PERFORMANCE INVESTIGATIONS OF FUZZY CONTROLLED HIGH POWER FACTOR RECTIFIER

A DISSERTATION

Submitted in partial fulfillment of the requirements for the award of the degree
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MASTER OF TECHNOLOGY
in
ELECTRICAL ENGINEERING
(With Specialization in Power Apparatus and Electric Drives)

By

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CANDIDATE'S DECLARATION

I here by declare that the work which has being presented in the Dissertation Report entitled **"Performance Investigations of Fuzzy Controlled High Power Factor Rectifiers"** in partial fulfillment of the requirements for the award of the degree **Master of Technology in Electrical Engineering** with specialization in **Power Apparatus and Electric Drives**, submitted in the **Department of Electrical Engineering, Indian Institute of Technology, Roorkee, INDIA - 247 667.** This is an authentic record of my own work carried out, under the supervision of **Dr Pramod Agarwal**, Professor and **Shri Y. P. Singh**, Assistant Professor, Department of Electrical Engineering, Indian Institute of Technology, Roorkee, INDIA - 247 667.

The matter embodied in this Dissertation Report has not been submitted by me for the award of any other degree or diploma.

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Date: 30-06-07

Place: ROORKEE

This is to certify that the above statements made by the candidate are correct to the best of my knowledge.

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ABSTRACT

The AC-DC conversion is increasingly used in a wide diversity of applications like power supply for microelectronics, household electric appliances, electronic ballast, battery charging, DC motor drives and power conversion, etc. The conventional line commutated rectifiers pollute the power supply which causes disturbances to other equipment connected to the same supply. They induce current harmonics into the supply resulting low power factor of the load. An extensive research work has been carried out to improve the power quality. The high power factor rectifiers are developed which draw nearly sinusoidal currents at a power factor near to unity. Current research has been focusing in the area of Pulse Width Modulated (PWM) rectifiers.

In the present work, a three phase voltage source PWM rectifier is considered. A new sensor less control scheme, namely Virtual Flux based Direct Power Control (VFDPC), is applied to PWM rectifier. It has the advantages that it provides sinusoidal line current even with distorted supply. A fuzzy controlled VFDPC PWM rectifier is considered and the steady state and dynamic response is illustrated through the simulation study, carried out in the MATLAB/SIMULINK. Also, different hybrid fuzzy control techniques are examined through simulation.

Finally, the experimental prototype of the considered PWM rectifier is developed and MOSFET switching is tested by generating gating pulses from the ICPDAS MATLAB embedded controller.

CONTENTS

CHAPTER 1
INTRODUCTION

1.1 GENERAL

The AC-DC conversion is increasingly used in a wide diversity of applications like power supply for microelectronics, household electric appliances, electronic ballast, battery charging, DC motor drives, power conversion, etc,[1]. Also, in modern industrial environment, need for variable DC is a must. The classical method of obtaining such variable DC is by the use of three phase controlled rectifiers. As power electronic equipments are increasingly being used in power conversion, they deteriorate the power quality in terms of low power factor, increase in harmonic content in the input current, voltage fluctuations and interference in nearby communication networks. Due to problems associated with low power factor and harmonics, utilities will enforce harmonic standards and guidelines which will limit the amount of current distortion allowed into the utility. So, there is a need to achieve good power quality i.e., rectification at close to unity power factor and low input current distortion. The following section will discuss some of the major power quality issues.

1.2 POWER QUALITY ISSUES

Power quality mainly deals with harmonics and their effect, low power factor and total harmonic distortion (THD). Power quality plays a crucial role in the operation of power utilities [1-2].

1.2.1 Harmonics and Their Effect

A harmonic is a sinusoidal component of a periodic waveform having a frequency which is integral multiple of fundamental frequency. Harmonic distortion of the power waveform occurs when fundamental, second, third and other harmonics are combined.

Most electronic equipments do not draw current as a smooth sinusoid. The supply harmonic current causes harmonic voltage to be experienced by other equipment connected to the same supply. As this harmonic voltage can cause disturbance to other systems connected to the same supply, some regulations are imposed on the harmonic content and distortion.

Some practical problems which may arise from excessive harmonic currents are:

- Poor power factor
- Interference to neighboring equipments
- Excessive heating of neutral conductors
- Excessive heating of transformers and associated equipments

1.2.2 IEEE 519 Standards For Regulating Harmonics

Recognizing the problems caused by nonlinear loads, the Institute of Electrical and Electronic Engineers (IEEE) developed IEEE Standard 519 titled, "*IEEE Recommended Practices and Requirements for Harmonic Control in Electrical Power Systems*"[3]. The standard places the responsibility for ensuring power quality on both the utility and the customer. As indicated by the title, IEEE Standard 519 is a "*recommended practice*" i.e., it may be used as a design guideline for new installations.. The standard makes the customer responsible for limiting the harmonic currents injected into the power system and the utility responsible for avoiding unacceptable voltage distortion.

IEEE Standard 519 defines harmonic current limits, shown in Table 1.1 for individual customers at the point of common coupling (PCC). Because voltage distortion is caused by the amount of harmonic currents in the system, larger customers are capable of causing more voltage distortion than smaller ones. Recognizing this, the standard allows a higher current THD for smaller customers' loads. The short circuit ratio (SCR) is used to differentiate customer size. IEEE Standard 519 also provides limits for specific ranges of frequencies, as shown in Table 1.1. Higher-order harmonics are constrained to have lower amplitudes for two reasons. First, higher-order harmonics cause greater voltage distortion than lower-order harmonics, even if they have the same amplitude, because the system inductive reactance is proportional to frequency. Second, interference with telecommunication equipment is more severe for higher-frequency harmonics. Note that Table 1.1 applies only to odd harmonics; even harmonics are limited to 25% of the values for the ranges they would occupy in Table 1.1

Table 1.1 Harmonics allowed by IEEE Standards 519

SCR	$h < 11$	11–15	17–21	23–33	$h > 33$	% THD
<20	4.0	2.0	1.5	0.6	0.3	5.0
20–50	7.0	3.5	2.5	1.0	0.5	8.0
50–100	10.0	4.5	4.0	1.5	0.7	12.0
100–1000	12.0	5.5	5.0	2.0	1.0	15.0
>1000	15.0	7.0	6.0	2.5	1.4	20.0

1.2.3 Power Factor

Harmonics have a negative effect on the power factor. The addition of harmonic currents to the fundamental component increases the total rms current. Because they affect the rms value of the current, power factor of the circuit will be affected. Power Factor, PF, is defined as the ratio of the real power to the apparent power.

$$PF = \frac{P}{V_{rms} I_{rms}} = \cos\theta \text{ (For linear loads)} \qquad (1.1)$$

Power factor can be defined in case of non-linear loads as shown below, which indicates the effect of harmonics.

$$PF = \frac{P}{V_{rms} I_{rms}} = \frac{P}{V_{rms} I_{rms} \sqrt{1 + \left(\frac{\%THD_F}{100} \right)^2}} \qquad (1.2)$$

where *THD* (Total *Harmonic Distortion)* is a measure of closeness in shape between a wave form and its fundamental component, is defined as

THD = r.m.s value of all harmonics considered (typically orders 2 to 50)

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r.m.s value of fundamental

$$THD = \frac{\sqrt{\sum_{h=2}^{\infty} I^2_{hrms}}}{I_{1rms}} \times 100 \tag{1.3}$$

Here I_{1rms} is the rms of the fundamental component and I_{hrms} is the amplitude of the harmonic component of order "h".

$$PF = \frac{P}{V_{rms} I_{rms}} \times \frac{1}{\sqrt{1 + \left(\frac{\%THD}{100}\right)^2}} \tag{1.4}$$

PF, the total power factor in Eq.1.4 is the product of two components, the first of which is called the *displacement power factor*. The second component is the *distortion power factor*, which results from the harmonic components in the current.

The supply power factor is critical for an economical design, efficient and reliable operation of power system.

Some of the disadvantages of low power factor are

- Over heating of the system components.
- It causes poor voltage regulation at the load.
- The power transfer capacity is adversely affected
- The investment in system facilities per KW of load supplied increases with decrease in supply power factor

1.3 EVOLUTION OF HIGH POWER FACTOR RECTIFIERS

Extensive research work is contributed towards the improvement of power quality. Many types of power filter (passive, active and hybrid) designs are proposed. But, research on new generation power converters which are free from pollution on AC side has been given higher priority than the former one. The high power factor rectifier with minimum input current harmonics are being developed. The most recommended high power factor rectifiers are Pulse Width Modulated (PWM) rectifiers. Because of the well known capabilities such as high input power factor, low Total Harmonic Distortion (THD), bidirectional power flow, controlled DC link voltage, PWM rectifiers become more and more popular in the industry applications. One of the important reasons for such a great development in PWM rectifiers is because of self commutating devices like MOSFETs (low power rating), IGBTs (medium power rating) and GTOs (high power rating).

CHAPTER2

HIGH POWER FACTOR RECTIFIERS

2.1 Three Phase PWM rectifiers

In power electronic systems, diode and thyristor rectifiers are commonly applied in the front end of DC-link power converters as an interface with the *AC* line power (grid).But, these rectifiers are nonlinear in nature and consequently inject harmonic currents into the *AC* line power, which create adverse effects on the power distribution system like:

- Low power factor
- Voltage distortion and electromagnetic interface (*EMI*) affecting other users of the power system,
- Increasing volt-ampere ratings of the power system equipment (generators, transformers, transmission lines, etc.).

Therefore, several standards [3](in USA: *IEEE 519* and in Europe: *IEC 61000-3-2*) have introduced important and stringent limits to the harmonics that can be injected into the power supply system by the rectifiers. As a consequence, a great number of new rectifier topologies [4] which are built with gate-turn-off semiconductors have been developed. They are known as Force-commutated rectifiers [5-6].

The gate-turn-off capability allows full control of the converter, because valves can be switched on and off whenever required. This allows commutation of the valves hundreds of times in one period which is not possible with line-commutated rectifiers, where thyristors are switched on and off only once in a cycle. This feature leads to the following advantages:

(a) the current or voltage can be modulated, known as pulse width modulation(PWM), generating less harmonic contamination;

(b) the power factor can be controlled;

(c) rectifiers can be built as voltage or current source types; and

(d) the reversal of power in force commutated rectifiers can be achieved either by reversal of voltage or by reversal of current where as in thyristor rectifiers, it is by the reversal of dc link voltage.

Interest and research towards the PWM rectifiers is increasing. It is because of the following advantages of PWM rectifiers:

- Bi-directional power flow,
- Nearly sinusoidal input current,
- Nearly unity input power factor and low harmonic distortion of line current (*THD* below 5%),
- Adjustment and stabilization of DC-link voltage (or current),
- Reduced capacitor (or inductor) size due to the continuous current.
- Can be properly operated under line voltage distortion and notching, and line voltage frequency variations.

The basic circuit of three phase PWM Voltage Source Rectifier is shown in FIG.2.1. In this topology, power reversal is done by current reversal at the dc link.

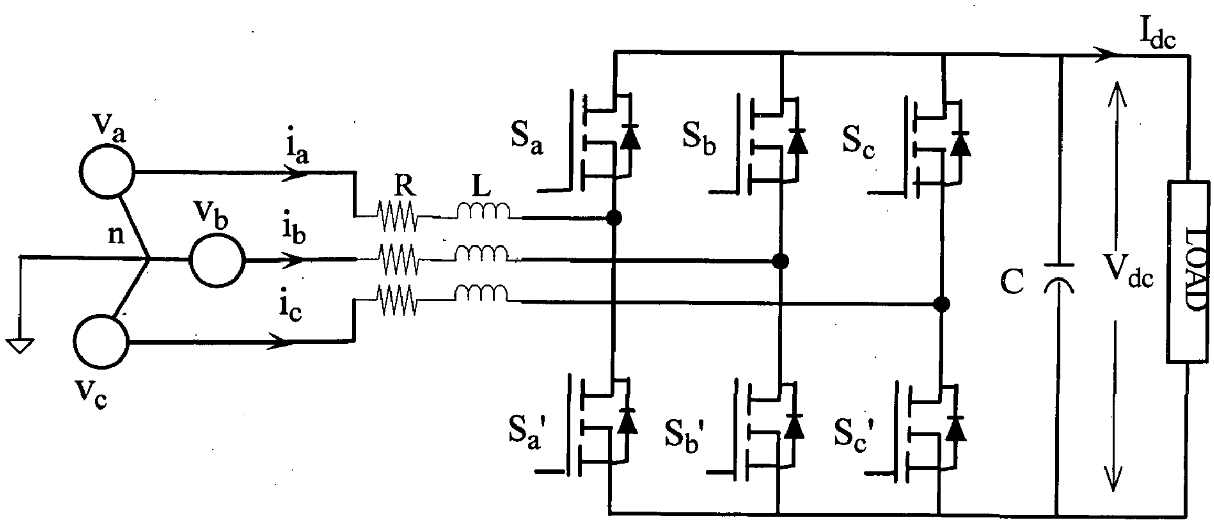


FIG.2.1 Basic circuit of three phase PWM Voltage Source Rectifier

In the area of variable speed AC drives, three-phase PWM Voltage source converter can replace the diode rectifier. The resulting topology consists of two identical bridge PWM converters. The line-side converter operates as rectifier (PWM rectifier) in forward energy flow, and as inverter in reverse energy flow. The AC side voltage of PWM rectifier can be controlled in magnitude and phase in such a way to obtain sinusoidal line current at nearly unity power factor (UPF). Although such a PWM rectifier/inverter (AC/DC/AC) system is expensive, and the control is complex, the topology is ideal for four-quadrant operation. Additional advantages of PWM rectifier are: it provides DC bus voltage stabilization and can also act as Active Line Conditioner (*ALC*) that compensates harmonics and reactive power at the point of common coupling of the distribution network.

2.2 Operation of PWM Rectifier

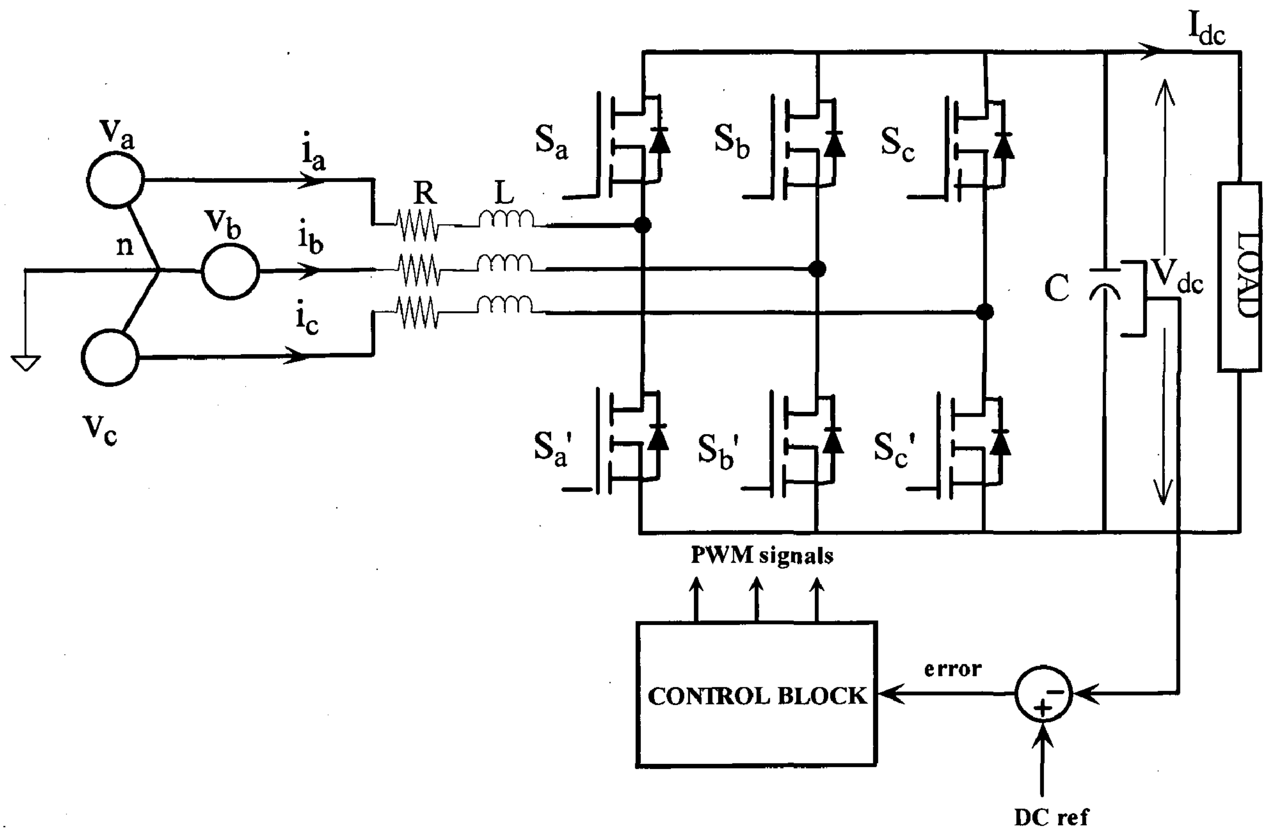


Fig. 2.2 DC link voltage control of Voltage Source PWM Rectifier

The basic operation principle of VSR consists of keeping the load DC link voltage, V_{dc} at a desired reference value, using a feedback control loop as shown in Fig.2.2. Maintaining V_{dcref} at a high value to keep the diodes of the converter blocked, the DC link voltage is measured and compared with the reference V_{dc} ref. The error signal generated is used to switch on and off the six switching devices of the VSR. In accordance with the DC link voltage value, power can be drawn from or sent to the AC source i.e., power flow can be controlled by controlling the DC link voltage V_{dc}, measured at the dc-side capacitor C.

When the DC load current I_{dc} is positive (rectifier operation), the capacitor C is being discharged, and the error signal becomes positive. Under this condition, the Control Block takes power from the supply by generating the appropriate PWM signals for the six power transistors of the VSR. In this way, current flows from the AC to the DC side and the capacitor voltage is recovered. Inversely, when I_{dc} becomes negative (inverter operation), the capacitor C is overcharged, and the error signal initiates the control block to discharge the capacitor returning power to the AC mains.

PWM consists of switching the valves on and off, following a pre-established template. This template could be a sinusoidal waveform of voltage or current. The PWM control not only can manage the active power, but also the reactive power, allowing the VSR to correct power factor. Besides, the AC current waveforms can be maintained almost sinusoidal, reducing harmonic contamination to the mains supply.

2.3 Model of Three Phase PWM Rectifier in Stationary α-β coordinates

Fig. 2.3 shows a single-phase representation of the PWM rectifier circuit presented in Fig. 2.1[7]. V_L is the line voltage and V_S is the bridge converter voltage controllable from the DC-side.

Applying KVL, the voltage equation can be written as

$$\overline{v_L} = \overline{v_S} + \overline{v_I} \tag{2.1}$$

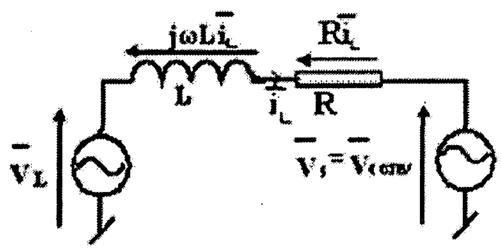


Fig.2.3 Single phase representation of three phase PWM rectifier

$$\overline{v_L} = R\overline{i_L} + \frac{d\overline{i_L}}{dt}L + \overline{v_s} \tag{2.2}$$

The voltage and current equations in a-b-c coordinates can be represented as:

$$\begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} = R\begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + L\frac{d}{dt}\begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} v_{sa} \\ v_{sb} \\ v_{sc} \end{bmatrix} \tag{2.3}$$

$$C\frac{dV_{dc}}{dt} = S_a i_a + S_b i_b + S_c i_c - I_{dc} \tag{2.4}$$

Applying transformation to eqns 2.3 and 2.4, the voltage and current equations can be represented in stationary **α-β** coordinates as:

$$\begin{bmatrix} v_{L\alpha} \\ v_{L\beta} \end{bmatrix} = R\begin{bmatrix} i_{L\alpha} \\ i_{L\beta} \end{bmatrix} + L\frac{d}{dt}\begin{bmatrix} i_{L\alpha} \\ i_{L\beta} \end{bmatrix} + \begin{bmatrix} v_{s\alpha} \\ v_{s\beta} \end{bmatrix} \tag{2.5}$$

$$C\frac{dV_{dc}}{dt} = i_{L\alpha}S_\alpha + i_{L\beta}S_\beta - I_{dc} \tag{2.6}$$

Where

$$S_\alpha = \sqrt{2/3}\left(S_a - 1/2\left(S_b + S_c\right)\right) \tag{2.7}$$

$$S_\beta = 1/\sqrt{2}\left(S_b - S_c\right)$$

Fig 2.4 shows block diagram representation of PWM rectifier in α-β coordinates.

