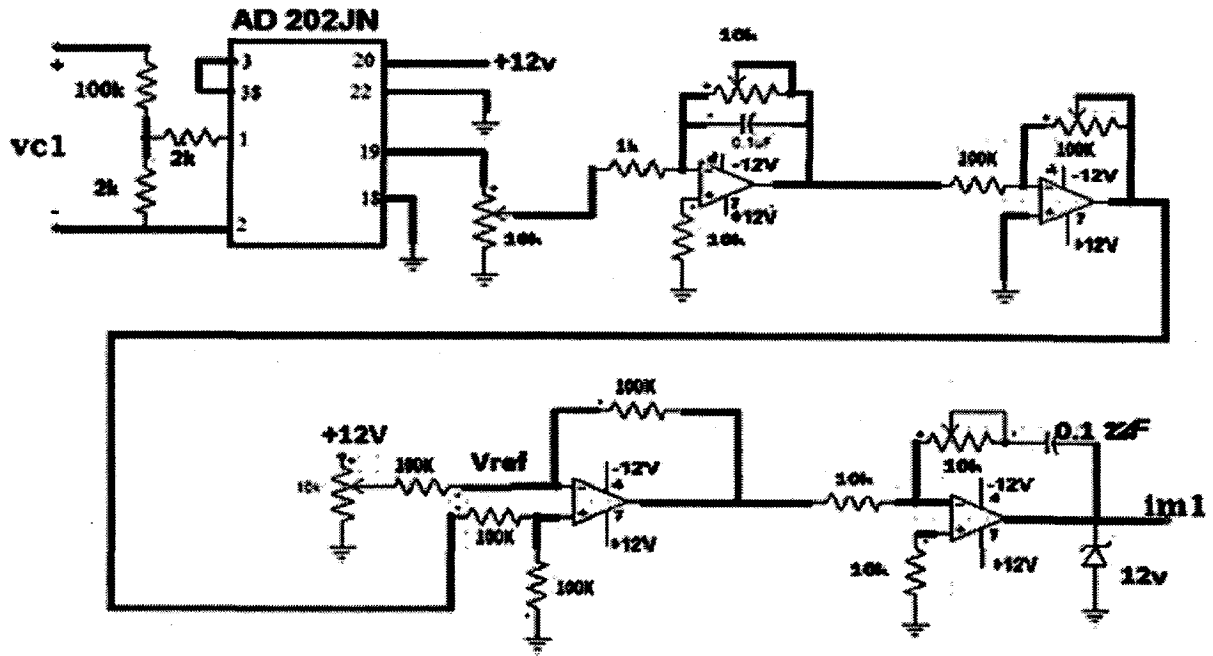


Fig.6.7 DC voltage sensing along with the PI controller circuit.

In Fig 6.7 DC sensing circuit and PI controller which generate im1 is shown. Another such circuit is to be used for the second capacitor voltage sensing and to generate im2. These two signals can be added to produce im, which is to be multiplied with the unit amplitude sinusoidal signal generated to produce the reference signal. AD202JN as used in constant gain mode, provides the same signal as that applied between 1st &2nd pins. As the output voltage consists of ripples, the voltage which is sensed also consists of ripples. Therefore a low pass filter is used at the output of AD202JN. The reference voltage signal is generated by using the potential divider as shown above. Then the reference signal and the actual voltage signals are compared in the operational amplifier comparator circuit. The PI controller is realized by using the operational amplifier as shown in fig. There is a Zener diode placed at the output of the PI controller to limit the control effort to 12V.

6.3.4 Multiplier Circuit:

Multiplier circuit is necessary to make the control effort of the PI controller, a sinusoidal signal and in phase with the supply voltage. The circuit configuration is as shown below in fig 6.8.

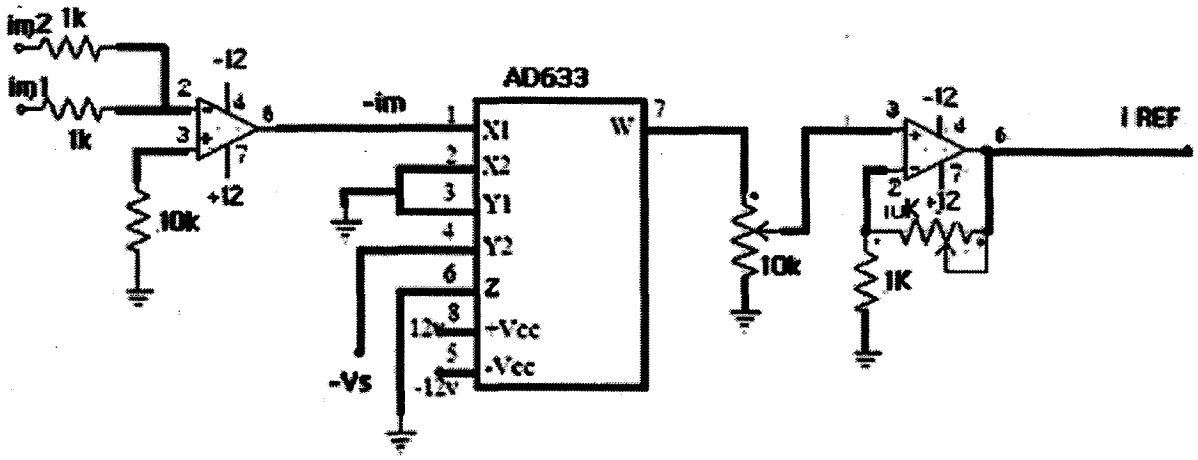


Fig 6.8 Multiplier circuit

AD633 is an analog multiplier chip. It includes high impedance, differential X and Y inputs and a high impedance summing input (Z). The low impedance output voltage is a nominal 10v full scale provided by a buried zener. The high (10MΩ) input resistance of AD633 make signal loading negligible. The differential X and Y inputs are converted to differential currents