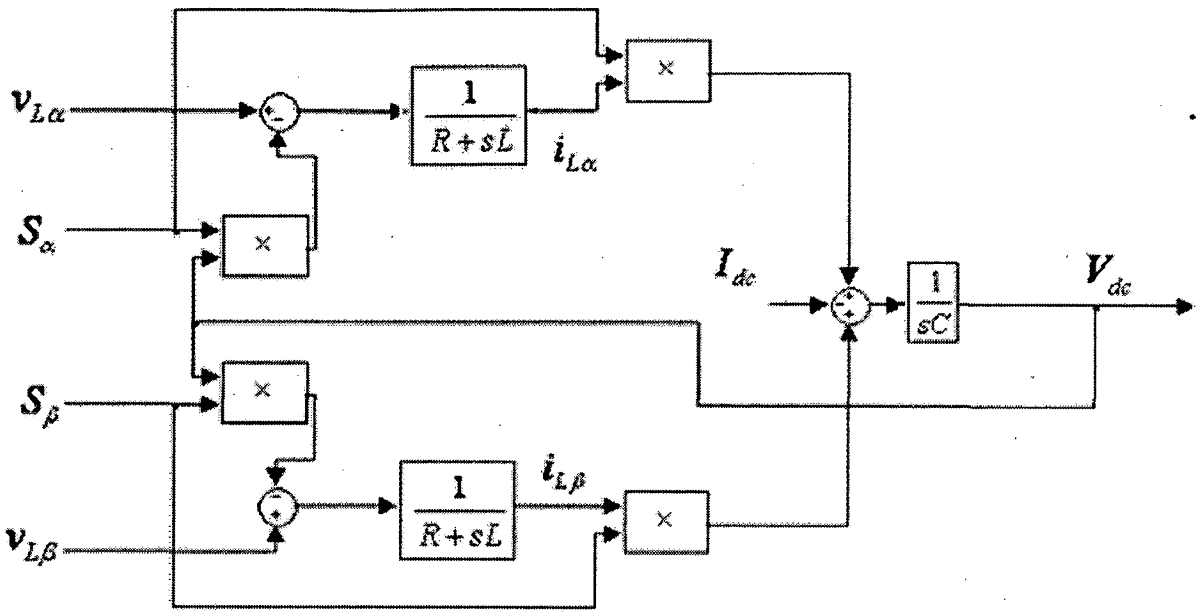


FIG.2.4 PWM rectifier represented in α-β coordinates

2.4 Steady State Properties

For proper operation of PWM rectifier, a minimum DC-link voltage is required. Generally it can be determined by the peak value of line-to-line supply voltage [7].

$$V_{dc\min} > \sqrt{3} * \sqrt{2} V_{LN} \tag{2.8}$$

i.e., $> 2.45 V_{LN}$

The inductor has to be designed carefully because low inductance will give a high current ripple and will make the design more depending on the line impedance. The high value of inductance will give a low current ripple, but simultaneously reduce the operation range of the rectifier. The voltage drop across the inductance has influence for the line current. This voltage drop is controlled by the input voltage of the PWM rectifier but maximal value is limited by the DC-link voltage. Consequently, a high current (high power) through the inductance requires either a high DC-link voltage or a low inductance (low impedance).

2.5 Applications

The advantages of PWM rectifiers make them better choice over line-commutated rectifiers for industrial applications. They permit new applications such as

- active filters, power factor compensators;
- four-quadrant operation of machine drives;
- frequency links to connect 50-Hz with 60-Hz systems;
- regenerative converters for traction applications and battery powered vehicles;
- Wind power generation.

One of the most important applications of Voltage source PWM rectifier is in machine drives. A rectifier- inverter link uses PWM VSR. The rectifier side controls the input current and the DC link voltage, and the inverter side controls the machine, which can be a synchronous, brushless DC, or an induction machine. The reversal of speed and power are possible with this topology. At the rectifier side, the power factor can be controlled. The inverter will become a rectifier during regenerative braking, which is possible by making slip negative (in an induction machine) or by making torque angle negative (in synchronous and brushless DC machines)

CHAPTER3

VIRTUAL FLUX BASED DIRECT POWER CONTROL

3.1 Introduction

Generally, the control variables of any AC-DC converter are DC link voltage and supply line current. DC link voltage control is needed to maintain constant DC voltage at the output of the converter. Input current control is required to achieve nearly unity power factor, lower harmonic content and for over current protection. To achieve the above mentioned requirements, two control loops are required, inner for current control and outer for regulating DC link Voltage. Two control loops make the system complex and bulky. This makes the evolution of Direct Power Control where the control scheme uses power as the control variable, rather than the line current or DC link voltage [8-9]. With single loop, both voltage and current can be controlled and the system becomes simple, reliable and cost effective.

PWM rectifier needs three kinds of sensors for measuring AC voltages, AC currents and DC voltage [7, 10-11].

- A DC voltage sensor is needed for DC link voltage feed back control
- Two AC voltage sensors are needed to detect phase angle of the supply voltage which is required for power factor control and
- Two AC current sensors are required for input current control as well as for over current protection.

Using all these sensors, the system becomes bulky and expensive. The signal sensed is also subjected to noise and incidental missing of the signal may make the system less reliable. Reducing the cost of the PWM rectifier is vital for compactness compared to other front-end rectifiers. The cost of power switching devices (e.g. IGBT) and digital signal processors (DSPs) are generally decreasing and further reduction can be obtained by reducing the number of sensors. Also, sensorless control exhibits advantages such as improved reliability and lower installation costs.

It is possible to replace the AC line voltage sensors with a line voltage estimator.

An important requirement for a voltage estimator is to estimate the voltage correctly and pre-existing harmonic voltage distortion under unbalanced conditions. Along with the fundamental component, the harmonic components and the voltage unbalance must be estimated so that it gives a higher power factor. It is possible to calculate the voltage across the inductance by the differentiating current. The line voltage can then be estimated by adding reference of the rectifier input voltage to the calculated voltage drop across the inductor. However, this approach has the disadvantage that when the current is differentiated, noise in the current signal is gained through the differentiation. To avoid this, Ac input voltages are extracted from the calculation of instantaneous active and reactive power according to each switching state of the PWM rectifier.

Various sensorless control strategies have been proposed in recent work on the PWM rectifier. The control techniques for PWM rectifier can be generally classified as voltage based and virtual flux based, as shown in Fig. 3.1 [11-12]

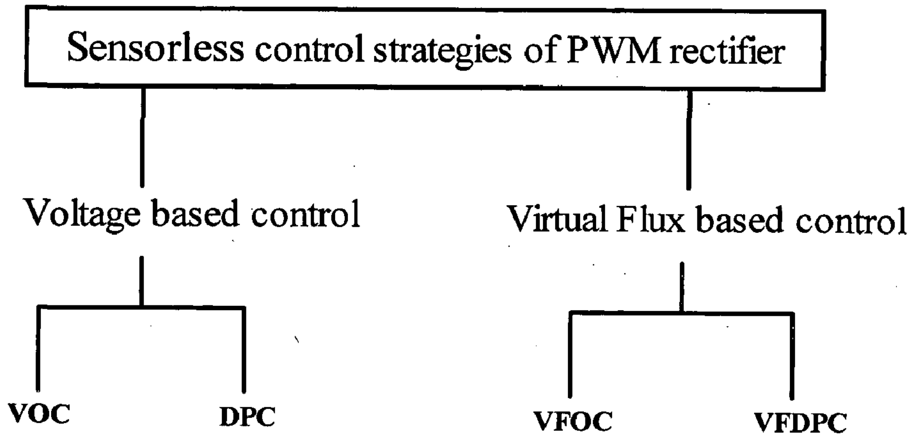


Fig 3.1 Classification of control strategies for PWM rectifier

A well-known method of indirect active and reactive power control, based on current vector orientation with respect to the line voltage vector is **voltage-oriented control (VOC)**. Although VOC guarantees high dynamics and static performance via internal current control loops, it has the disadvantage that the final configuration and performance of the VOC system largely depends on the quality of the applied current control strategy. Another known method based on instantaneous direct active and reactive power control is

Direct Power Control (DPC) [13-19]. The main idea of DPC is correct and fast estimation of the active and reactive line power. Both the methods mentioned above give high power factor and low harmonic distortion.

But, when the input supply is distorted, they can not produce sinusoidal input current and high power factor. Only a DPC strategy based on virtual flux instead of the line voltage vector orientation, called **VF-DPC**, provides sinusoidal line current and lower harmonic distortion.

3.2 Virtual Flux based Direct Power Control:

This method [7, 15-18] uses an estimated Virtual flux (VF) vector instead of the line voltage vector in the control. Consequently, voltage sensorless line power estimation is much less noisy because of the natural low-pass behavior of the integrator used in the calculation algorithm. Also, differentiation of the line current is avoided in this scheme. Therefore, the use of the virtual flux (VF) signal for power estimation leads to the following advantages of the VF-DPC.

- Lower sampling frequency compared to DPC
- Simple algorithm and easy implementation
- When compared to the VOC, no current control loops, coordinate transformation and separate PWM voltage modulator are required.
- Provides sinusoidal line current and low THD under distorted supply

It is possible to replace the ac-line voltage sensors with a virtual flux estimator, which provides simplification, isolation between the power circuit and control system, reliability, and cost effectiveness.

Virtual flux

The line voltages and the ac-side resistors and inductors are assumed to be quantities related to a virtual ac motor as shown in Fig. 3.2. Therefore, resistance and inductance of reactors, **R** and **L** respectively, represent the stator resistance and the stator leakage inductance of the virtual motor. Virtual flux can be estimated by integrating the line-to-line voltages $\mathbf{V}_{ab}$, $\mathbf{V}_{bc}$, $\mathbf{V}_{ca}$ which would be induced by a virtual air-gap flux.

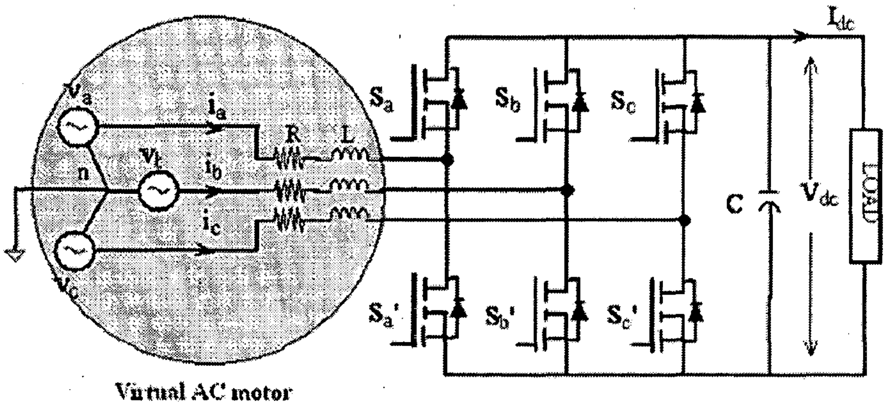


FIG 3.2 Three phase PWM rectifier system with ac side presented as virtual ac motor

3.3 Block Control Scheme

The main idea of Virtual Flux based Direct Power Control of PWM rectifier is to control the instantaneous power estimated based on Virtual Flux. The block diagram of whole control scheme is shown in FIG.3.3.

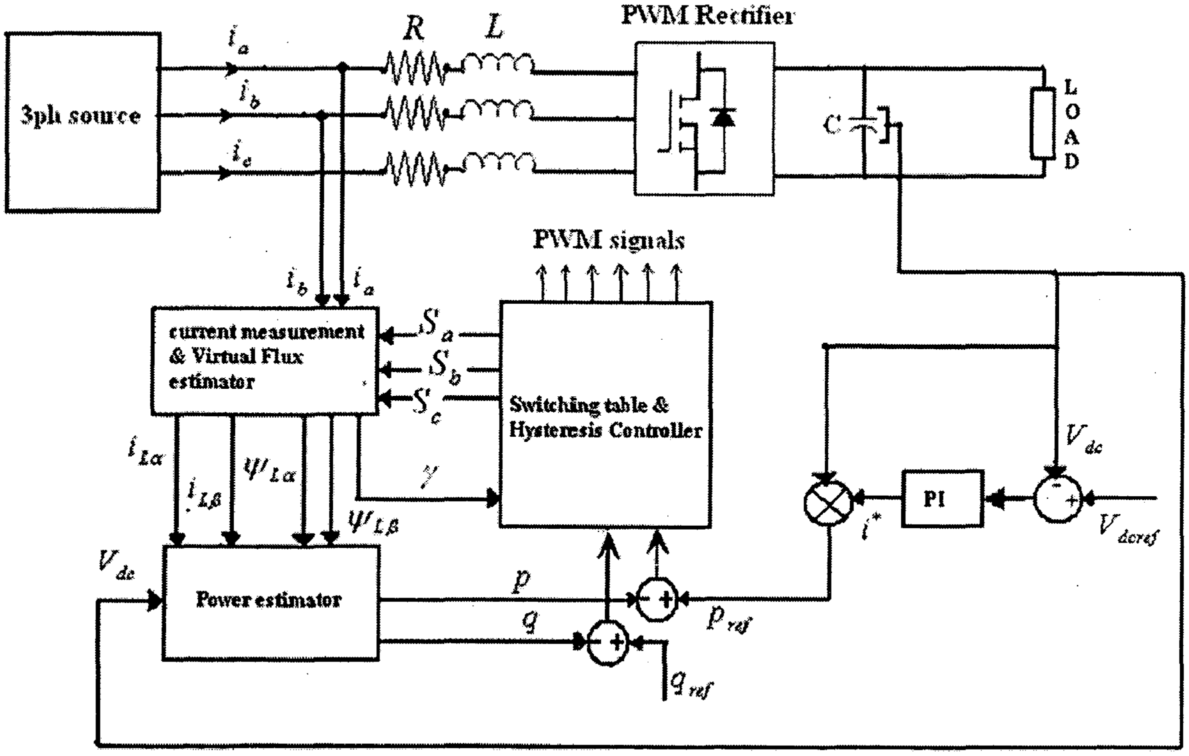


FIG.3.3 Block diagram of Virtual Flux based Direct Power Control

The control scheme involves the following major blocks.

1. PWM rectifier
2. Current measurement and Virtual Flux Estimator
3. Power estimator
4. Sector selection
5. Switching table

The dc link voltage of three phase PWM rectifier is measured and an error is generated comparing it with the reference dc value. A PI controller is used to generate controlled value of current in accordance with the error and then active power reference, p_{ref} is obtained by multiplying this with output DC voltage. Reactive power reference, q_{ref} is set to zero for unity power factor. Error between reference power and estimated power (output of Power estimator) are digitized to d_p and d_q by hysteresis controllers as

$$d_p = 1 \; for \; p < p_{ref} - H_p \tag{3.1a}$$

$$d_p = 0 \; for \; p > p_{ref} + H_p \tag{3.1b}$$

$$d_q = 1 \; for \; q < q_{ref} - H_q \tag{3.2a}$$

$$d_q = 0 \; for \; q > q_{ref} + H_q \tag{3.2b}$$

where H_q & H_p are the hysteresis bands.

Sector selection block identifies the sector corresponding to the phase angle of the Virtual Flux vector which is obtained from Virtual Flux estimator. The three signals n, d_p and d_q are inputs to Switching table and according to the combination of these inputs, optimal switching states S_a, S_b and S_c are given to the converter.

Current measurement and Virtual flux estimator block measures line currents I_a and I_b and transforms them into □-□ reference frame as $I_□$ and $I_□$. Also, it calculates Flux vector using the optimum switching states S_a, S_b and S_c and measured DC voltage. Using currents $I_□$, $I_□$ and estimated Flux vector ,instantaneous active and reactive power are estimated in the Power Estimator block.

This is the overall idea how Direct Power Control takes place by estimating the

Virtual Flux which in turn reduces the number sensors and makes system simple, reliable and cost effective.

An in depth details of each control block are given below.

The block diagram of the three phase Voltage source PWM rectifier is shown in FIG.3.4

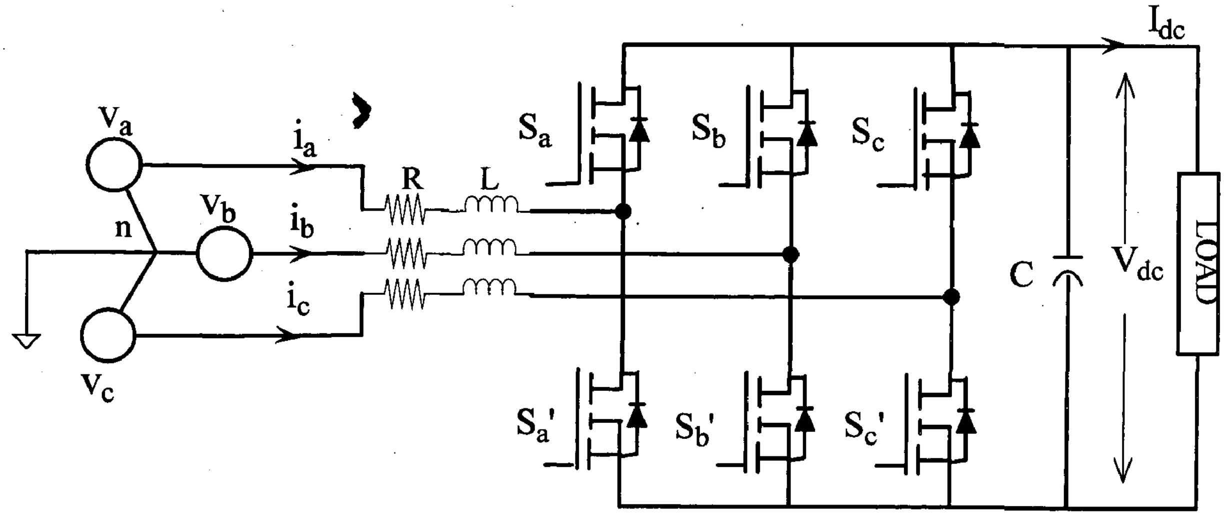


FIG.3.4 Block diagram of three phase Voltage source PWM rectifier

3.4 Current measurement & Virtual Flux estimator

The current measurement block measures input line currents I_a and I_b and transforms them to □-□ coordinates using the eqn 3.3, given below.

$$\overline{i_L} = \begin{bmatrix} i_{L\alpha} \\ i_{L\beta} \end{bmatrix} = \sqrt{2/3}\begin{bmatrix} 3/2 & 0 \\ \sqrt{3/2} & \sqrt{3} \end{bmatrix}\begin{bmatrix} i_a \\ i_b \end{bmatrix} \tag{3.3}$$

The Virtual Flux estimator estimates Virtual Flux (VF) vector $\overline{\Psi_L}$ in stationary α-β coordinates by integrating line- to-line voltages V_{ab}, V_{bc} and V_{ca} using the eqn.3.5

$$\overline{\psi_L} = \begin{bmatrix} \psi_{L\alpha} \\ \psi_{L\beta} \end{bmatrix} = \begin{bmatrix} \int V_{L\alpha} dt \\ \int V_{L\beta} dt \end{bmatrix} \tag{3.4}$$

where

$$\overline{v_L} = \begin{bmatrix} V_{L\alpha} \\ V_{L\beta} \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & \frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} V_{ab} \\ V_{bc} \end{bmatrix} \tag{3.5}$$

Based on the assumption that the line current i_L is controlled by the voltage drop across the inductor L interconnecting two voltage sources (line and rectifier), the line voltage v_L can be expressed as:

$$\overline{v_L} = \overline{v_S} + \overline{v_I} \tag{3.6a}$$

Similar to this, VF equation can be presented as:

$$\overline{\psi_L} = \overline{\psi_S} + \overline{\psi_I} \tag{3.6b}$$

Based on the measured dc link voltage V_{dc} and optimum switching states S_a, S_b and S_c, the virtual flux $\overline{\psi_L}$ components in stationary (α-β) coordinates system can be estimated as

$$\psi_{L\alpha(est)} = \int \left(V_{s\alpha} + L \frac{di_{L\alpha}}{dt} \right) dt \tag{3.7a}$$

$$\psi_{L\beta(est)} = \int \left(V_{s\beta} + L \frac{di_{\beta}}{dt} \right) dt \tag{3.7b}$$

Where,

$$V_{S\alpha} = \sqrt{\frac{2}{3}} V_{dc} \left(S_a - \frac{1}{2}(S_b + S_c) \right) \tag{3.8a}$$

$$V_{S\beta} = \frac{1}{\sqrt{2}} V_{dc} (S_b - S_c) \tag{3.8b}$$

Phase angle of the flux vector is calculated as

$$\gamma = \arctan\left(\psi_{L\beta} / \psi_{L\alpha}\right)$$

The block diagram of the current measurement and Virtual flux estimator is given in FIG.3.5

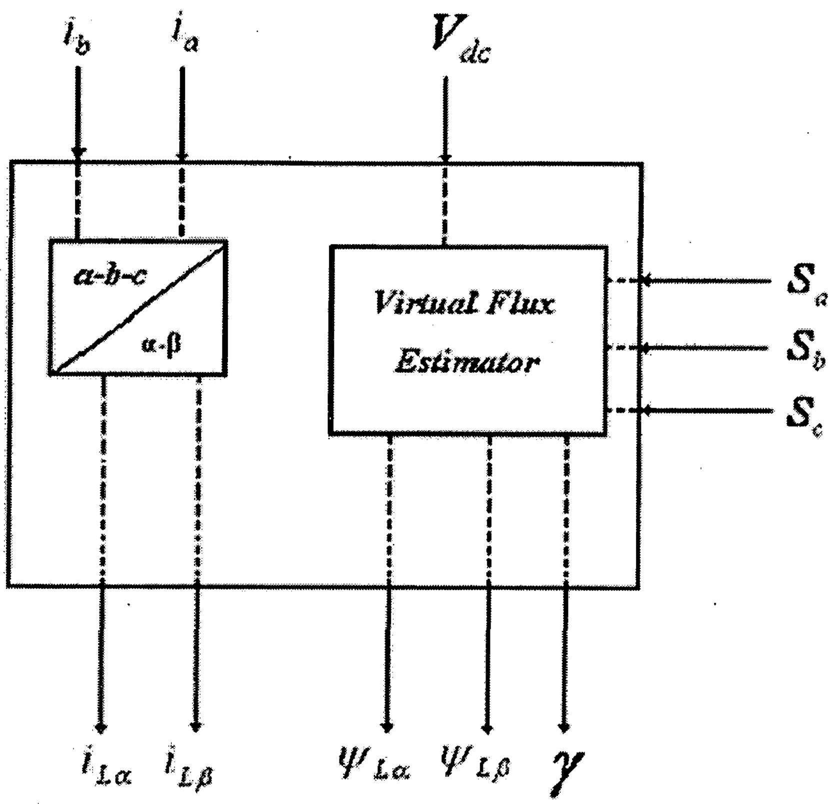


FIG.3.5 Block diagram of current measurement & Virtual Flux estimator

3.5 Power Estimator

Instantaneous power can be estimated using the currents i□, i□ and the estimated virtual flux components □L□, □L□, The voltage Eqn.3.9 can be written as

$$\overline{v_L} = L\frac{d\overline{i_L}}{dt} + \frac{d}{dt}\overline{\psi_S} = L\frac{d\overline{i_L}}{dt} + \overline{u_S} \qquad (3.9)$$

The instantaneous power can be calculated as

$$p = \text{Re}(\overline{v_L}.\overline{i_L}^*) \qquad (3.10)$$

$$q = \mathrm{Im}(\overline{v_L}.\overline{i_L}^*) \qquad (3.11)$$

where * denotes conjugate of the line current vector. The line voltage can be expressed in terms of Virtual Flux as

$$\overline{v_L} = \frac{d\overline{\psi_L}}{dt} = \frac{d}{dt}(\psi_L e^{j\omega t}) = \frac{d\psi_L}{dt}e^{j\omega t} + j\omega\psi_L e^{j\omega t}$$

$$= \frac{d\psi_L}{dt}e^{j\omega t} + j\omega\overline{\psi_L} \qquad (3.12)$$

$$\overline{v_L} = \frac{d\psi_L}{dt}\Big|_\alpha + j\frac{d\psi_L}{dt}\Big|_\beta + j\omega(\psi_{L\alpha} + j\psi_{L\beta}) \qquad (3.13)$$

$$\overline{v_L}.\overline{i_L}^* = \left\{\frac{d\psi_L}{dt}\Big|_\alpha + j\frac{d\psi_L}{dt}\Big|_\beta + j\omega(\psi_{L\alpha} + j\psi_{L\beta})\right\}(i_{L\alpha} - ji_{L\beta}) \qquad (3.14)$$

where $\overline{\psi_L}$ denotes the space vector and ψ_L is its amplitude. From Eqns.3.10 and 3.11 active and reactive powers can be written as given below.

$$p = \left\{\frac{d\psi_L}{dt}\Big|_\alpha i_{L\alpha} + \frac{d\psi_L}{dt}\Big|_\beta i_{L\beta} + \omega.(\psi_{L\alpha}i_{L\beta} - \psi_{L\beta}i_{L\alpha})\right\} \qquad (3.15)$$

$$q = \left\{-\frac{d\psi_L}{dt}\Big|_\alpha i_{L\beta} + \frac{d\psi_L}{dt}\Big|_\beta i_{L\alpha} + \omega.(\psi_{L\alpha}i_{L\alpha} + \psi_{L\beta}i_{L\beta})\right\} \qquad (3.16)$$

For sinusoidal and balanced supply, the derivatives of the flux amplitudes are zero. Therefore, the instantaneous active and reactive powers can be computed as

$$p = \omega.(\psi_{L\alpha}i_{L\beta} - \psi_{L\beta}i_{L\alpha}) \qquad (3.17)$$

$$q = \omega.(\psi_{L\alpha}i_{L\alpha} + \psi_{L\beta}i_{L\beta}) \qquad (3.18)$$

The diagrammatic representation of Power estimation is shown in FIG 3.6

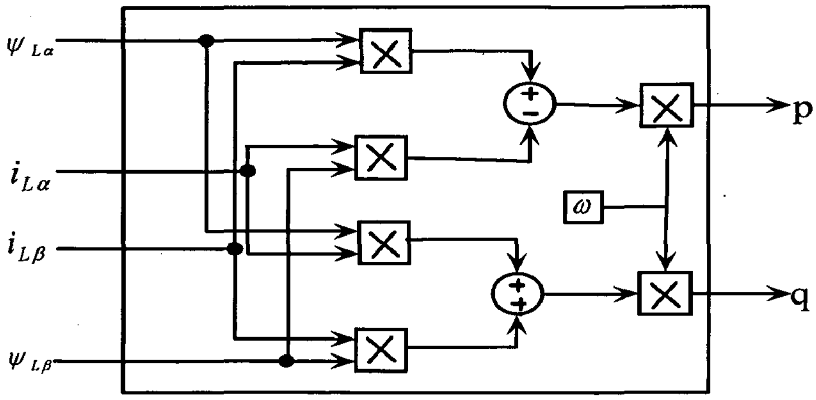


Fig 3.6 Instantaneous Power Estimator based on Virtual Flux

3.6 Sector Selection

In order to track the instantaneous power reference, sector division method is used. Since the instantaneous power is adjusted by controlling the magnitude and phase angle of the Flux vector, it is found that sector division method is more effective in case of instantaneous power control. Input to the Sector selection block is phase angle of Virtual flux vector and it identifies the sector corresponding to this phase angle as given below.

The stationary coordinates are divided into twelve sectors as shown in FIG.3.7.

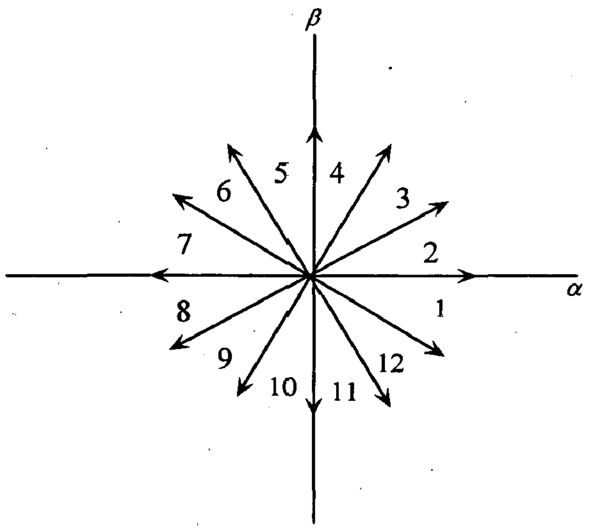


FIG.3.7 Sector Division of stationary coordinates

The phase angle of the Flux vector is digitized using the Eqn. 3.19.

$$(n-2)\pi/6 \le \gamma_n < (n-1)\pi/6 \qquad (3.19)$$

$$n=1, 2, 3, \ldots\ldots\ldots, 12$$

3.7 Switching Table

The digitized signals d_p, d_q, corresponding to the errors between reference and instantaneous powers, and sector n are inputs to the switching table (shown in Table-I.). By using this switching table, the optimum switching state, S_a, S_b and S_c of the converter is selected according to the combination of inputs. The selection of optimum switching state is performed so that the power errors can be restricted within the hysteresis bands.

Table-I Switching Table

S_p	S_q	1	2	3	4	5	6	7	8	9	10	11	12
1	0	101	101	100	100	110	110	010	010	011	011	001	001
1	1	110	111	010	000	011	111	001	000	101	111	100	000
0	0	101	100	100	110	110	010	010	011	011	001	001	101
0	1	100	110	110	010	010	011	011	001	001	101	101	100

3.8 Simulink Model of Virtual Flux based Direct Power control of PWM rectifier

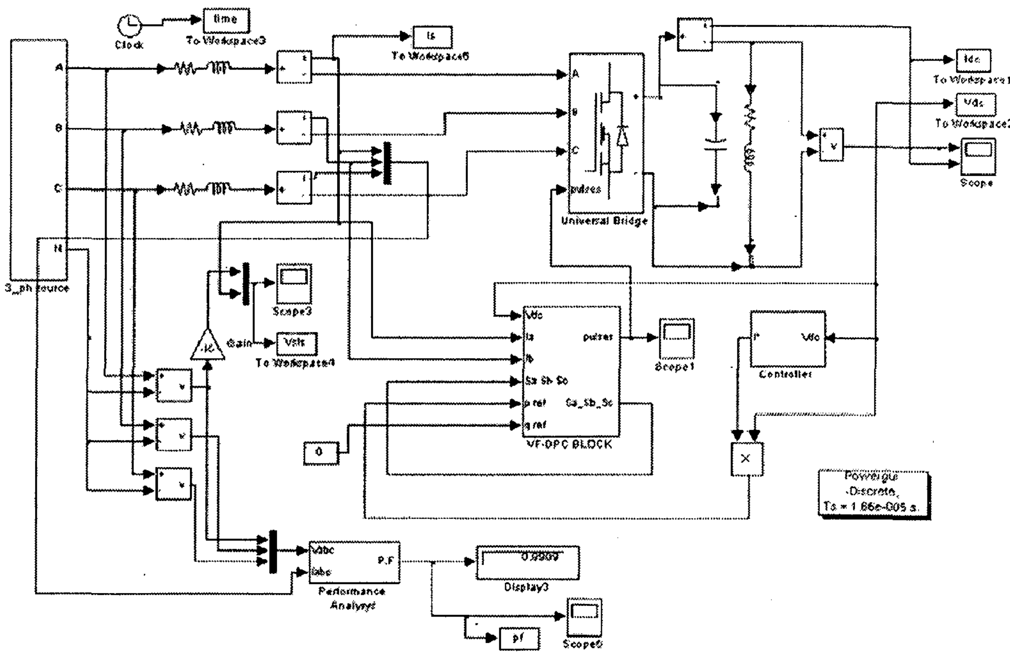


FIG.3.8 Simulink model of VFDPC PWM rectifier

CHAPTER4
FUZZY CONTROLLED HIGH POWER FACTOR RECTIFIERS

4.1 Introduction

Most of the industrial applications are complex and non linear systems. They require precise and robust control even under disturbances. But, conventional controllers like Proportional, PI and PID may not produce satisfactory results under these conditions [20]. Also, they require accurate mathematical model of the system to be controlled. It is very difficult to find out accurate mathematical model for modern industrial applications. Recently, fuzzy logic controllers (FLCs) have generated a good deal of interest in certain applications. They are increasingly finding acceptance in industry due to their proven performance in the control of complex non-linear systems. These controllers have been producing promising results in power electronics and drives control.

The advantages of FLCs over the conventional controllers are as follows:

1) it does not need accurate mathematical model;

2)it can work with imprecise inputs;

3) it can handle nonlinearity and

4) it is more robust than conventional nonlinear controllers.

So far, FLCs in power electronics have been designed by trial and error. Power converters are inherently nonlinear because they include a saturating inductances, semiconductor devices etc. With the advances in power electronics, power converters are getting complicated, resulting in complex mathematical models. The FLC seems to be a viable controller for power electronic applications which can assure good results.

4.2 Fundamentals of Fuzzy Logic Control

The concept of Fuzzy Logic (FL) was conceived by Lotfi Zadeh, a professor at the University of California at Berkeley. Fuzzy logic is a problem solving control system methodology that lends itself to implementation in system ranging from simple embedded microcontrollers to large networked multi channel PC or workstation based data acquisition and control systems. It can be implemented in hardware, software, or a combination of both. Fuzzy logic (FL) provides a simple way to arrive at a definite conclusion based upon vague, ambiguous, imprecise, noisy or missing input information. FL's approach to control problems mimics how a person would make decisions much faster.

FL incorporates a simple rule based, IF X AND Y, THEN Z approach to solve control problem rather than attempting to model a system mathematically. The FL model is empirically based, relying on an operator's experience rather than their technical understanding of the system. FL is capable of mimicking this type of behavior but at a higher rate.

FL requires some numerical parameters in order to operate such as what is considered significant error and significant rate of change of error. But exact values of these numbers are usually not critical unless very responsive performance is required in which case empirical tuning would determine them. It is very robust and forgiving of operator and data input and often works when first implemented with little or no tuning.

FL offers several unique features that make it a particularly good choice for many control problems.

- It is inherently robust since it doesn't require precise, noise free inputs and can be programmed to fail safely if a feedback sensor quits or is destroyed. The output control is smooth control function despite a wide range of input variations.
- Since the FL controller processes user defined rules governing the target control system, it can be modified and tweaked easily to improve or drastically alter system performance. New sensors can easily be incorporated into the system simply by generating appropriate governing rules.
- FL is not limited to a few feedback inputs and one or two control outputs, nor it is necessary to measure or compute rate of change parameters in order for it to be implemented. Any sensor data that provides some indication of a system's actions and reactions is sufficient. This allows the sensors to be inexpensive and imprecise, thus keeping the overall system cost and complexity low.

- Because of the rule-based operation, any reasonable number of inputs can be processed and numerous outputs can be generated. Although defining the rule base quickly becomes complex if too many inputs and outputs are chosen for a single implementation, since rules defining their interrelations must also be defined. It would be better to break the control system into smaller chunks and use several smaller FL controllers distributed on the system, each with more limited responsibilities.
- FL can control nonlinear systems that would be difficult or impossible to model mathematically. This opens doors for control systems that would normally be deemed unfeasible for automation.

4.3 Fuzzy Logic Control Structure

Basic structure of fuzzy logic controller is shown in FIG.4.1 [20-22].

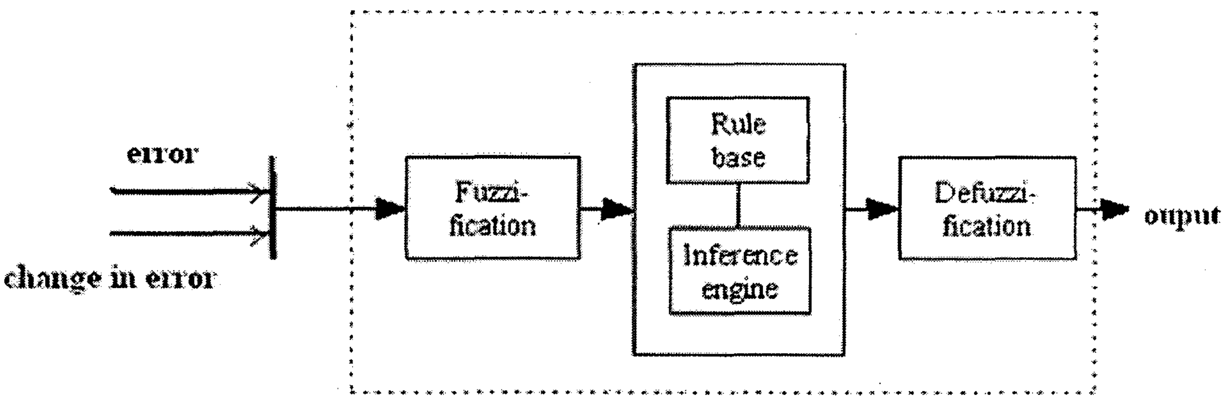


FIG.4.1 The basic structure of Fuzzy Logic Controller

The input to the fuzzy logic controller is error and change in error. A reference input is compared with the regulated output to produce an error. These two inputs are normalized to obtain error e(k) and change in error Δe(k) in the desired range of -1 to 1. FLC performs some functional steps to generate output.

$$\Delta e(k) = e(k) - e(k-1)$$

The functional steps in FLC are:

1) Fuzzification;
2) Rule base
3) Decision making; and
4) Defuzzification.

Fuzzification

Fuzzy logic uses linguistic variables instead of numerical variables. In real world, ensured quantities are real numbers (crisp). The process of converting a numerical variable (real number) into a linguistic variable (fuzzy number) is called fuzzification. For a given crisp input, the fuzzification finds the degree of membership in the universe of discourse 'U' chosen in the interval of -1 to 1 namely PB, PM, PS, ZE, NS, NM, NB on the basis of normalized inputs of error and change in error.

Rulebase

While the differential equations are the language of conventional control, IF-THEN rules about how to control the system are the language of fuzzy control. An IF-THEN operator is the simplest and most widely used interpretation which provides computational efficiency. Fuzzy rules serve to describe the quantitative relationship between variables in linguistic terms. Instead of developing a mathematical model of a system, a knowledge based system is implemented. The number of rules in the controller depends on the total number of linguistic variables. The rule base of a fuzzy system with m-input variables has p^m rules, where p is the number of linguistic terms per input variable. As the dimension and complexity of a system increase, the size of the rule base increases exponentially. Generally, the rules for the present problem are structured as

If ERROR is X and CHANGE IN ERROR is Y then OUTPUT is Z

Decision making

It is the decision-making logic, which is the kernel of FLC. It has the capability of simulating human decision making based on fuzzy control actions employing fuzzy implication and the rules of inference in Fuzzy logic. Conventional controllers have control gains or control laws which are combination of numerical values. In FLC, the equivalent terms are the rules which are linguistic in nature. In accordance with the linguistic rules and the linguistic values of the inputs for the fuzzifier, the linguistic value of the output is computed. The first two linguistic values are associated with the input variables e(k) and $\Delta e(k)$, while the third linguistic value is associated with the output.

Defuzzification

The process of transforming the fuzzy output of a fuzzy inference system into a crisp value is called defuzzification. The rules of FLC produce required output in a linguistic variable. According to real world requirements, linguistic variables are to be transformed to crisp output. The input for the defuzzification process is a fuzzy set (the aggregate output fuzzy set) and the output is a single number crispness recovered from the fuzziness.

There are various defuzzification methods like Center of area method (COA), Height method (HM), Mean of Maxima (MOM), Bisector of Area method (BOA) available and depending on control system, suitable method is choosen.

4.4 Fuzzy Controlled PWM Rectifier

In this work, a Fuzzy logic control based Virtual Flux based Direct Power Controlled three phase PWM rectifier is implemented in MATLAB environment using SIMULINK. With Fuzzy Logic Tool Box, Fuzzy Logic controller is designed [22-25].

The disadvantages of conventional PI controller, applied to PWM rectifiers, are overshoot or undershoot, increased rise time and settling time, poor results under parameter variation, nonlinearities and load disturbance. Under circumstances, Fuzzy logic controller is proven to be suitable choice for PWM rectifiers and for drive applications.

In the Virtual Flux based Direct Power Control applied to three phase PWM rectifier (shown in FIG.3.3), conventional PI controller can be replaced by a Fuzzy Controller as shown in FIG.4.2

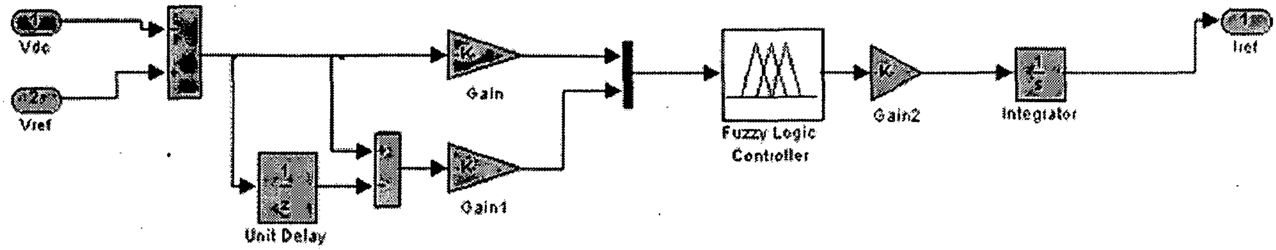


FIG.4.2 Fuzzy Logic Controller

The inputs to the Fuzzy Logic Controller are error, generated by comparing dc link voltage with the reference value, and change in error. These inputs must be scaled in order to fit in the universe of discourse. Fuzzy controller gives change in output after applying the four processes as mentioned earlier. This output is applied to an integrator to get controlled current, I^*.