by voltage to current converters, the product of these currents is genrated by a multiplying core. The sum of (X*Y)/10+Z is then applied to the output amplifier. The amplifier summing node Z allows the user to add two or more multiplier outputs, convert the output voltage to a current, and configure various analog computational functions. It is to be noted that here the multiplication is done for the signals –Vs and –im. Therefore the output is Vs*im/10. The output of the AD 633 is given to the non-inverting amplifier to generate the reference signal.

6.3.5 Hysteresis current controller:

Hysteresis controller compares the actual current and the reference current and produces the firing pulses for the devices. The circuit consists of an error amplifier, schmitt trigger and a delay circuit to ensure the complete turn-off of the device before another device is being triggered.the circuit shown in Fig.6.9

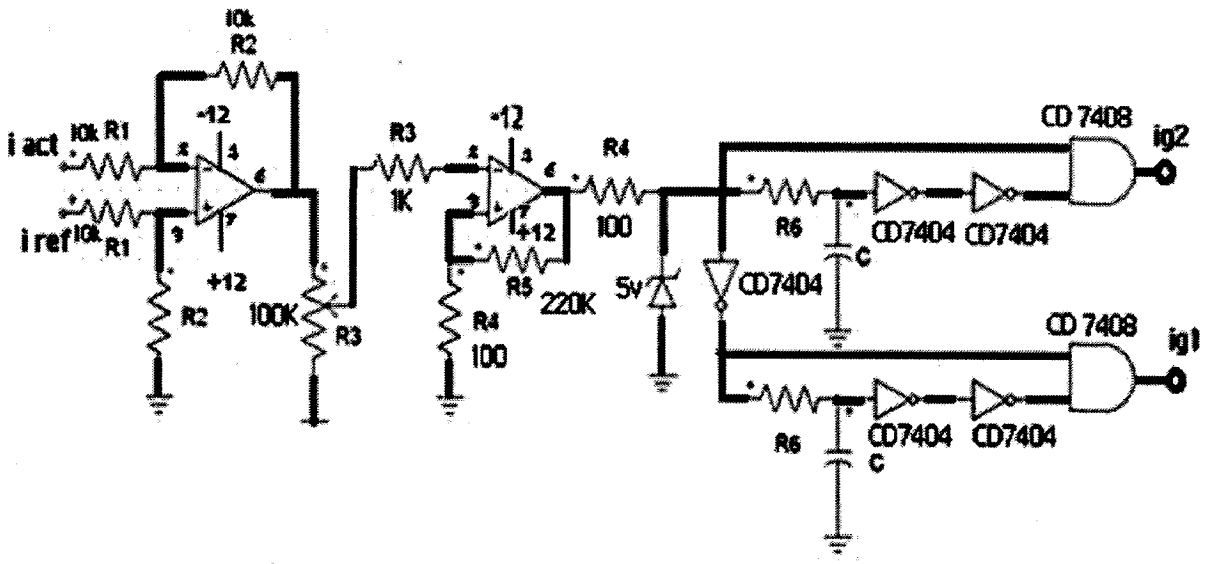


Fig 6.9 Hysteresis Controller with Dead band circuit.

The circuit consists of an error amplifier, schmitt trigger and a delay circuit to ensure the complete turn-off of the device before another device is being triggered. The error amplifier generates a signal which is the differerence between the actual and reference signals. The output is of the error amplifier is given to Shmitt trigger circuit. In shmitt trigger circuit, the output is either +12V or -12V. The upper threshold of the Schmitt is +12*(R4/(R4+R5)). The lower threshold is -12*(R4/(R4+R5)). Whenever the signal at 2nd pin of the op-amp used in shmitt trigger circuit is positive and more than the upper threshold limit, the output is -12V. It remains -

12V untill the signal at the 2nd pin is negative and less than the lower threshold value. Whenever this signal decreses below the lower threshold value,the output changes to +12V. Therefore the error is limited with in the band given by 2*12*(R4/(R4+R5)) which is known as the hysteresis band. For obtaining a hysteresis band of 0.01, R4=100□ and R5= 220K are selected. By using logic AND and logic OR gates, the firing pulses are genertaed for the switches.The ouput of schmitt trigger is +/-12V, which is not suitable for logic gates. Therefore at the ouput of shmitt trigger a zener diode of 5V is placed. The delay circuit is provided such as to aviod the simulataneous conduction of the swithches between the switching transients.

6.4 Power Supplies

DC regulated power supplies (+12V,-12V, +5V) are require for providing biasing to various circuits like pulse amplification and isolation, voltage sensor circuits and analog inputs providing reference frequency and voltage using ICs 7812,7912 and 7805 for +12V,-12V and +5V respectively. Primary side of 230V/12V single phase transformer is fed through a single phase 230V, 50Hz supply, secondary side is connected to a diode bridge. 1000μF, 50V capacitor is connected at the input supply of the regulator. 100μF, 25V capacitor is connected at the output of the IC voltage regulator of each supply for obtaining the constant ripple free DC voltage as shown in Fig.6.10 & 6.11.

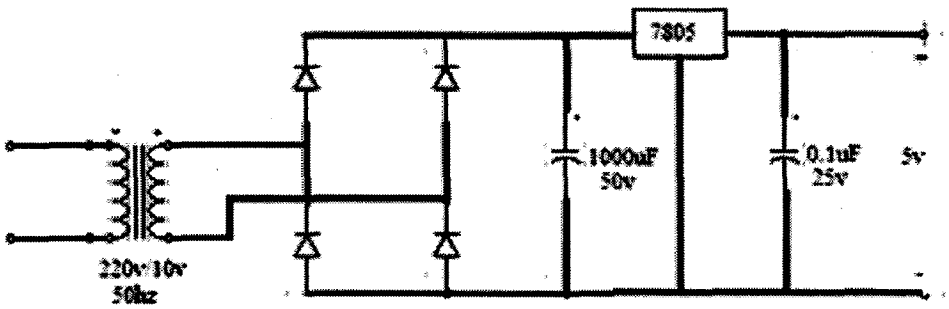


Fig 6.10 +5V Regulated DC supply.

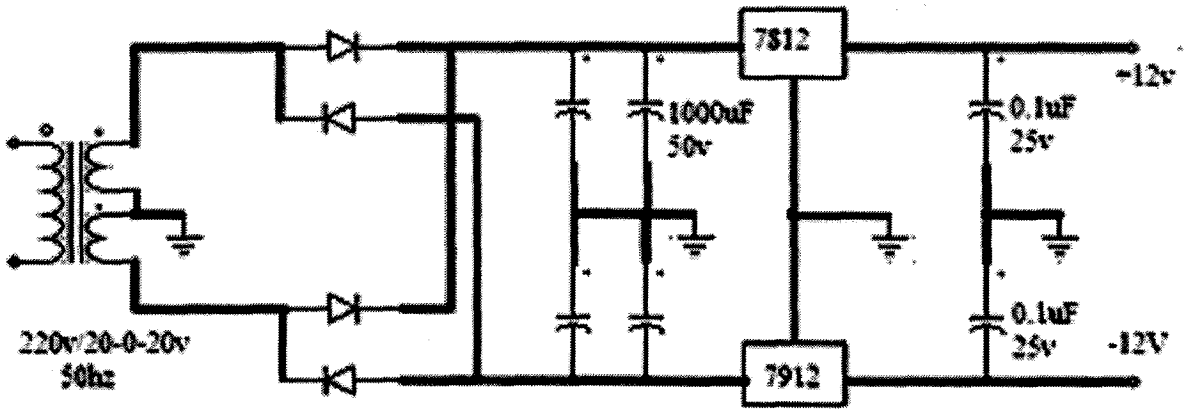


Fig 6.11 12 V Regulated DC Supply.

6.5 Conclusion

In this chapter the various components developed for the hradware implementation are discussed. The various circuits of power, measurement and control circuitry are shown. The experimental results of this developed prototype are shown and discussed in next chapter.

CHAPTER 7

EXPERIMENTAL RESULTS

The complete hardware required to test four switch single phase neutral point diode clamped active rectifier is developed using the circuits given in the chapter 6. The output Dc voltage is sensed using the voltage sensing circuit of section 6.7. The reference DC voltage and the DC output voltage are the inputs to the PI controller. The output of PI controller, reference current magnitudes is the inputs to the AD633 multiplier circuit of section 6.8. The output of the multiplier circuit is the instantaneous reference current. The reference current and the actual source current sensed through the current sensing circuits of section 6.6 are compared using a op-amp subs tractor circuit followed by Schmitt trigger circuit discussed in section 6.9. The output of the hysteresis controller is pulses to switches are shown in section 6.6. There after the four switch pulses are given to their respective pulse amplification and drive circuits of section 6.3 to get final gating pulses for four switches.