. The adopted Fuzzy controller has the following characteristics

a. seven sets for each input and output (NB, NM, NS, ZE, PS, PM and PB)
b. Triangular membership functions for NM, NS, ZE, PS, PM and Trapezoidal membership functions for NB and PB.
c. Fuzzification using continuous universe of discourse
d. Implication using mamdani's min operator
e. Defuzzification using Bisector method

Fig. 4.3(a), (b) and (c) shows the normalized membership functions used in fuzzification.

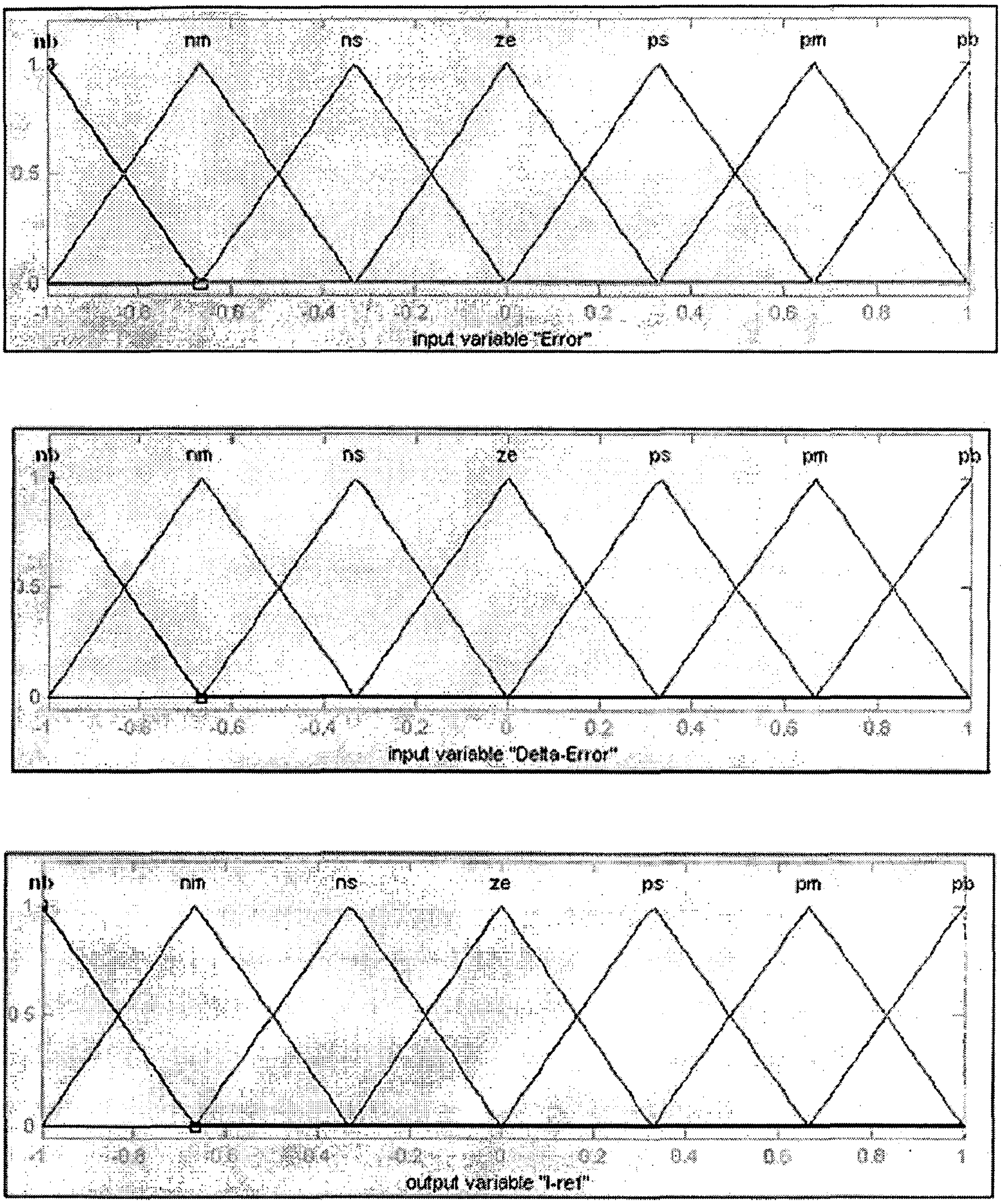


FIG.4.3 (a) Membership functions for error (b) Membership functions for change in error (c) Membership functions for change in output

The decision making rules for the fuzzy controller are given in Table-I [21]

e(k) / Δ e(k)	NB	NM	NS	ZE	PS	PM	PB
NB	NB	NB	NM	NM	NS	NS	ZE
NM	NB	NM	NM	NS	NS	ZE	PS
NS	NB	NM	NS	NS	ZE	PS	PS
ZE	NM	NS	NS	ZE	PS	PS	PM
PS	NM	NS	ZE	PS	PS	PM	PM
PM	NS	ZE	PS	PS	PM	PM	PB
PB	NS	ZE	PS	PM	PM	PB	PB

After applying the above mentioned rule base in decision making process, the rule surface can be viewed as shown below (FIG.4.4)

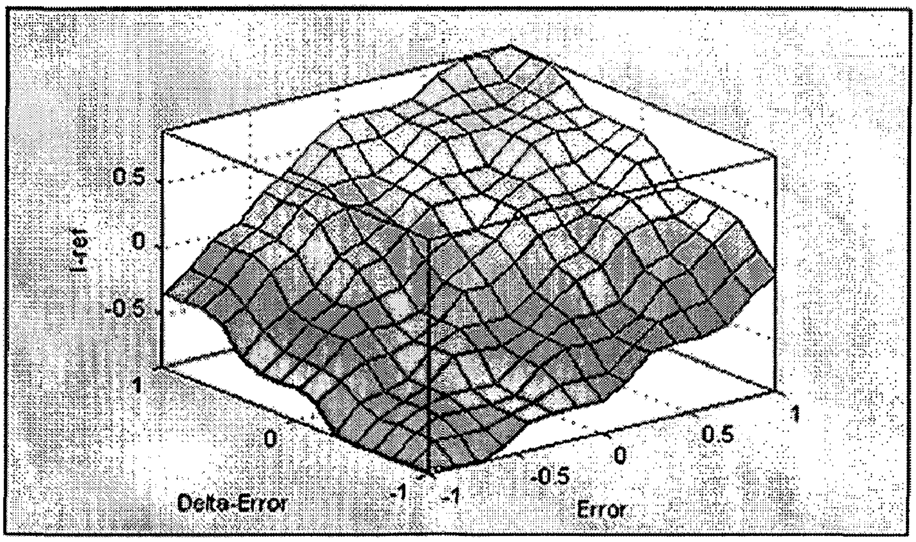


FIG.4.4 Rule surface view

The output dc voltage of the PWM rectifier is well controlled by the adapted Fuzzy Logic controller. The dynamic response of the controller is much better when compared to conventional PI controller.

Apart from the advantages of Fuzzy Logic controller, it has a disadvantage that it gives steady state error. In order to achieve better dynamic and steady state results, hybrid control techniques are introduced.

4.5 Hybrid Control using Fuzzy and PI

As mentioned earlier, PI controller suffers from overshoots, undershoots, large settling time, poor performance under nonlinearities and load disturbances. But PI controller has the advantages like simple, control with zero steady state error and no chattering at set point.

Considering these advantages, a hybrid control using fuzzy and PI is introduced. In this work, Hybrid Fuzzy PI controller and Fuzzy pre compensated PI controller are designed and implemented in MATLAB SIMULINK.

4.5.1 Hybrid Fuzzy PI controller

The schematic block diagram of the hybrid fuzzy PI controller is shown in Fig.4.5 and it is described by the following equations [21].

The voltage error and the change in voltage error can be given as:

$$V_{dc}e(k) = V_{dcref}(k) - V_{dc}(k) \tag{4.1}$$

:

$$\Delta V_{dc}e(k) = V_{dc}(k) - V_{dc}(k-1) \tag{4.2}$$

The Fuzzy Logic is used to provide the fast control and to compensate the nonlinearities present in the model as:

The Fuzzy Logic Controller output term $F(V_{dc}e(k), \Delta V_{dc}e(k))$ is used to provide fast transient response and to reduce the effect of nonlinearities. The Fuzzy Logic

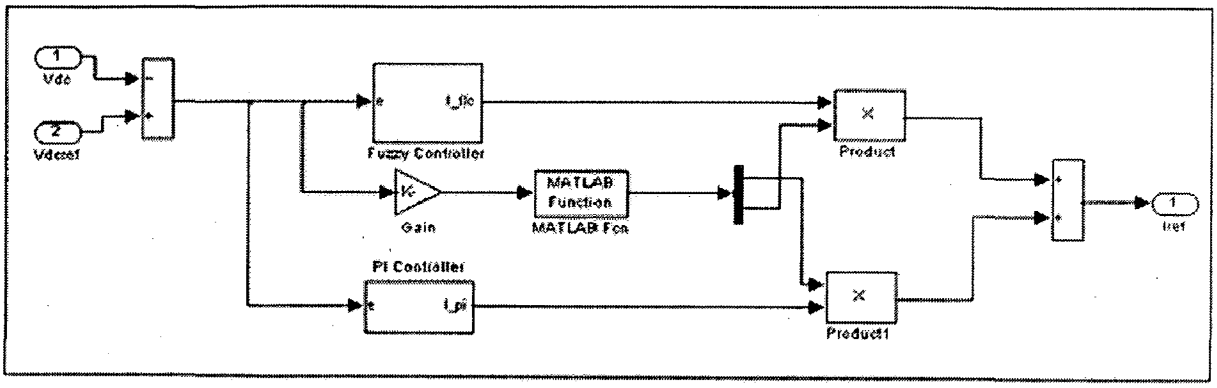


FIG.4.5 Block diagram of Hybrid Fuzzy PI controller

Controller output along with PI controller output is used to generate the controlled current in hybrid form to obtain the modified current reference (I_{ref}) as follows:

$$I_{ref} = K_{PI} I_{refPI} + K_{Fuzzy} I_{refFuzzy} \quad (4.3)$$

where K_{PI} is membership function for selection of hybrid proportion of the PI controller and K_{Fuzzy} is membership function for selection of hybrid proportion of the Fuzzy Logic controller and I_{refPI}, $I_{refFuzzy}$ are the output of PI controller and Fuzzy Logic controller respectively.

The membership function of Hybrid Fuzzy PI controller is shown in FIG.4.6 [21]

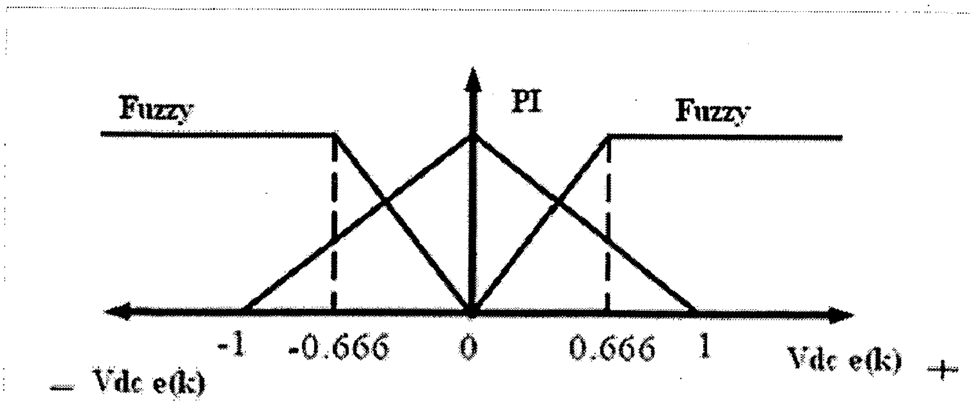


FIG.4.6 Membership function of Hybrid Fuzzy PI controller

The design of Fuzzy controller is same as mentioned earlier. Membership functions shown in FIG.4.3, are used for fuzzification and same rulebase (in Table-I) is used in decision making process.

The hybrid fuzzy control compensate undershoot or overshoot in the output response with consideration of all the advantages of PI control like zero steady-state error and no chattering at set point.

4.5.2Fuzzy Pre-compensated PI controller

The basic structure of Fuzzy Pre-compensated PI controller [25-26] is shown in FIG.4.7

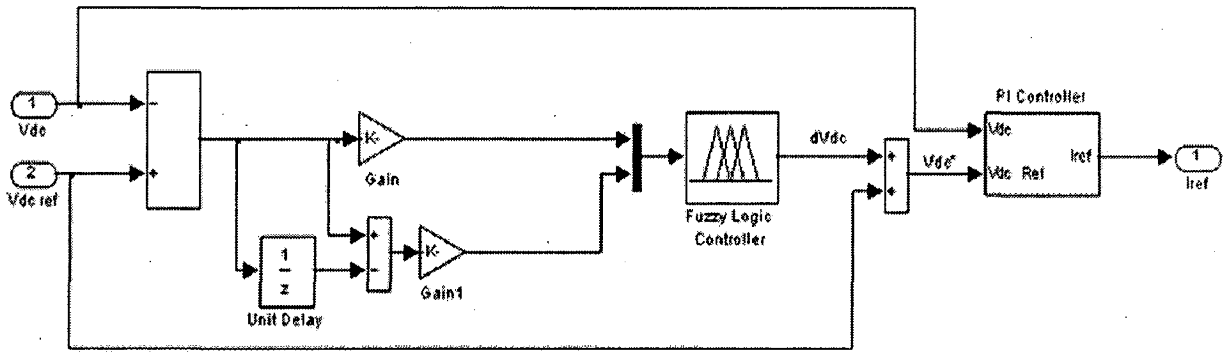


FIG.4.7 Fuzzy Pre-compensated PI controller

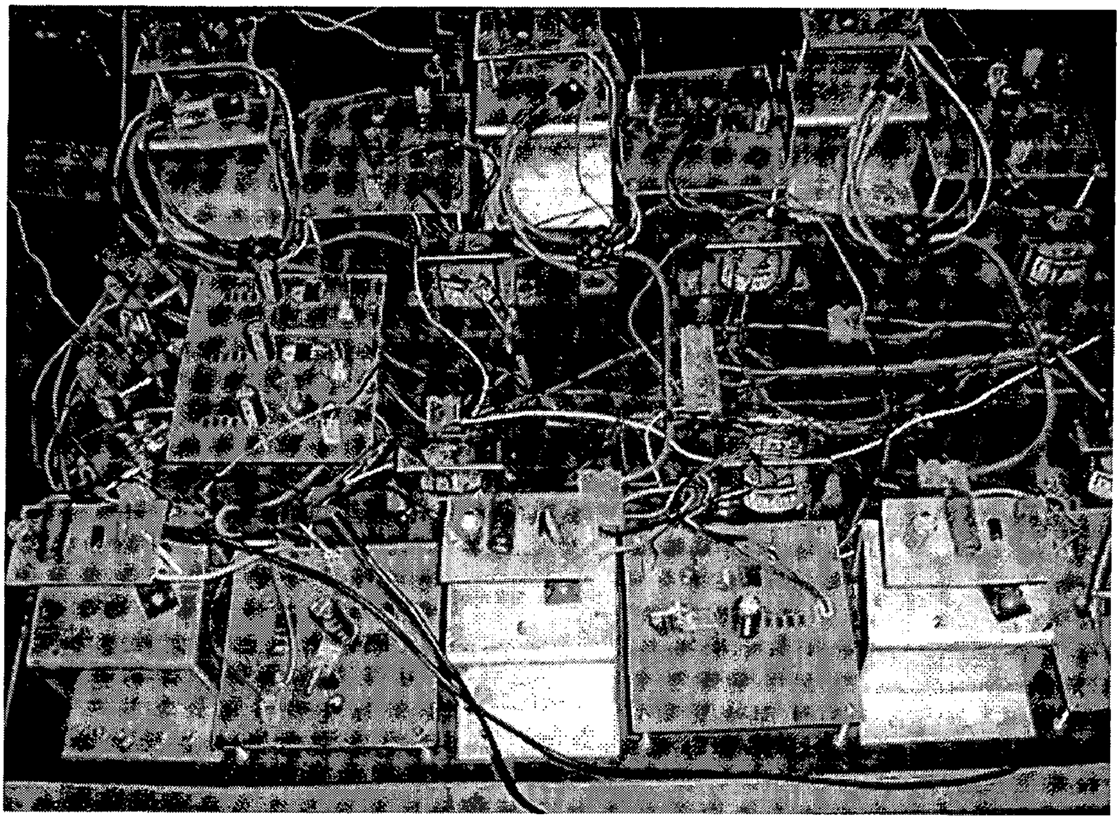
It consists of Fuzzy controller as a pre-compensator block followed by a PI controller. The Fuzzy pre compensation block provides the artificial reference signal V_{dc}* to PI controller. The overshoot and under shoot conditions are detected from the inputs, error and change in error (with the membership functions shown in FIG.4.1). This controller takes decision based on decision based on the rule base (shown in Table-I)

The compensated reference signal V_{dc}* is then applied to the conventional PI controller. The PI controller is used for zero dc voltage regulation. The dc link voltage of the rectifier is sensed and compared with the reference voltage V_{dc}*. Finally, PI controller generates controlled value of current.

CHAPTER-5
HARDWARE IMPLEMENTATION

5.1 Hardware Design

The complete hardware of three phase PWM rectifier is implemented.



The system hardware can be divided into following blocks:

- Power circuit
- Pulse amplification and isolation circuits
- Power supplies
- Circuit protection

Power circuit

Fig. 5.1 shows the power circuit of Three phase PWM voltage source rectifier. Each MOSFET switch used in the circuit consists of an inbuilt anti parallel free wheeling diode. No forced commutation circuits are required for MOSFETs because they are self commutated devices (they turn on when the gate signal is high and turn of when the gate signal is low). The source inductance restricts large di/dt through MOSFETs and hence only turnoff snubber is required for protection. An RCD (resistor, capacitor and diode) turn-off circuit is connected to protect the circuit against high dv/dt and is protected against power voltage by connecting MOV (Metal Oxide Varistor).

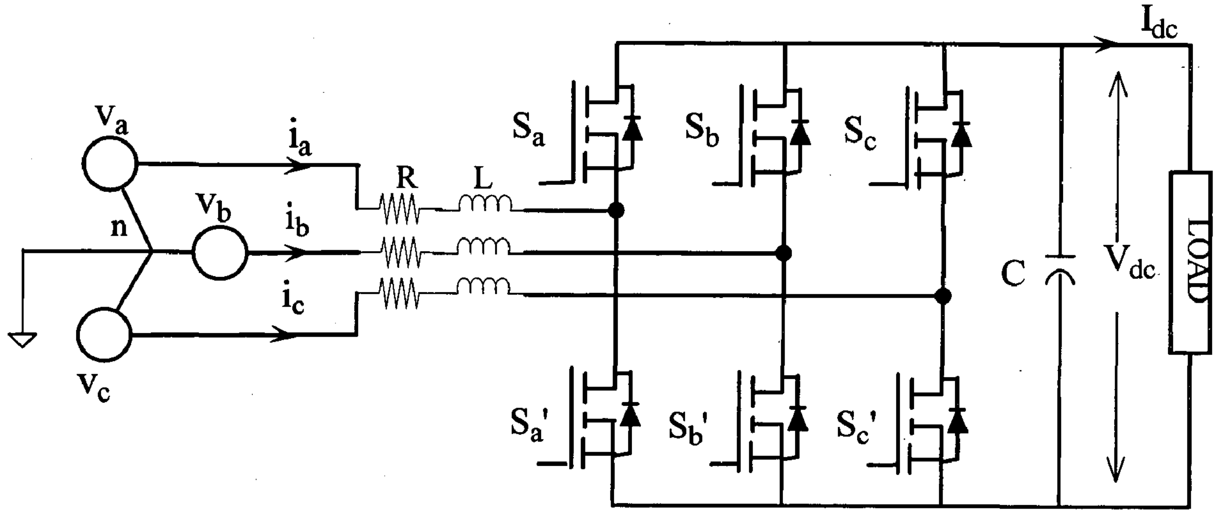


Fig 5.1 Basic circuit of Three phase PWM Voltage Source Rectifier

Pulse amplification and isolation circuit

The pulse amplification and isolation circuit for MOSFET is shown in Fig. 3.2. The opto-coupler (MCT-2E) provides the necessary isolation between the low voltage isolation circuit and high voltage power circuit. The pulse amplification is provided by the output amplifier transistor 2N222.