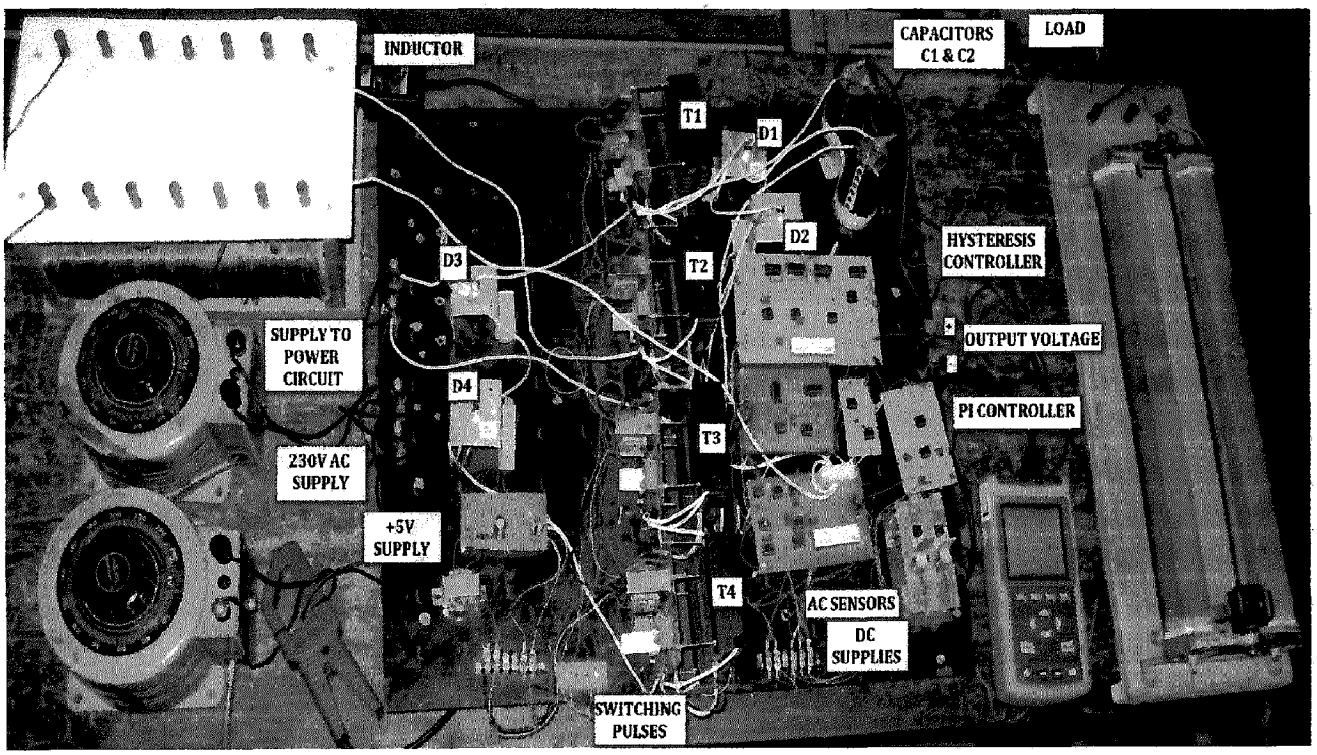


Fig. 7.1 LABORATORY EXPERIMENTAL SETUP

The performance of the system is investigated experimentally with certain basic Parameters selected for the experimental verification is as follows:

V_S (source voltage) = 44.55V(peak value)

L (Boost inductance) = 3.0mH

Dc link capacitors $C_1 = C_2 = 2200\mu F$

R_0 (load resistance) = 325ohm

The following Fig.7.2 shows the observed Dc output voltage waveform. The supply voltage & input current waveforms are shown in Fig.7.3. It is clear that the input current is in phase with supply voltage and the Power Factor is almost unity (0.99) is shown in Fig 7.4.the THD of input current is shown in Fig.7.5. The THD of the source current is not within the permissible limit and somewhat higher compared to simulated reason because the reference current is directly generated from supply voltage and it is already having harmonics. The AC side two level voltage and corresponding switching pulses are shown in Fig.7.6 and Fig. 7.7.

Two level PWM control scheme:

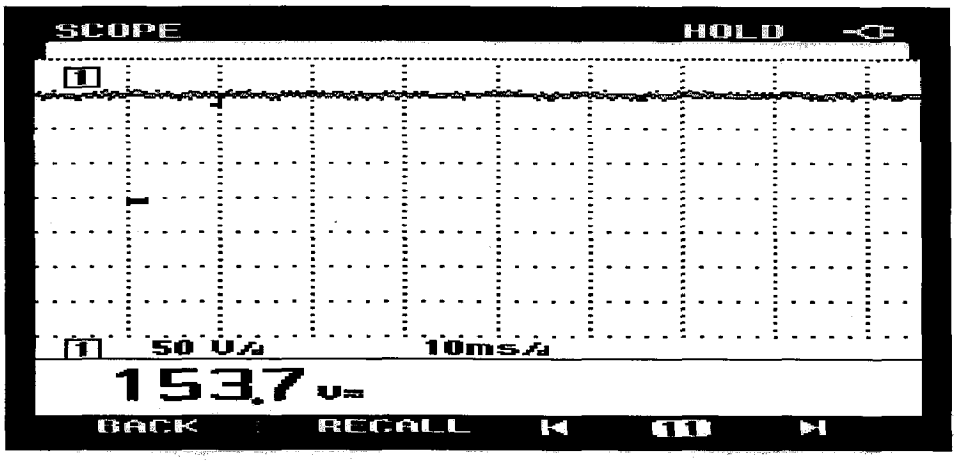


Fig.7.2 Output Dc voltage

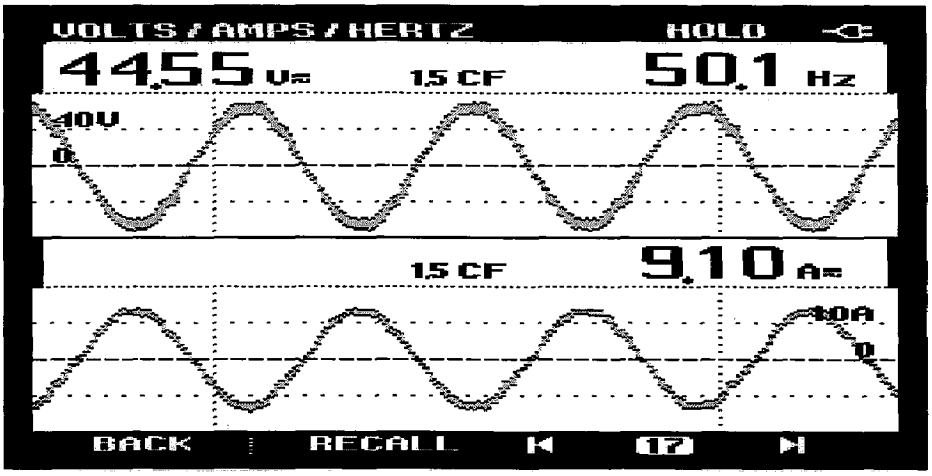


Fig. 7.3 Source voltage & current

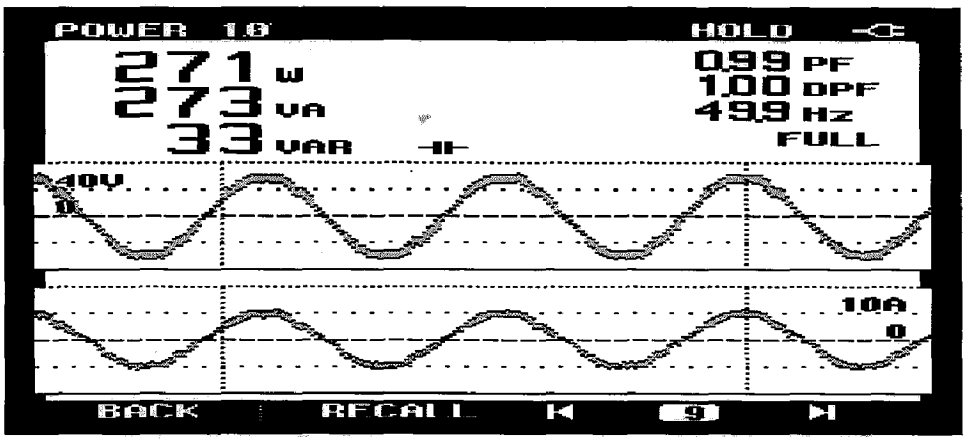


Fig. 7.4 Power Factor of input current

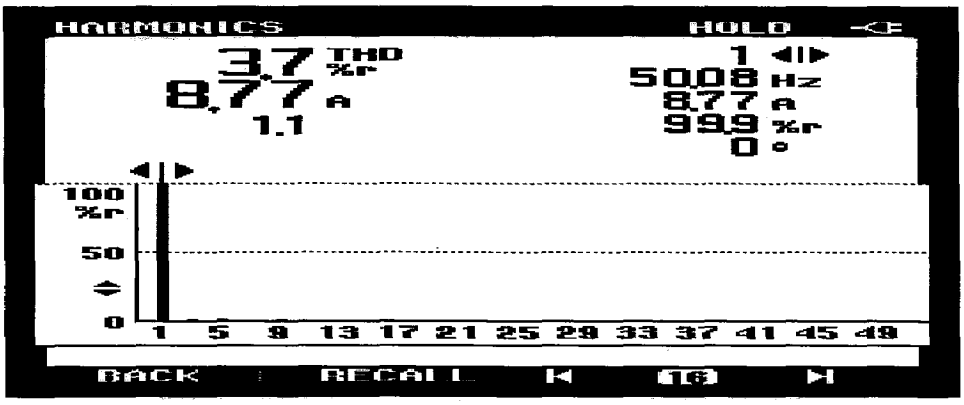


Fig. 7.5 Total Harmonic Distortion of input current