When the input gating pulse is at +5V level, the transistor saturates, the LED conducts and the light emitted by it falls on the base of phototransistor, thus forming its base drive. The output transistor thus receive no base drive and, therefore remains in cut-off state and a +12V pulse (amplified) appears across it's collector terminal (w.r.t. ground). When the input gating pulse reaches the ground level (0V), the input switching transistor goes into the cut-off state and LED remains off, thus emitting no light and therefore a photo transistor of the opto-coupler receives no base drive and, therefore remains in cut-off state. A sufficient base drive now applies across the base of the output amplifier transistor, it goes into the saturation state and hence the output falls to ground level. Therefore circuit provides proper amplification and isolation. Further, since slightest spike above 20V can damage the MOSFET, a 12 V zenor diode is connected across the output of isolation circuit. It clamps the triggering voltage at 12 V.

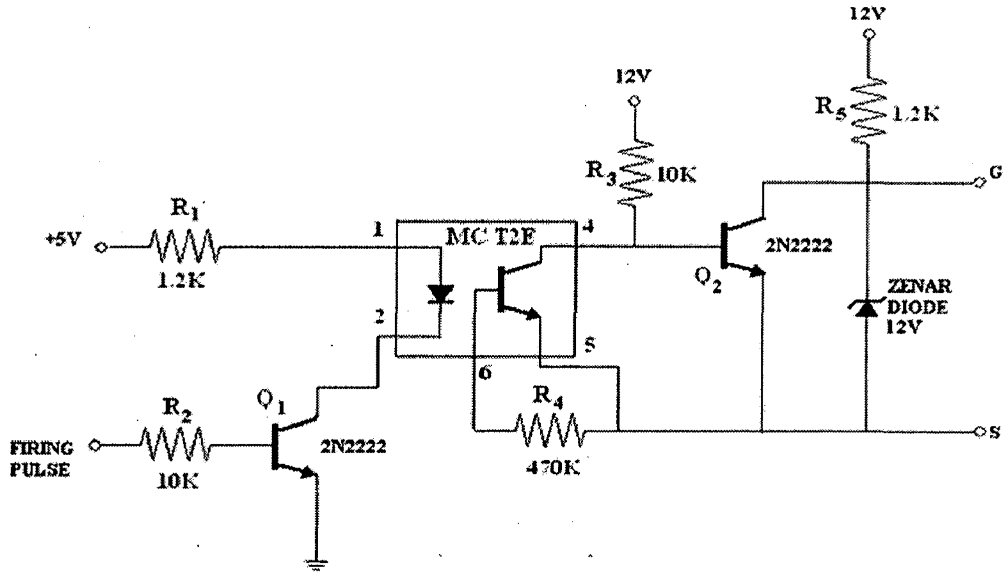
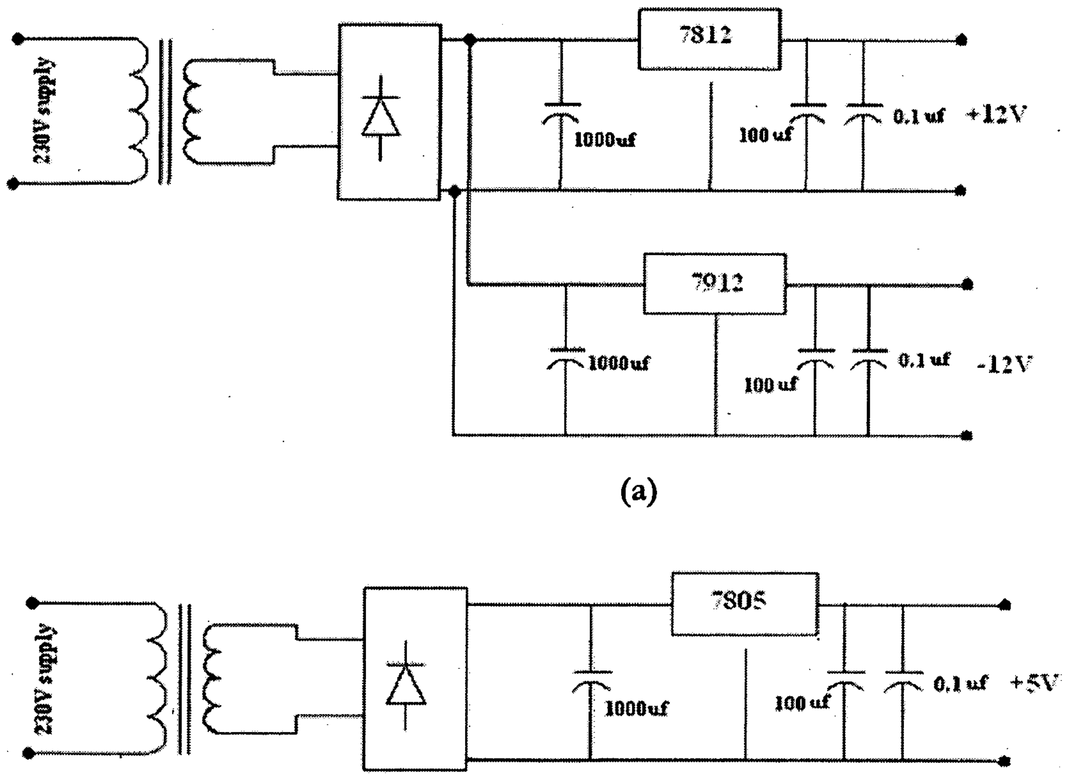


Fig 5.2 Pulse amplification and isolation circuit

Power supplies

D.C regulated power supplies (±12 V and +5 V) are required for providing the biasing to various ICs, etc. the system development has in-built power supplies for this purpose. The circuit diagram for various dc regulated power supplies are shown in Fig. 3.3. As, shown the single phase AC voltage is stepped down and the rectified using diode bridge rectifier. A capacitor of 1000μF, 50V is connected at the output of the bridge rectifier for smoothing out the ripples in the rectified dc voltage of each supply. IC voltage regulated chips, 7812, 7912, 7805 are used for obtaining the dc-regulated voltages. A capacitor of 0.1μF, 50 V is connected at the output of the IC voltage regulator of each supply for obtaining the constant, ripple-free dc voltage.

DC VOLTAGE	IC REGULATOR
+5V	7805
+12V	7812
-12V	7912



(b)

FIG.5.3 Power supplies (a) ± 12v supply (b) +5v supply

Protection of MOSFETS

An RC snubber circuit is used to reduce the dv/dt switching, as MOSFET is sensitive to over voltages emitter and collector. The diode prevents the discharging of capacitor via the switching device, which could damage the device owing to large discharge current. An additional protective device Metal–Oxide-Varistor (MOV) is used across each device to provide the protection against the over voltages. MOV acts as a back to back zenor and by passes the transient over voltages across the devices.

A 3.3 KΩ, 5W resistor and 10μF, 500V capacitor have been used

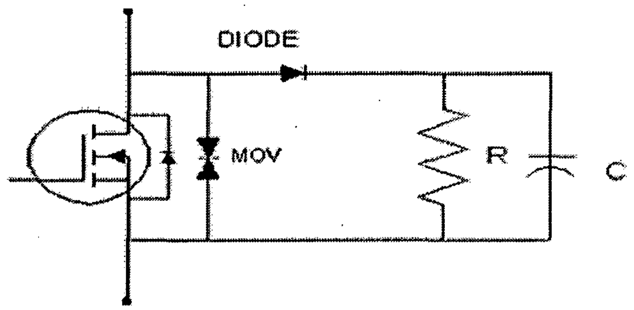


Fig.5.4. Snubber circuit for the protection of MOSFET

5.1.5 Delay circuit

Values of R and C are chosen to provide a delay around 5μs i.e. larger than turn-off transition time of the MOSFET. The switching signals from the lockout delay circuit are sent to the pulse amplification and isolation circuit.

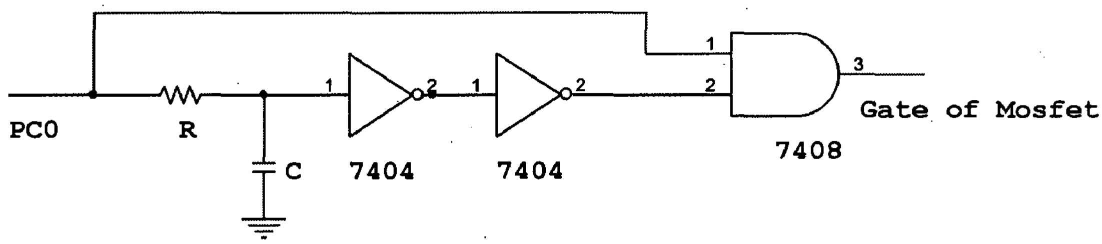


FIG.5.5 Delay circuit

This circuit provides 5μS delay and R=5kΩ and C=0.001μF

5.2 Implementation of High Power Factor Rectifier using Embedded Controller

5.2.1 Introduction

I-8438 is the ICP DAS MATLAB Embedded Controller [27] solution built in Ethernet and series interface with I/O expansion slot for Matlab development environment. For this application there are over 20 I/O bridges and system-level Simulink Blocksets have been developed. By using Simulink development environment and these Matlab Driver's blocksets, control algorithm can be easily constructed and verified without writing any code. Once the algorithm has been verified, by pressing a build button, users can convert a model to executable code, and download it to controller for test or practical application via RS232, Ethernet, RS485 and even Modem. The I-8000 Matlab solution gives us the function needed for the control program to download and upload experimental data through the media of RS232 & Ethernet communication interfaces.

The following table is a list of supported I-8000 I/O modules by Matlab Driver. They include DI, DO, DIO, AI, AO, relay, and encoder modules.

Type	Description	Module Model
DI	Digital input module	I-8040, I-8051, I-8052,I-8053, I-8058
DO	Digital output module	I-8041, I-8056, I-8057
DIO	Digital input & output module	I-8042, I-8054, I-8055, I-8063
AI	Analog input module	I-8017H
AO	Analog output module	I-8024
Relay	Relay output module	I-8060, I-8064
Encoder	Encoder counter board	I-8090

Limitations

The ICPDAS I-8000 series module software driver for MATLAB only supports *single tasking* and *Fixed-step* modes, due to the limitations of the RTW Embedded Coder.

1. Single tasking: In Simulink, *single tasking* means that only one sample rate can be used in the whole control system. That is, every block must have the same sampling rate. It is suggested that users set the *Sample time* to be –1 when the option is available in the block.

2. Fixed-step: Because the RTW 4.x or 5.0 have not supported variable step time, the *Solver options* on the *Simulation Parameters* dialog box can only be set to *Fixed-step.*

Furthermore, the RTW Embedded Coder does not support the following built-in Simulink blocks yet:

1. Simulink\Continuous

- No blocks in this library are supported

2. Simulink\Discrete

- First-Order Hold

3. Simulink\Function and Tables

- MATLAB Fcn

4. Simulink\Math

- Algebraic Constraint
- Matrix Gain

5. Simulink\Nonlinear

- Rate Limiter

6. Simulink\Signals & System

- Bus Selector
- IC

7. Simulink\Sinks

- XY Graph
- Display
- To File

8. Simulink\Sources

- Clock
- Chirp Signal
- Pulse Generator
- Ramp
- Repeating Sequence
- Signal Generator

The steps involved in developing a simulink model with ICPDAS driver is explained in appendix.

The digital input-output module, DIO (I-8054) is an ICPDAS driver simulink block. It outputs the pulses generated from the MATLAB/SIMULINK model so that they can be used for the triggering of switches.

The pulses, generated from the MATLAB/SIMULINK model, need to be converted from binary form to decimal equivalent before applying to DIO. This is done by the following circuit, shown in FIG.5.6.

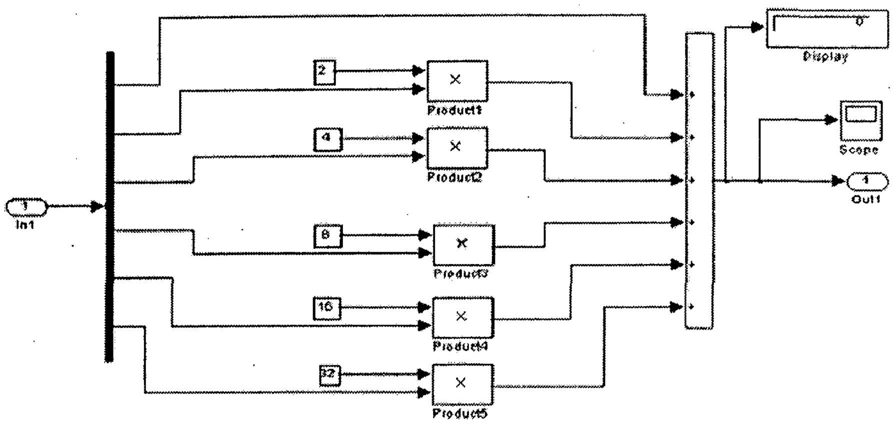


FIG.5.6 Binary to decimal conversion of pulses

5.2.2 Hysteresis Current Control (HCC)

This is the simplest control technique. In the implementation of this technique, the reference currents are generated from the dc voltage error and actual line currents are compared with them. Error values are applied to hysteresis controller to generate gating pulses. Using ICPDAS driver, a simulink model of HCC technique is implemented (shown in Fig 5.7).

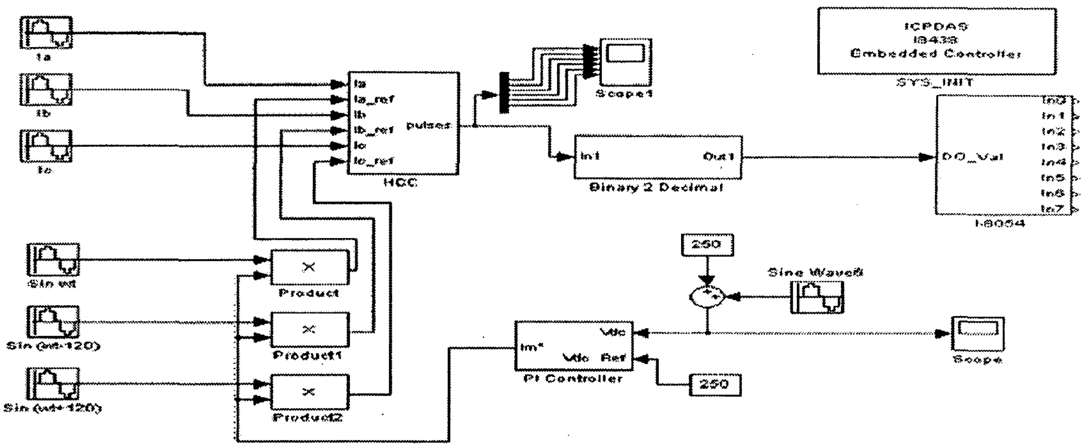


FIG 5.7 HCC simulink model with *ICPDAS* driver

5.2.3 Sinusoidal PWM

Simulation model of sinusoidal PWM is shown in FIG.5.8. As the embedded controller does not support repeating sequence, the carrier wave is generated by using the simulink model as shown in FIG.5.9. Because of the limitations associated with sampling time and frequency, the max frequency of the carrier is limited to 125 Hz. This carrier wave is compared with a sine wave to generate Pulses.

These pulses are converted to decimal equivalent and they are applied to DIO (I-8054).

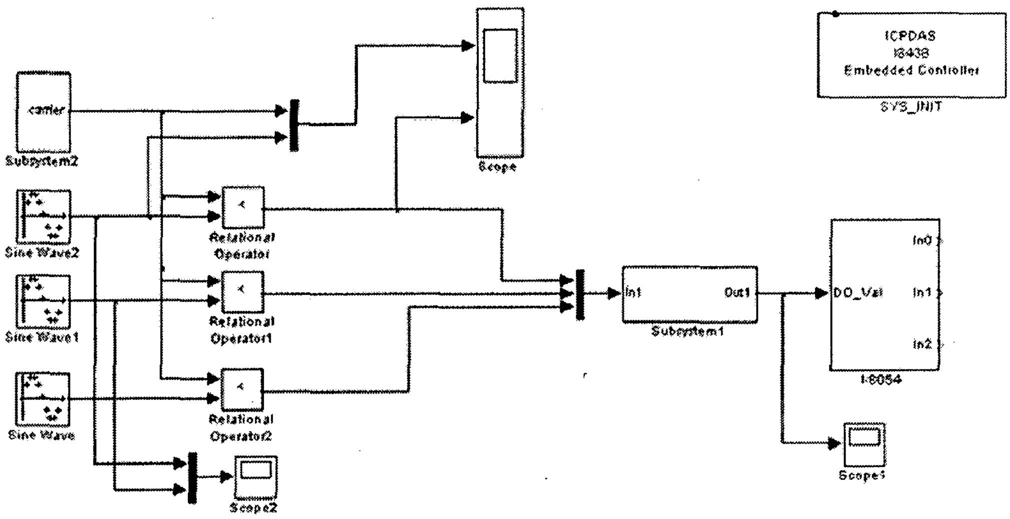


FIG.5.8 Pulse generation using SPWM

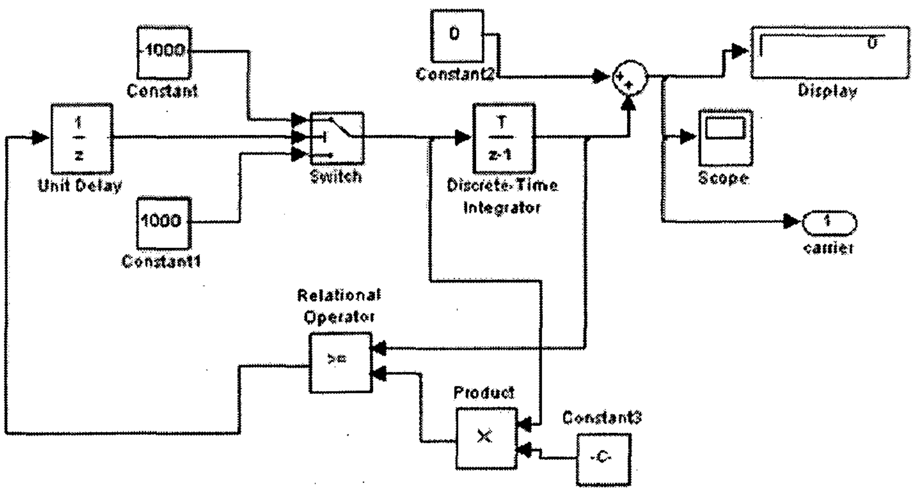


FIG.5.9 Carrier wave generation

CHAPTER6
RESULTS AND DISCUSSIONS

6.1 Simulation Results

An extensive simulation work is carried out to verify the validity of the Virtual Flux based Direct Power Control for the control of three phase PWM rectifier using different controllers. Simulation model of three phase PWM rectifier and the control strategies are developed using MATLAB^{TM} /SIMULINK environment.

Virtual Flux based Direct Power Control of Three phase PWM rectifier

The control strategy is verified in the following aspects

a. The line current drawn from the AC mains is sinusoidal.
b. Power factor near to unity is obtained
c. The DC link voltage is maintained at the reference value.
d. The dynamic response of the PWM rectifier is satisfactory.
e. Sinusoidal line current and unity power factor even with distorted supply voltage

Also, improved results are obtained with the Fuzzy logic controller. FIG.6.1, 6.2, 6.3 and 6.4 shows dc output voltage using different controllers.