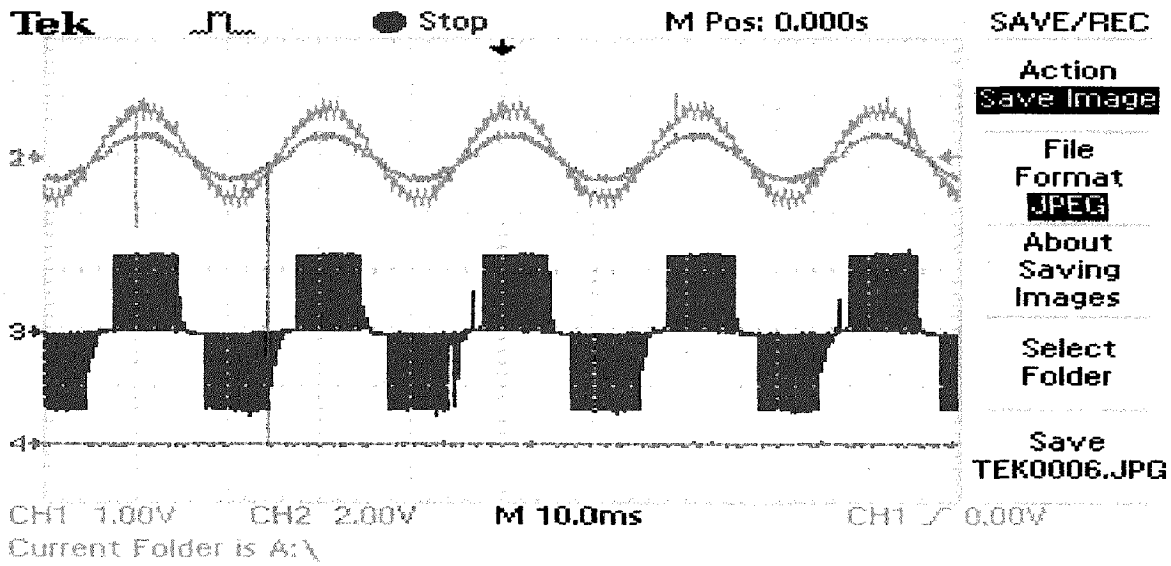


Fig. 7.6 Ac side two level voltage

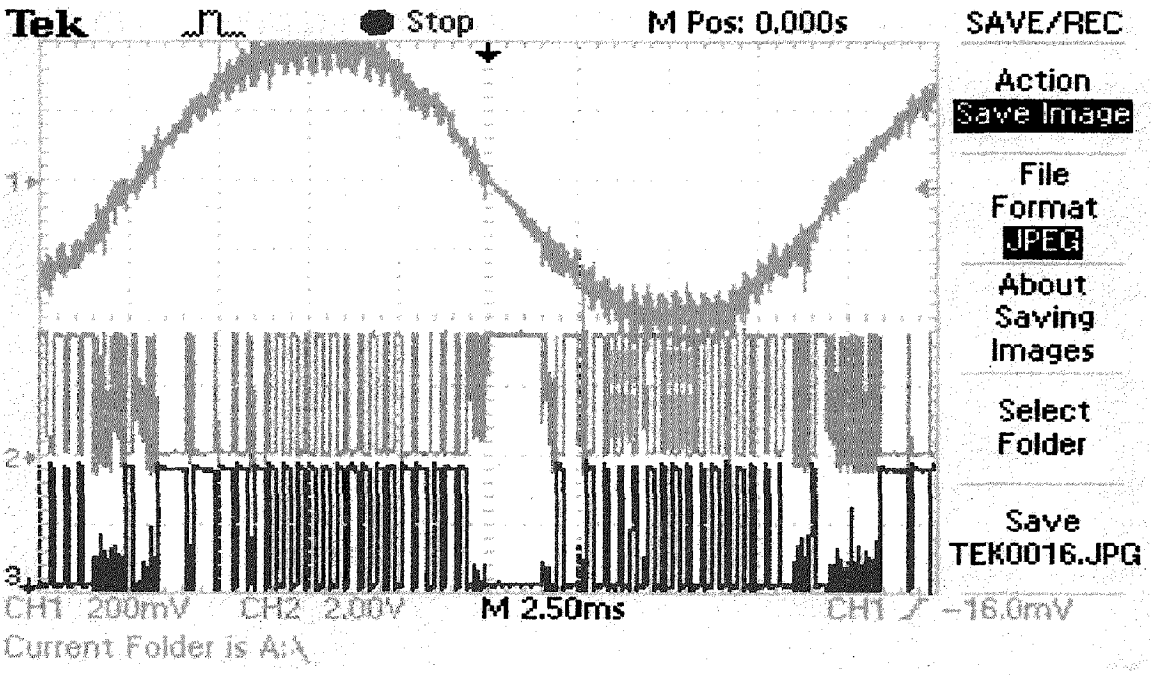


Fig. 7.7 Switching pulses

Three level PWM control scheme:

The results with this scheme are shown below. THD is less compared to two level scheme is shown in Fig.7.11