6.1.1 Steady State Response

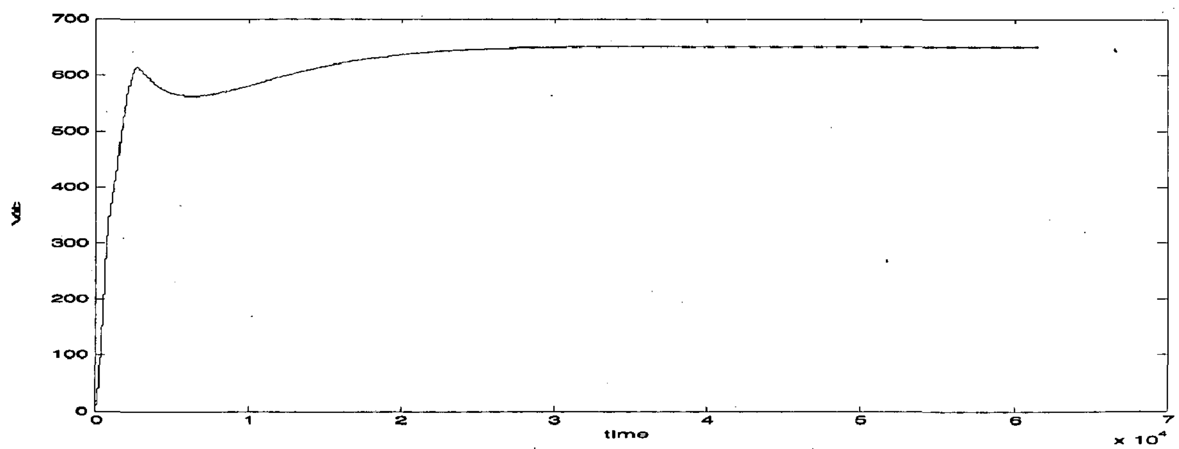


FIG.6.1 DC voltage output with PI controller

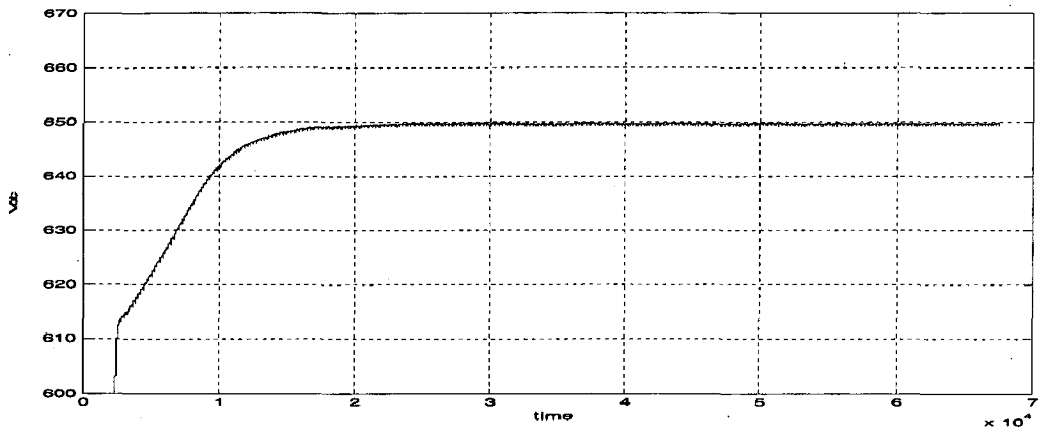


FIG.6.2 DC voltage output with fuzzy controller

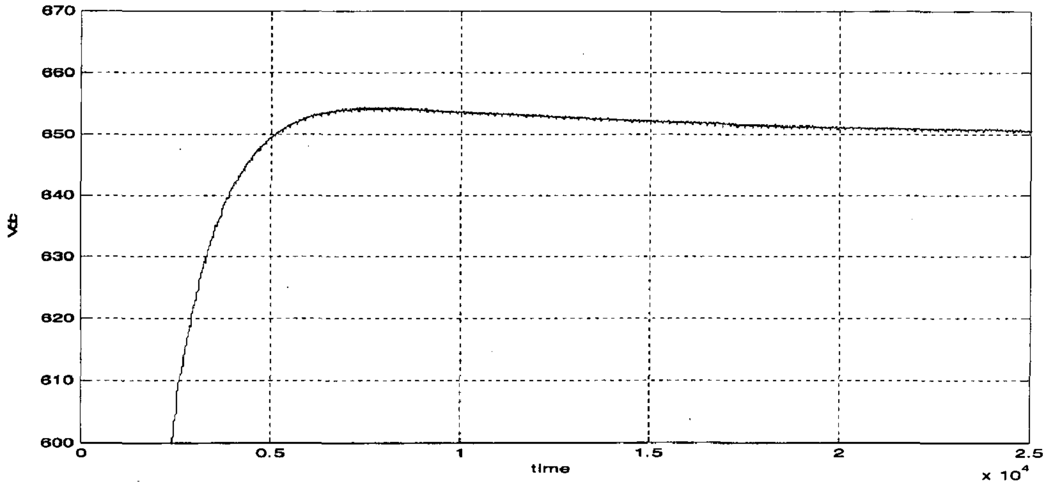


FIG.6.3 DC voltage output with hybrid fuzzy PI controller

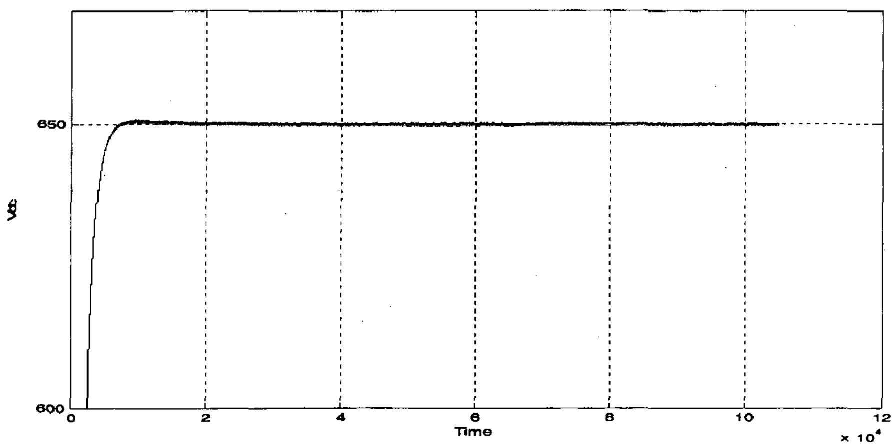


FIG.6.4 DC voltage output with fuzzy pre-compensated PI controller

FIG.6.5 to FIG.6.7 illustrates supply voltage, three phase currents and instantaneous power with a fuzzy pre-compensated PI controller is used. Nearly sinusoidal line currents with a power factor of 0.988 is obtained.

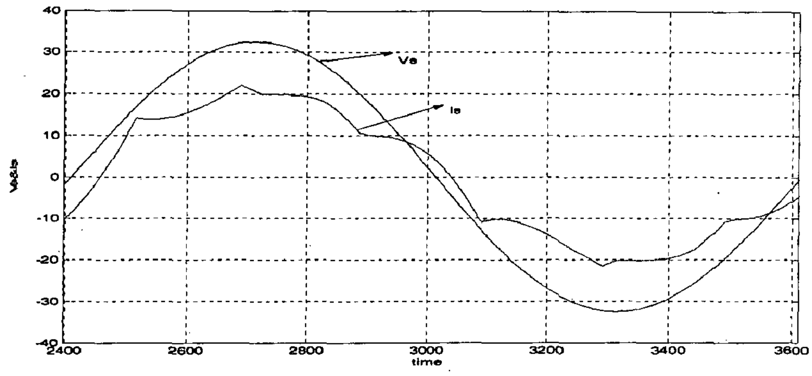


FIG.6.5 Supply voltage and current

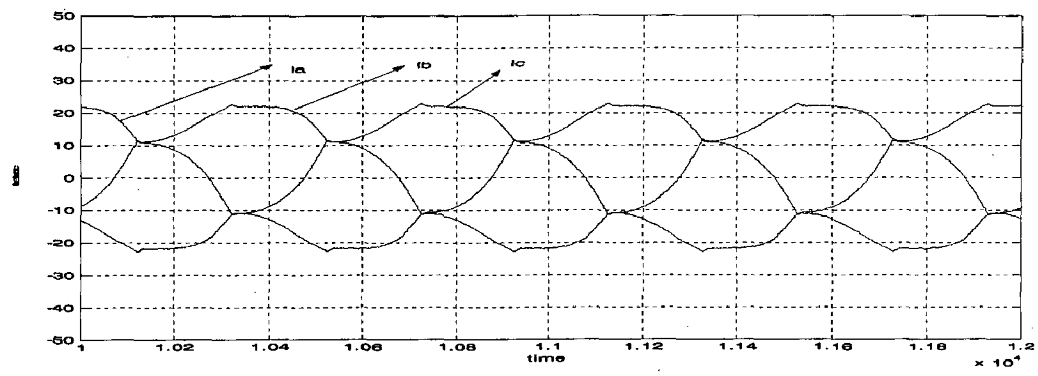


FIG.6.6 Three phase currents

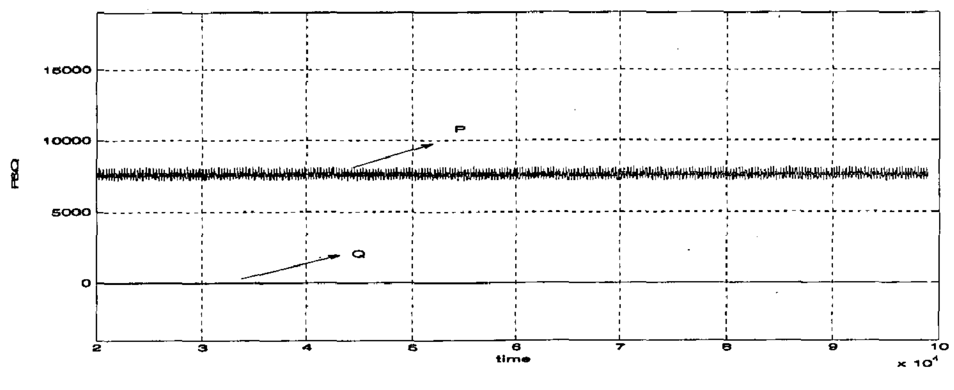


FIG.6.7 Instantaneous active and reactive power

6.1.2 Dynamic Response

A. When load is decreased:

FIG.6.8 to 6.11 shows the dynamic response of the dc link voltage when load is decreased (load resistance is increased from 40 ohms to 60 ohms).

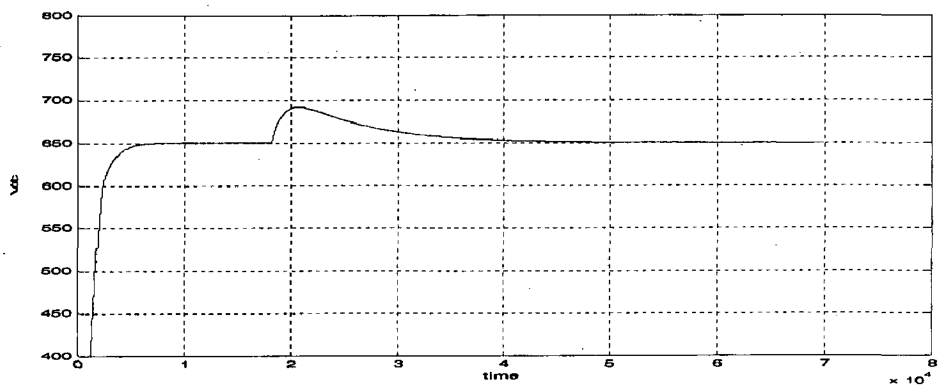


FIG.6.8 DC voltage output (Fuzzy pre-compensated PI)

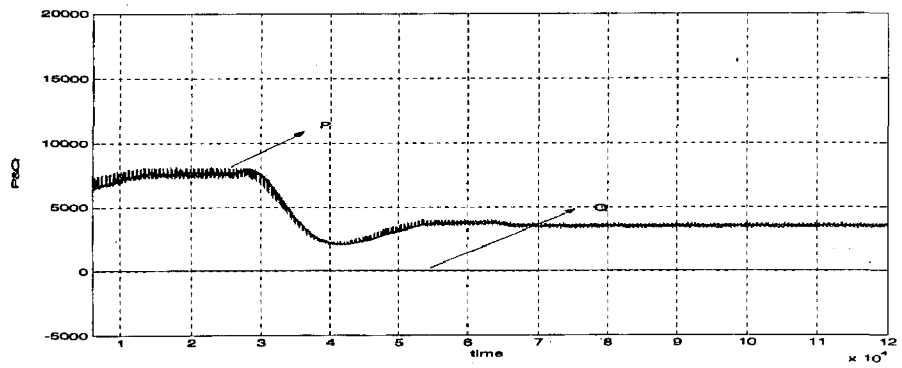


FIG.6.9 Instantaneous power

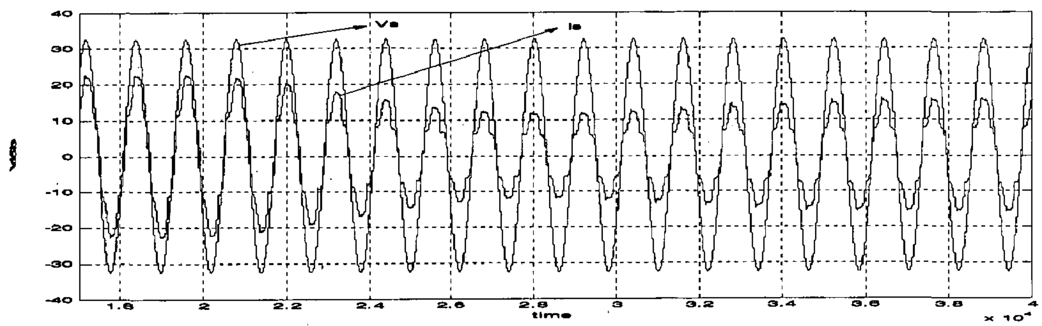


FIG.6.10 Supply voltage and currents

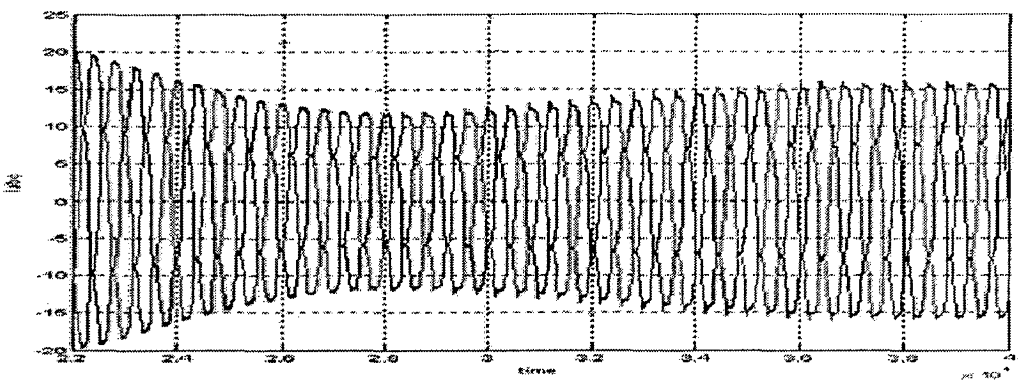


FIG.6.11 Change in three phase currents

B. Change of DC Reference

Fig. 6.12 to Fig. 6.15 illustrates the transient waveforms of the DC link voltage, input currents and instantaneous power for the step change in the reference DC voltage from 650V to 700V and back to 650V. One sees that the magnitude of input current, with Fuzzy pre-compensated PI controller, changes according to the step change of the reference voltage and that the DC link voltage follows the voltage command.

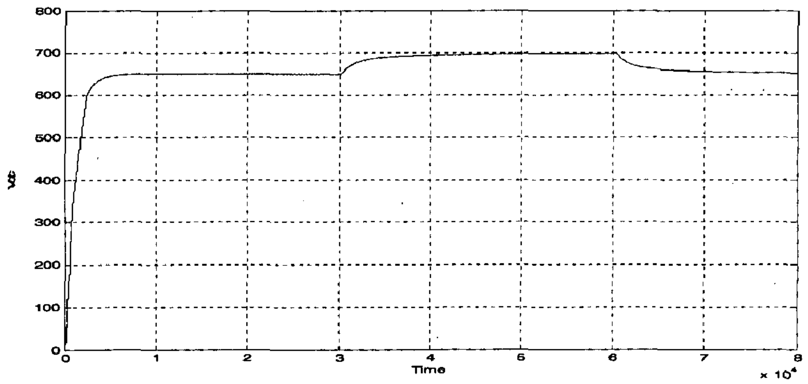


FIG.6.12 Step change in DC voltage output

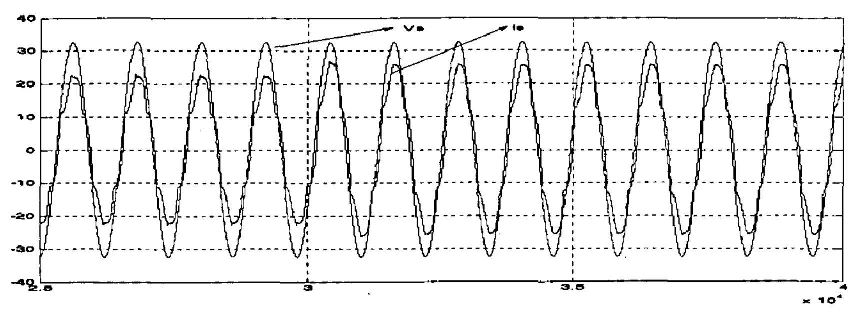


FIG.6.13 Source voltage and current

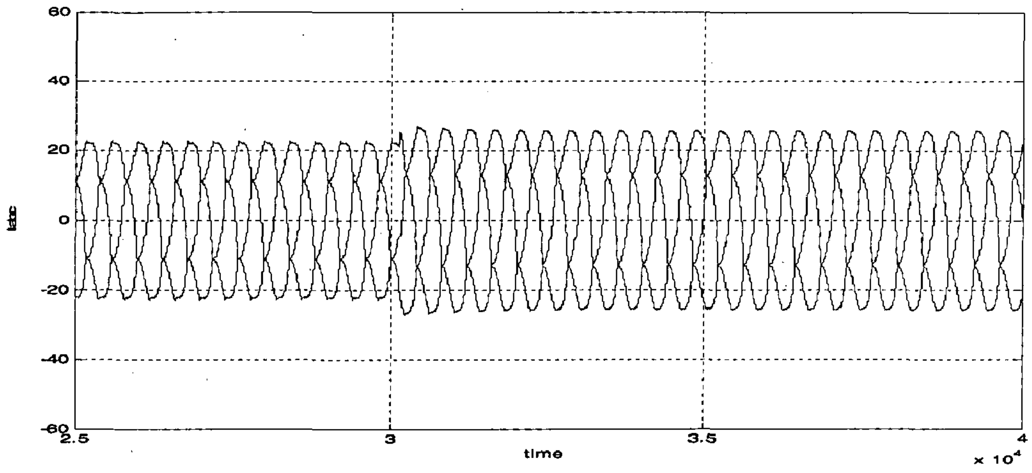


FIG.6.14 Three phase currents

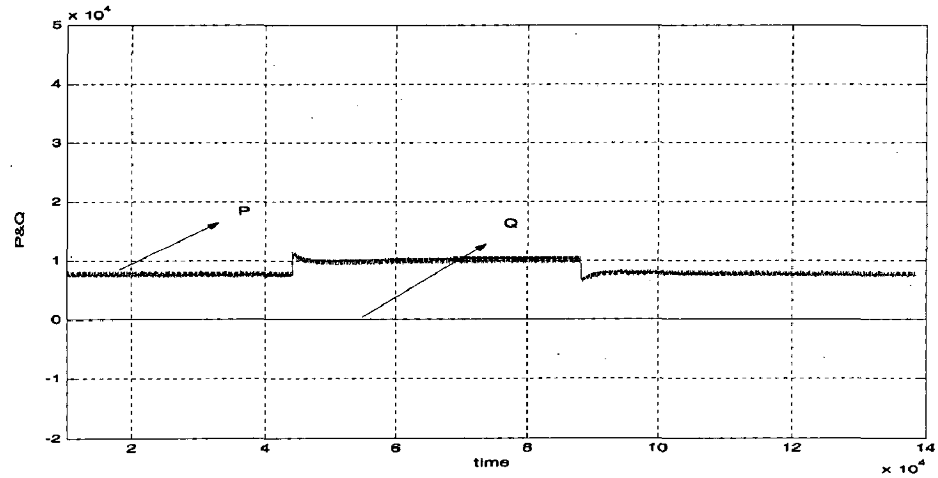


FIG.6.15 Step change of instantaneous active power

6.1.3 Operation Under Distorted Supply Voltage:

FIG.6.16 to 6.18 shows waveforms of supply voltage, sinusoidal line currents and instantaneous power, when 2^{nd} and 3^{rd} harmonics of magnitude 0.15pu and 0.2pu respectively are injected into the supply. Power factor near to unity is maintained even with distorted supply.