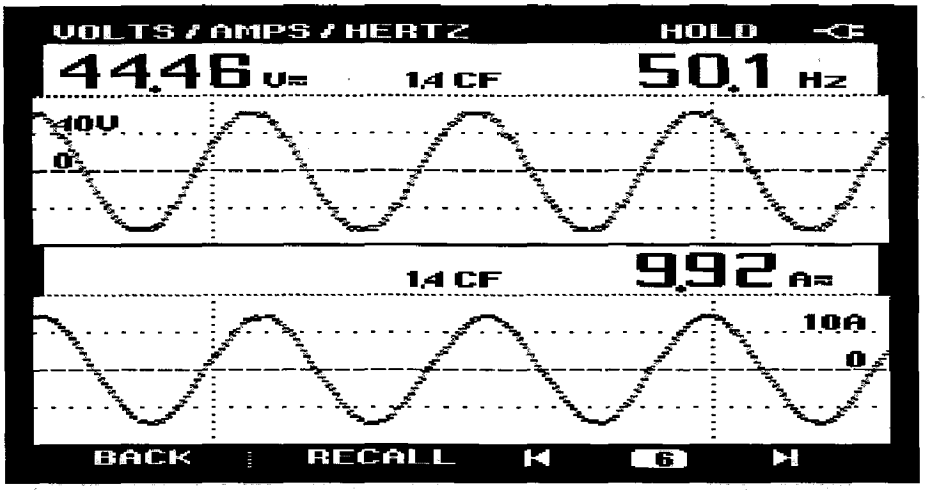


Fig. 7.8 Source voltage & current

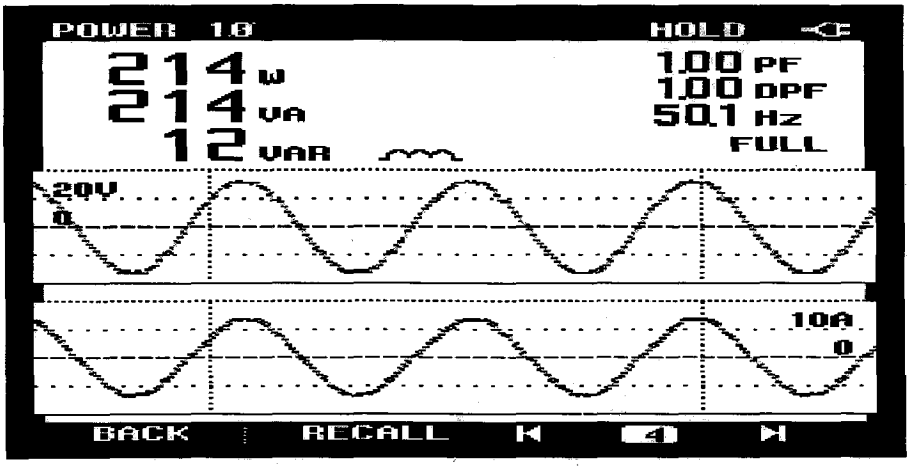


Fig. 7.9 Power Factor of input current

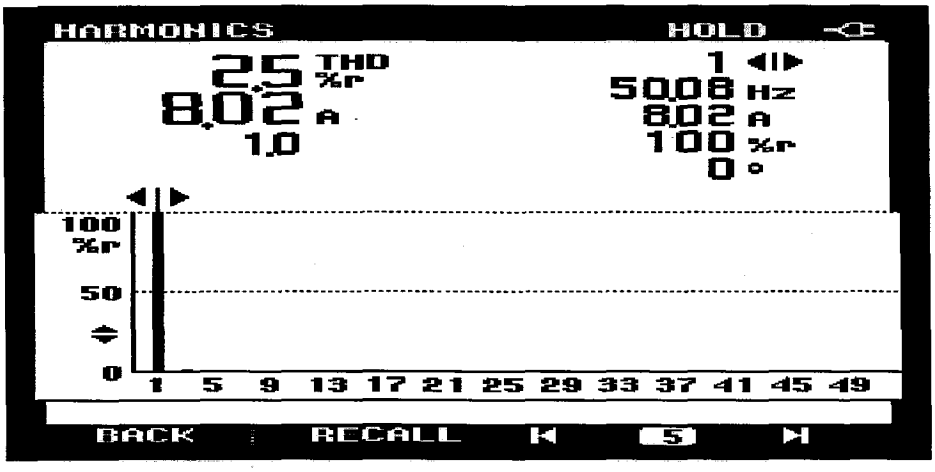


Fig. 7.10 Total Harmonic Distortion of input current

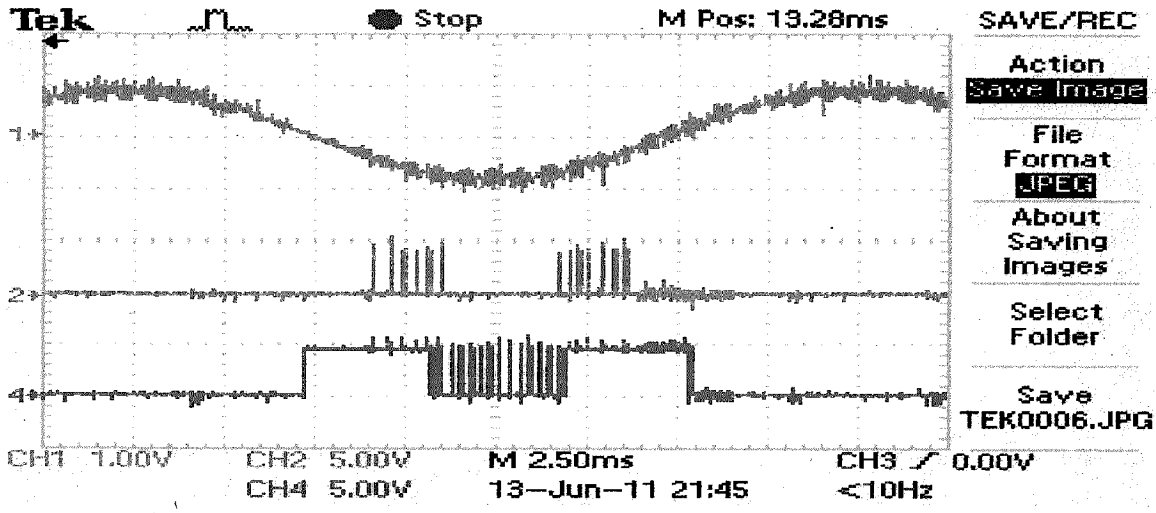


Fig 7.11 Switching pulses for switches T1 and T2

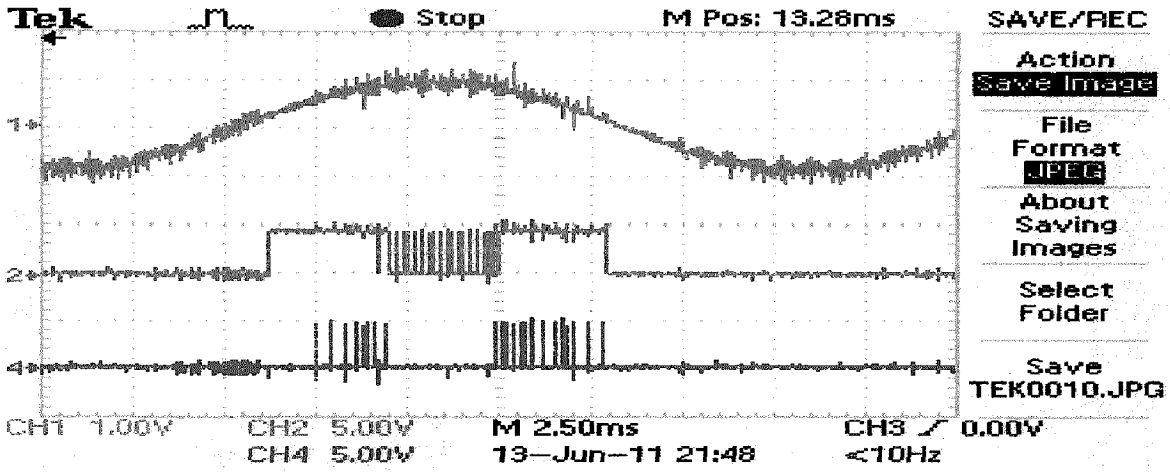


Fig 7.12 Switching pulses for switches T3 and T4

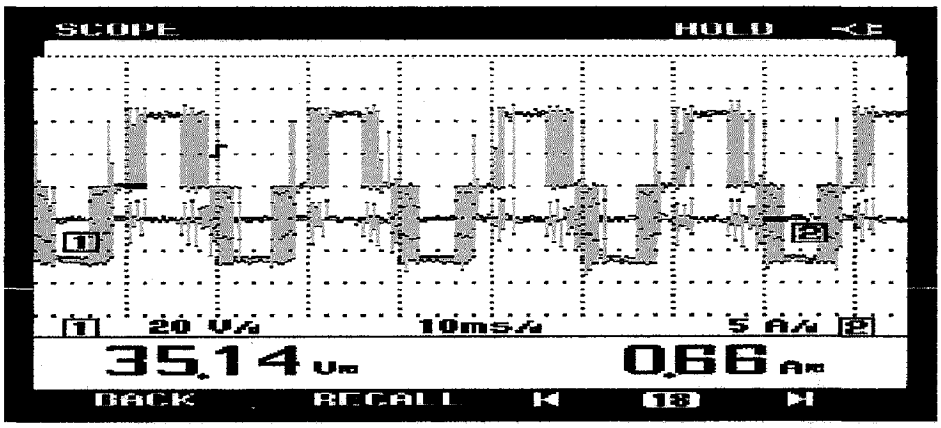


Fig.7.13 Ac side three level voltage

7.1 Conclusion

The hardware results that obtained are similar to the simulated results. The hardware set up is able to decrease the harmonics and THD level of the source current. The THD levels in the source currents are high compared to the simulated values; this is because the unit templates are generated by stepping down the input voltages assuming the voltages to be harmonic free and here no PLL circuit is used, however the voltage contain harmonics and the same harmonics are again replicated in reference current waveform. Hence the THD values are higher than those of simulated values.

CHAPTER 8
CONCLUSIONS AND FUTURE SCOPE

8.1 CONCLUSIONS:

The brief introduction of the power quality issues and their causes has been discussed. The causes of harmonics, sub-harmonics and inter-harmonics on the power systems have been discussed in detail. These harmonics produces in the system by use more no. of non-linear loads like AC-DC converters are discussed. Conventional diode/thyristor rectifiers can pollute AC supply with significant levels of low frequency harmonics, pulsating input current (electromagnetic interference (EMI)), and excessive VAR. with tough regulations and severe economic restraints, the design of Active rectifier which draws nearly sinusoidal current with unity power factor is very important.