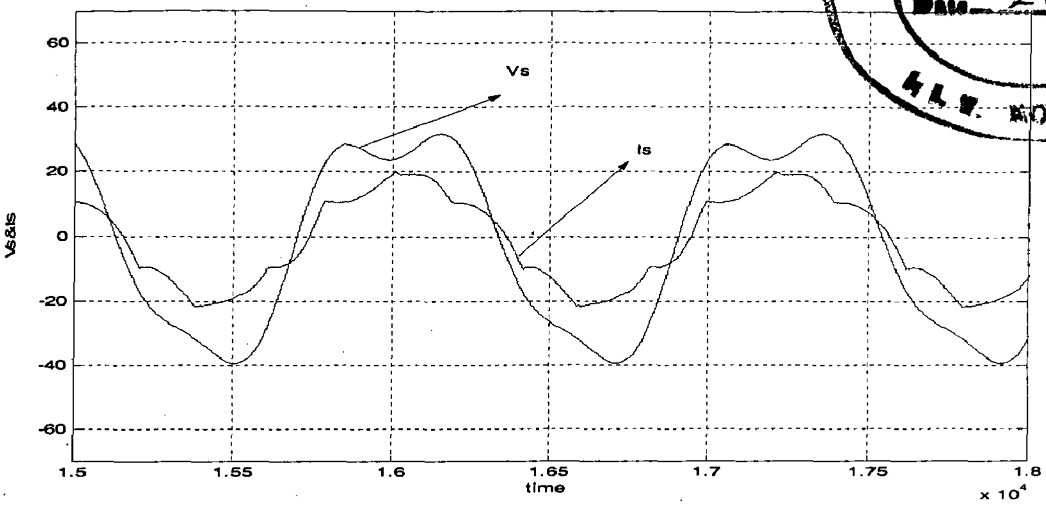


FIG.6.16 Distorted supply voltage and sinusoidal line current

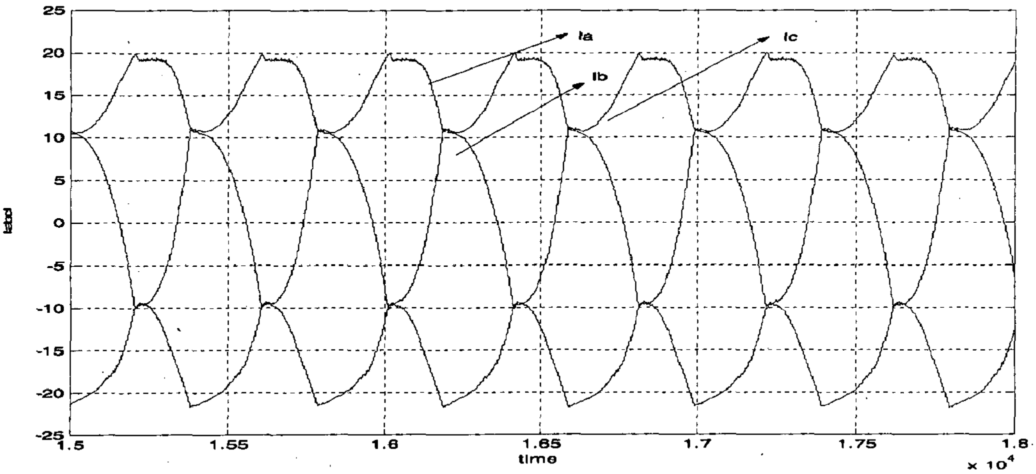


FIG.6.17 Three phase currents

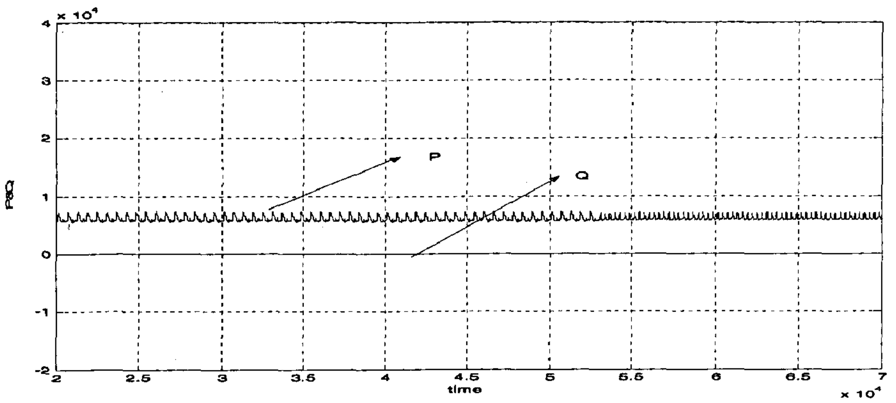
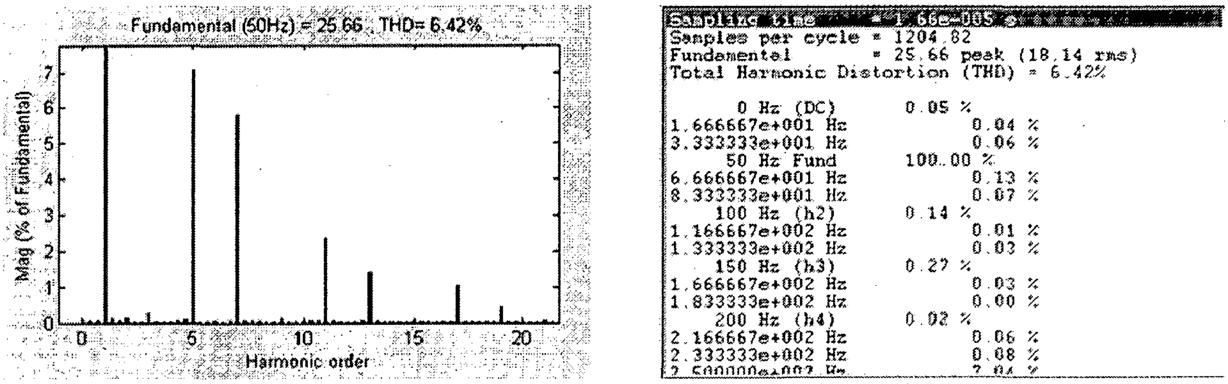
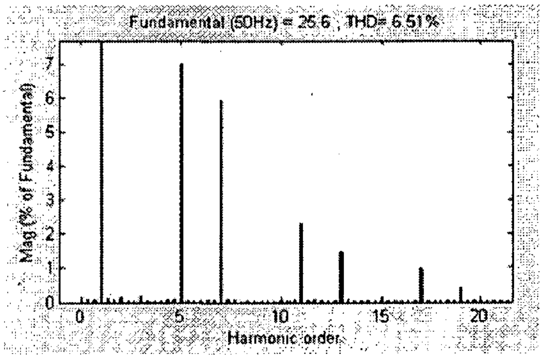


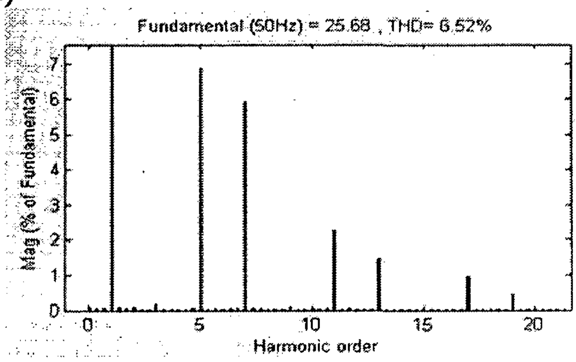
FIG.6.18 Instantaneous power

FIG.6.19 shows harmonic spectrum of three phase currents. THD of I_{sa}, I_{sb} and I_{sc} is 6.42%, 6.51% and 6.52% respectively which are satisfying the IEEE standards for harmonics.



(a)





(b) (c)

FIG.6.19 Harmonic spectrum of a) Isa b) Isb c)Isc

6.2 Experimental Results:

Sinusoidal PWM signals to the upper leg of the rectifier are generated from the embedded controller using the simulink model shown in FIG.5.8. The embedded controller is an open collector type. So, pull-up resistors of value 470-ohm are connected at the out put ports of DIO module through Vcc(+5V).

These pulses are then applied to a NOT gate to get the pulses to the lower leg. The pulses for six switches are then passed through the delay circuits in order to get protection from shoot through faults. There after, the pulses are given to their respective pulse amplification and driver circuits to get the final gating.

The embedded controller is supporting a carrier wave at a maximum frequency of 125Hz. So, the gating pulses are unable to switch on all the six MOSFETS at a time due to loading effect. So, it is not possible to operate the rectifier using the embedded controller.

The MOSFETs are triggered individually, applying a load of 50 ohms (shown in FIG 6.20) and the output voltage waveforms across drain and source are obtained as shown below.

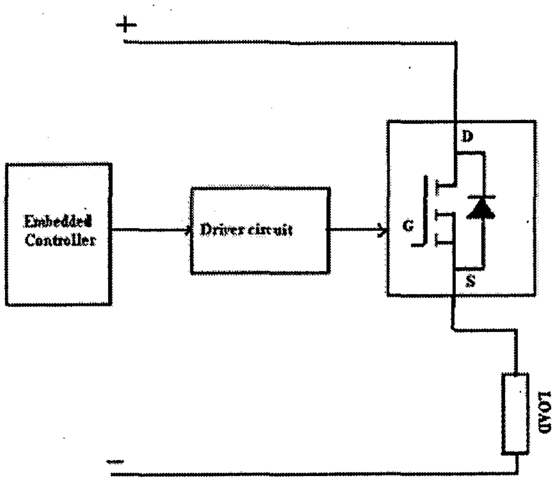
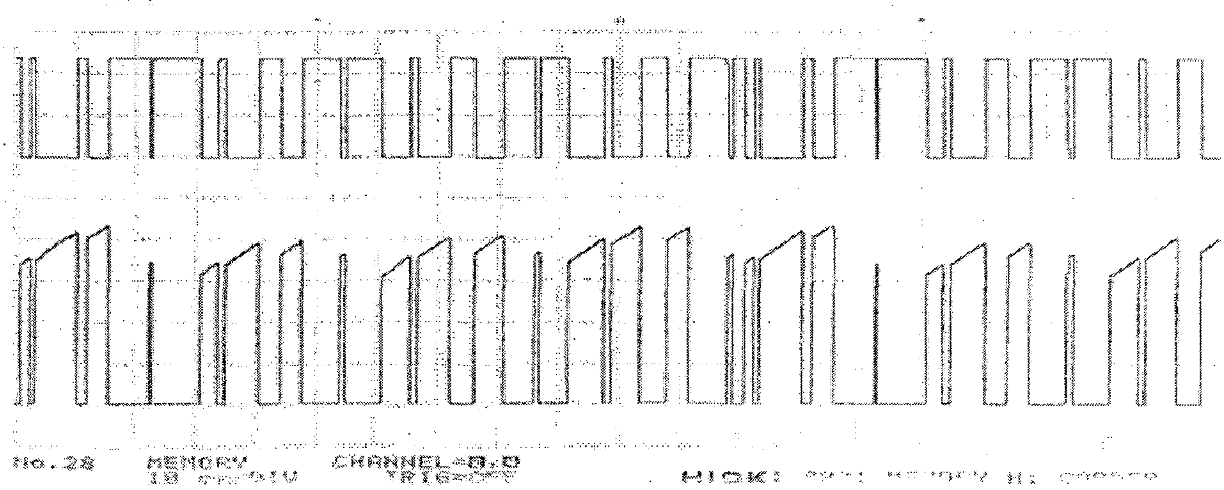
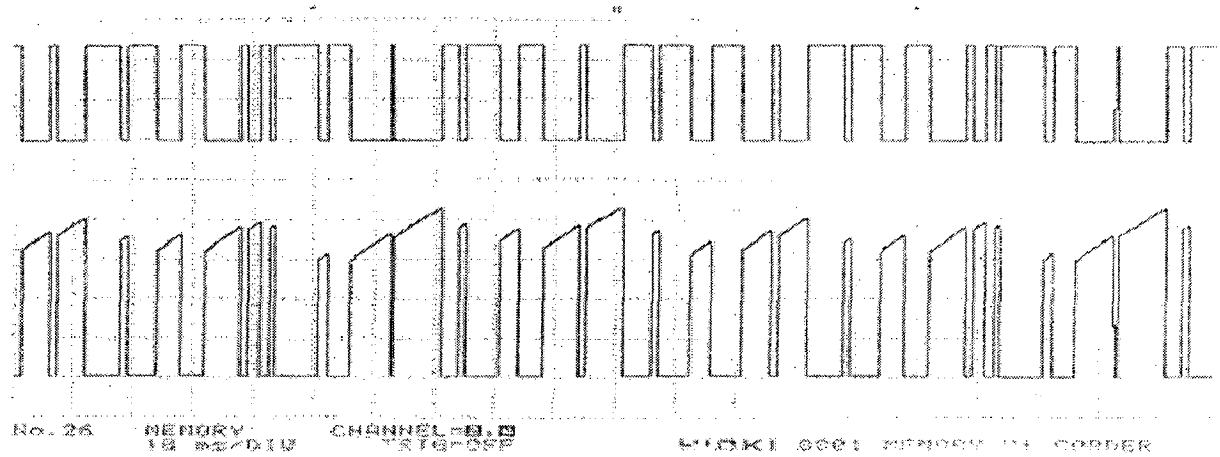


FIG.6.20 Testing of MOSFET

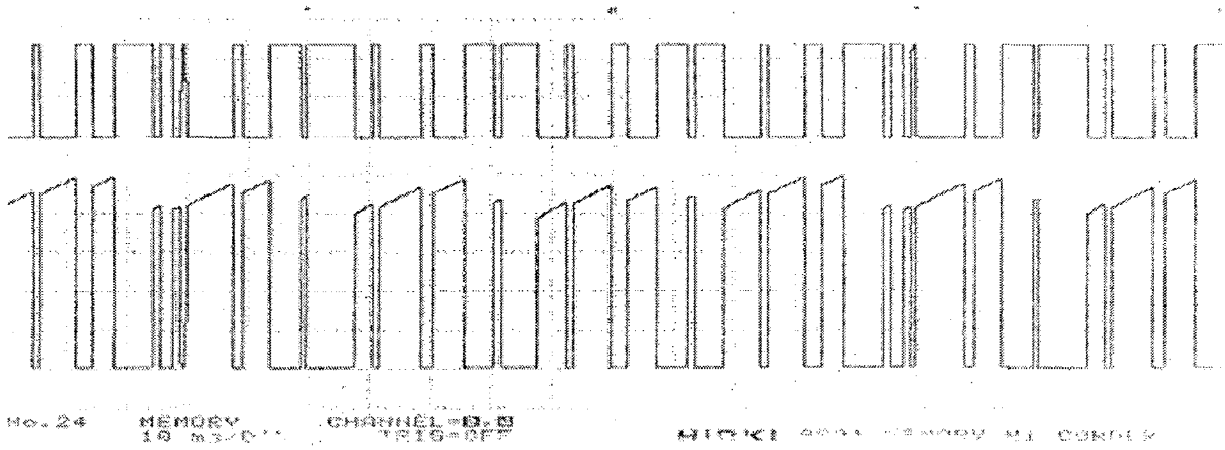
S1 and V_{DS}



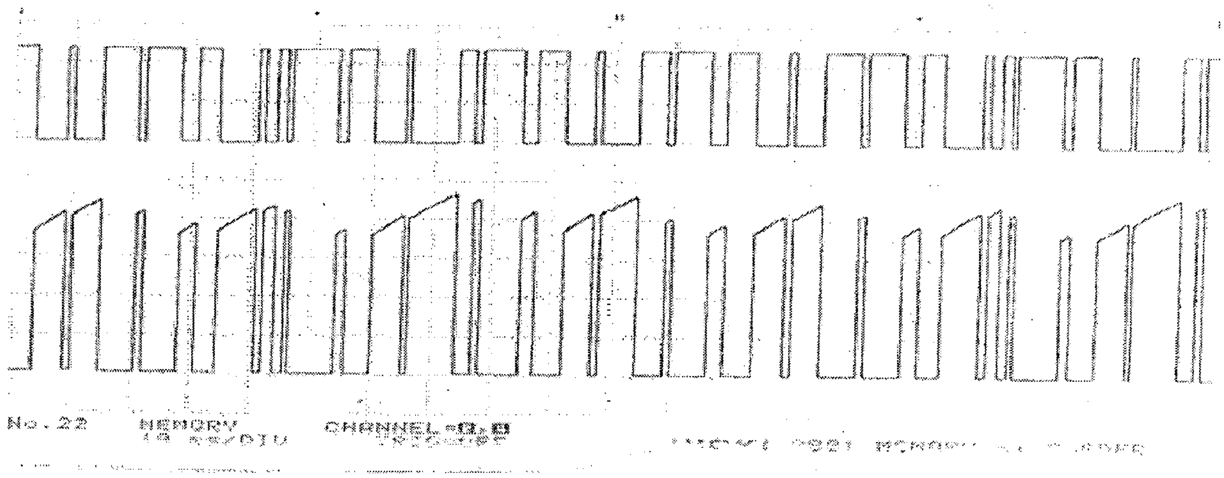
S4 and V_{DS}



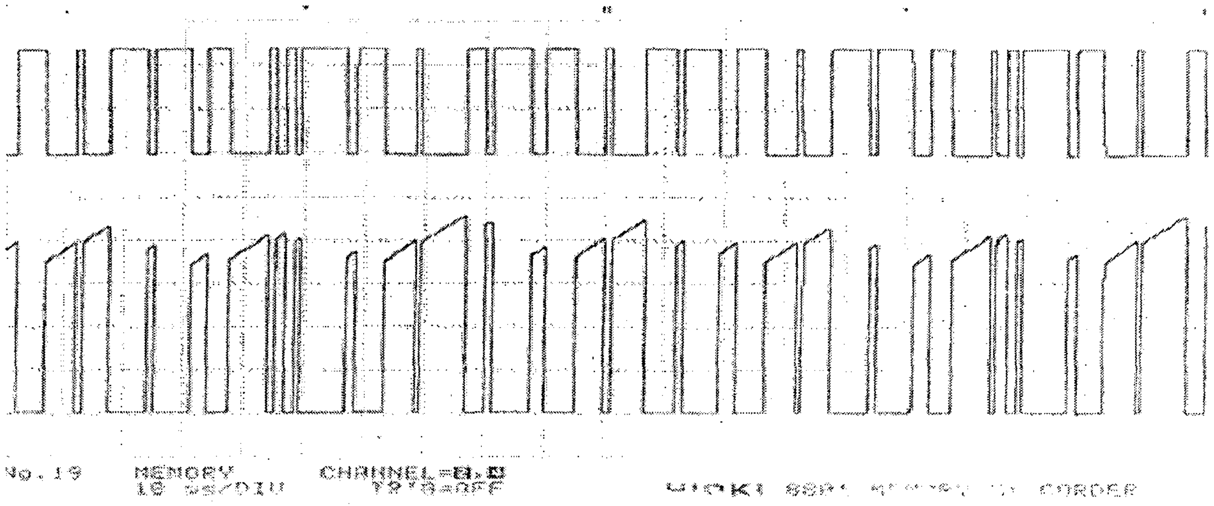
S3 and V_{DS}



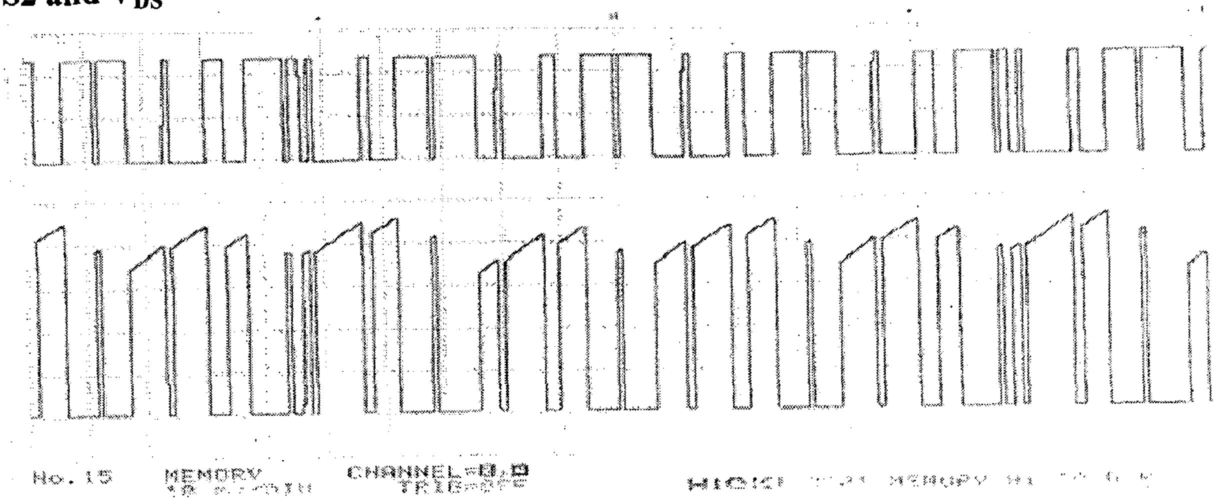
S6 and V_{DS}



S5 and V_{DS}



S2 and V_{DS}



CHAPTER 7
CONCLUSIONS AND FUTURE SCOPE

Conclusions

The following conclusions can be drawn from the present work

- The conventional line commutated rectifiers pollute the power supply with significant levels of harmonics and low power factor. Therefore, these rectifiers can be replaced by high power factor rectifiers.
- Three phase PWM rectifier draws nearly sinusoidal line currents at a power factor near to unity.
- The advantages of Virtual Flux based Direct Power Control such as maintaining unity power factor and low THD are verified through simulation study.
- Fuzzy controlled high power factor rectifiers have shown good steady state and dynamic response
- Different hybrid control techniques using fuzzy and PI controllers are applied to high power factor rectifiers and a controlled dc voltage output and nearly unity power factor are obtained
- An experimental prototype of PWM rectifier is developed and MOSFET switching of is done by applying the SPWM signals generated from the embedded controller.