Multilevel converter topologies and their use in improving power quality are discussed. These are used for high power applications. Single phase three level converter topologies, simulated results are discussed. Although with increase of levels the power quality improves yet three level converters are commonly used in industrial applications due to complex voltage balance problem associated with five or higher level power converters. Reduced switch count posses several desirable features such as low cost, more reliability, high efficiency and less complexity of control strategy.

In this research work reduced switch single phase neutral point diode clamped rectifier is implemented. The various performance parameters are evaluated like Dc output voltage, input power factor, ripple in the output voltage, and response time with varying load conditions and then the dynamic performance is evaluated by applying changes in load, reference, supply voltage by using simulations. Comparative analysis has been done for various topologies of multilevel converters.

The considered rectifier prototype has been designed and developed. From theoretical and experimental results the system can be not only used to eliminate harmonics but also for balancing the load. And the system is operating at unity power factor with high efficiency. So, the system is cost effective, simple and easy for implementation for eliminating harmonics.

8.2 SCOPE FOR FUTURE WORK:

In this thesis, theoretical and experimental work of single phase neutral point diode clamped rectifier has done and the performance is investigated. There are other techniques such as capacitor clamped topology and H-bridge topology can also be used to implementation of converter. These techniques can also be extended for the three phase converters.

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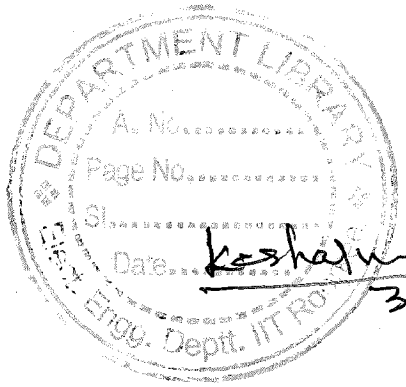

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