Future Scope

In the present work, because of the limitations associated with the embedded controller, only MOSFET switching through the SPWM signals is done. The Virtual Flux based Direct Power Control can be implemented by using a controller which can produce gating pulses in the kHz frequency range.

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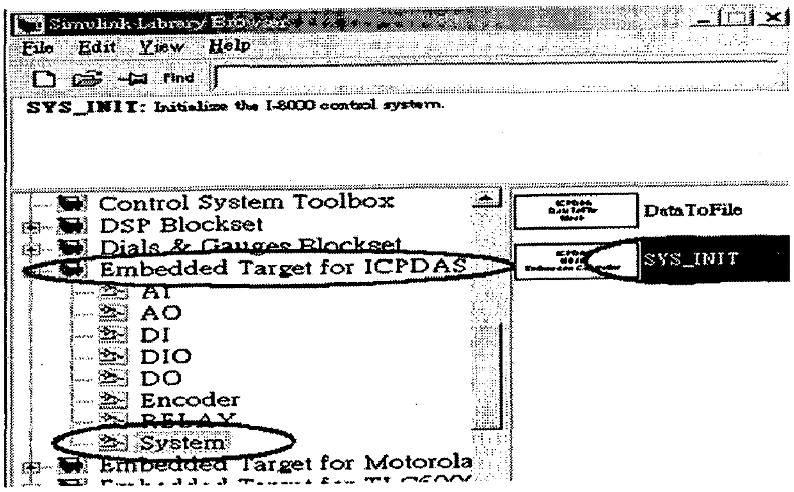
The Parameters used for simulation study

Phase Voltage, V	=	230 rms;
Source voltage frequency	=	50 Hz;
R	=	0.08 ohms;
L	=	22 mH;
DC link Capacitor	=	2mF;
Load resistance	=	40 ohms;
Load reactance	=	1m H;
Sampling frequency	=	60 kHz;
Average switching frequency	=	4kHz;
DC link voltage	=	650 V;

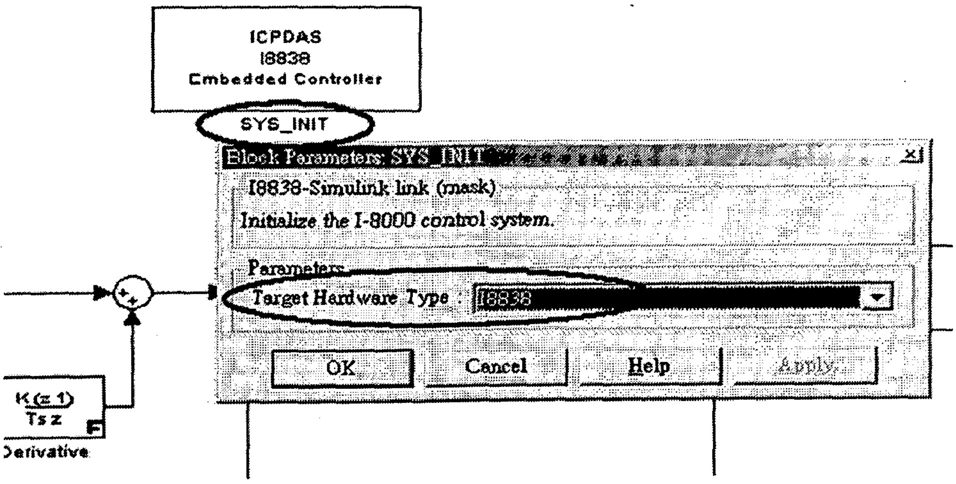
Simulink Model with ICPDAS Driver

If the simulation output was satisfied, you can replace the built-in Simulink blocks with the I-8000 driver blocks. To add an I-8000 driver block to the model, follow these steps:

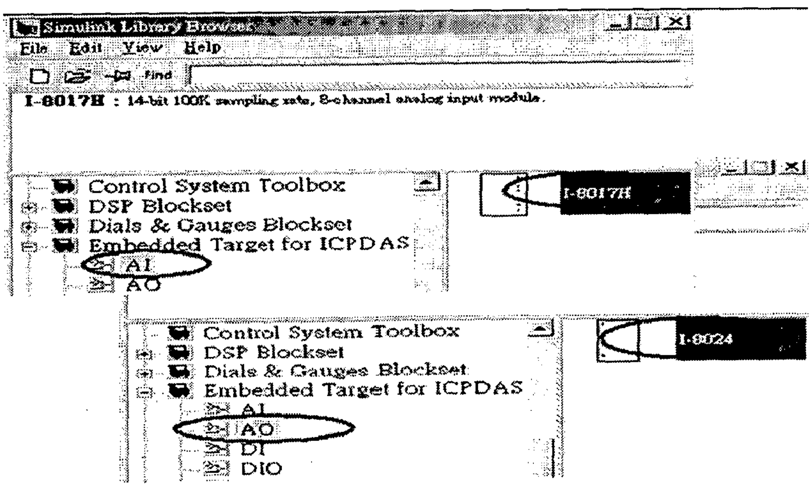
Step 1: Insert a SYS_INIT block from the System block library.



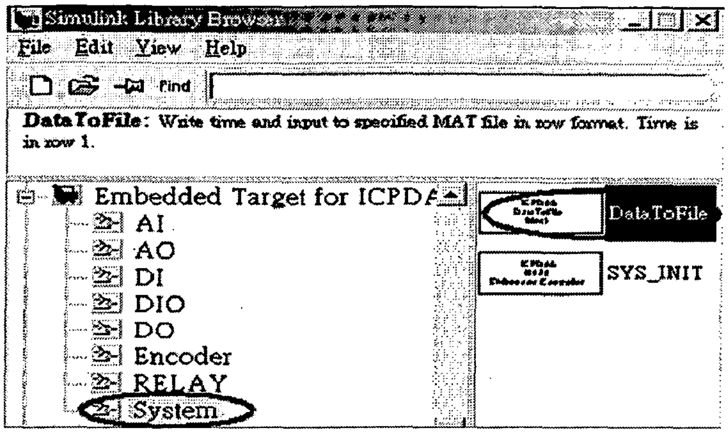
Step 2: Double-click on the SYS_INIT block to open the SYS_INIT dialog box. Then select the correct type from the popup menu on the dialog box. Here, select the type as I8838.



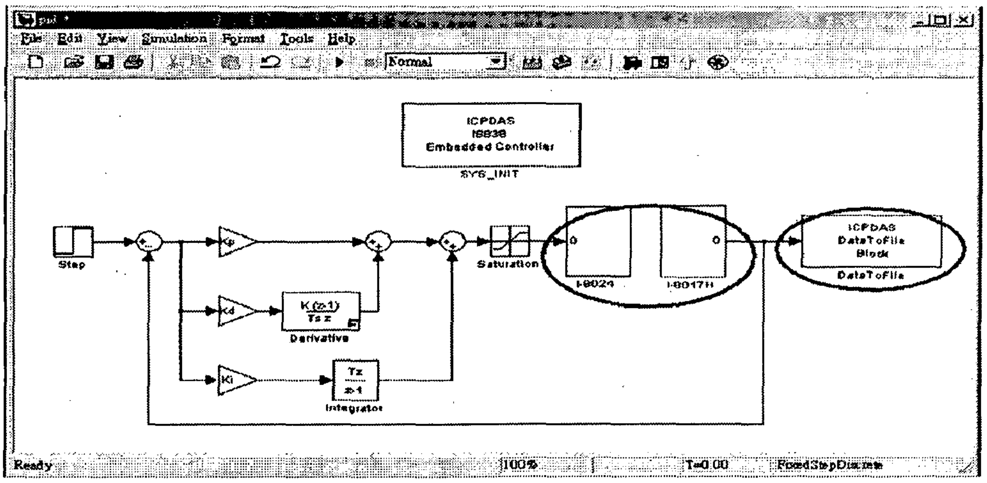
Step 3: Remove the Plant subsystem block and copy an I-8024 and an I-8017H block from the AI and AO library respectively



Step 4: Replace the Scope block with a Data To File driver block.



Step 5: Connect the blocks as shown in the following figure.

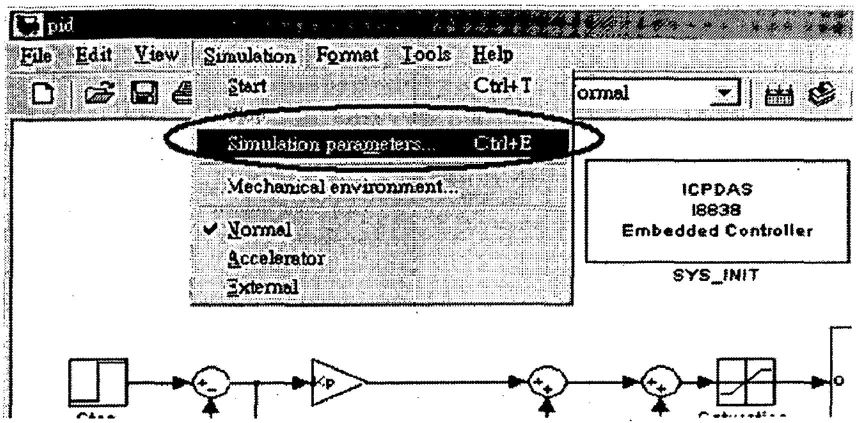


After the above steps are done, process can be started to build control model with the ICPDAS I-8000 driver blocks.

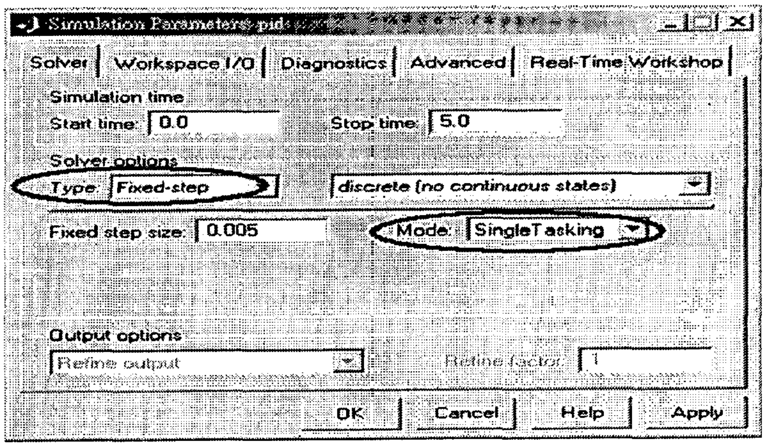
BUILD THE PROGRAM BY RTW

The steps to convert the control model created in the previous section into an .exe file by RTW are as follows:

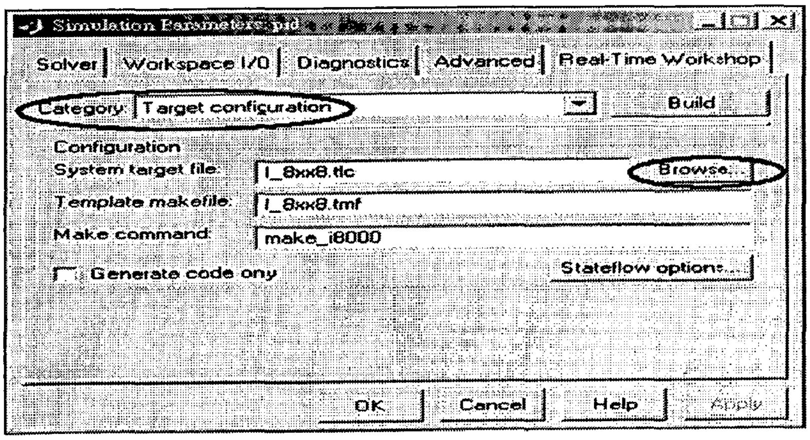
Step 1: Open the Simulation Parameters dialog box by choosing *Simulation parameters* from the *Simulation* menu.



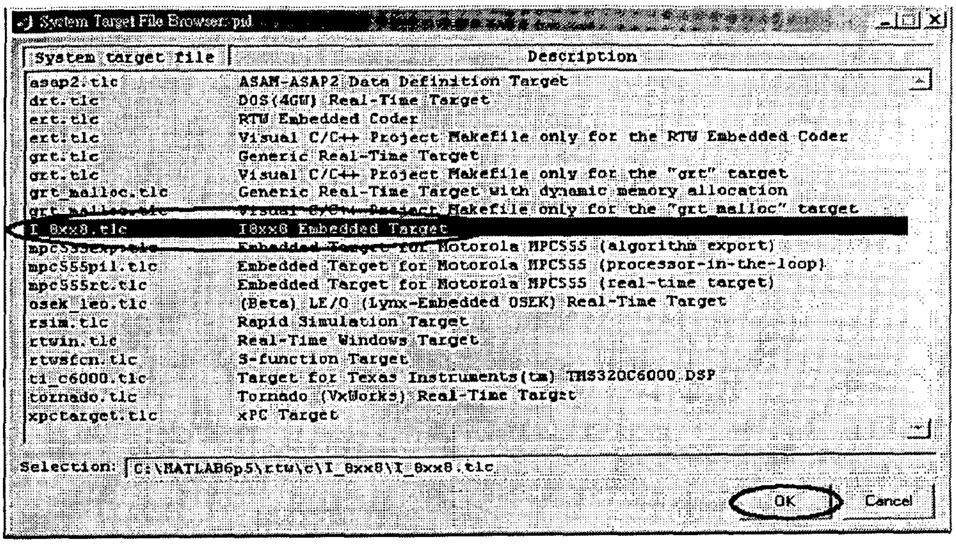
Step 2: On the dialog box that displays, select Type as *Fixed-step*, Mode as *Single Tasking* in the "Solver options" field.



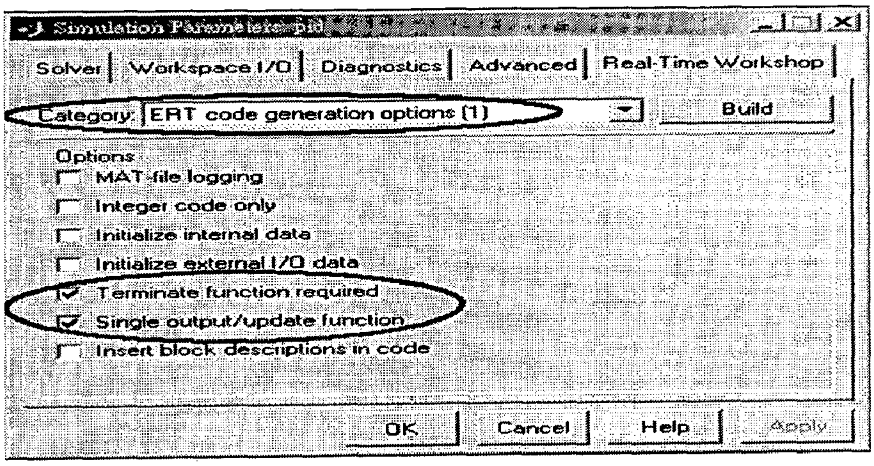
Step 3: Then click the "Real-Time Workshop" tab and the pane changes. On the pane that shows up, select "Target configuration" from the "Category" field. Then click the Browse button to open the "System Target File Browser" window.



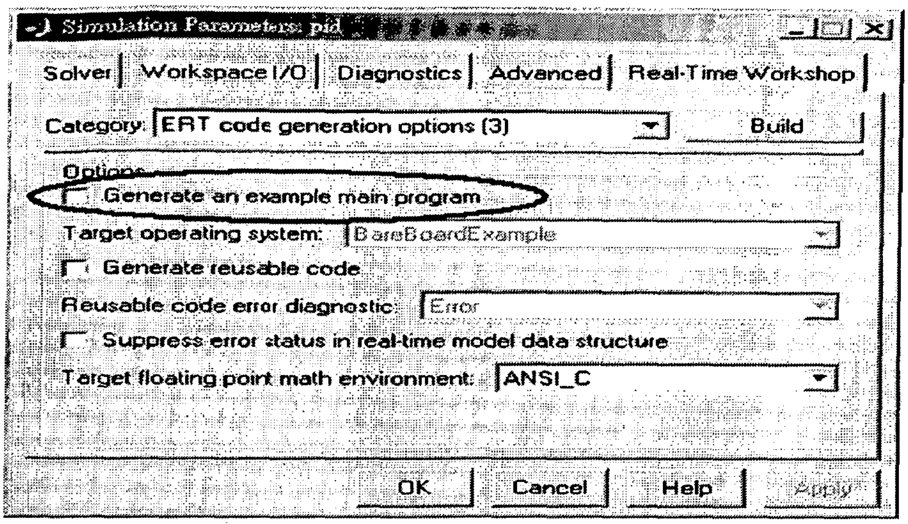
Step 4: On the System Target File Browser dialog, select the correct system target file from the list and then click the OK button to close the dialog box. Here, choose I_8xx8.tlc.



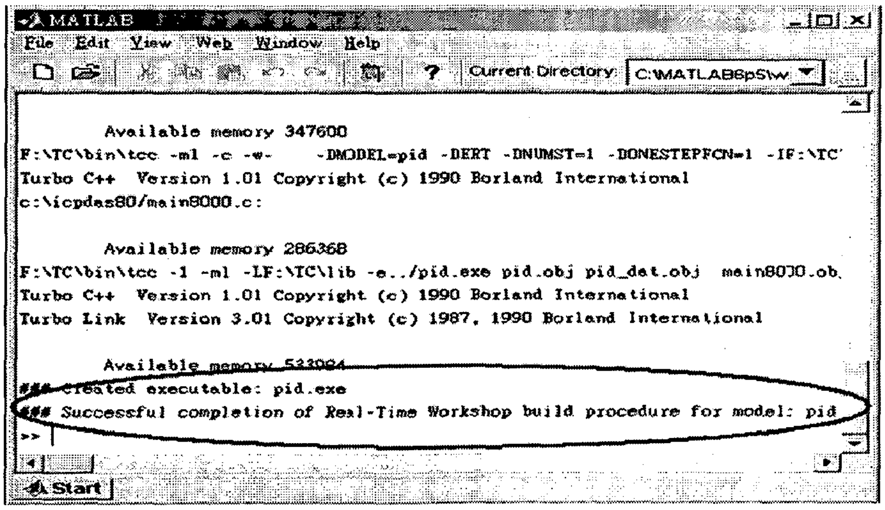
Step 5: And select the "ERT code generation options" (for MATLAB 6.1) or "ERT code generation options (1)" (for MATLAB 6.5) in the Category field. Then check the **Terminate function required** and **Single output/update function** options on the pane.



Step 6: For MATLAB 6.5, you have to select "ERT code generation options (3)" from the Category field. Then cancel the option **Generate an example main program**.



Step 7: When the above steps are done, click the Build button to start the build process. After the process ends successfully, the message in the MATLAB command window looks like as the following figure.



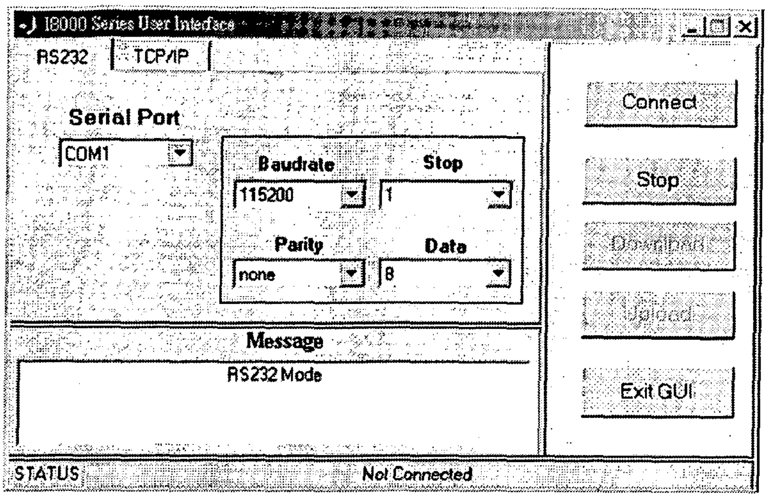
Note:

①The name of the model cannot be over 4 characters. (This is due to the limitation of Turbo C/C++ Compiler.)

Program Downloading & Data Uploading

After the build process is completed, you can download the executable file generated to the I8xx8 embedded controller in the following way:

Enter **gui8000** at the MATLAB prompt, and the GUI dialog box appears. It provides two communication modes, RS232 and TCP/IP, for you to download application program.



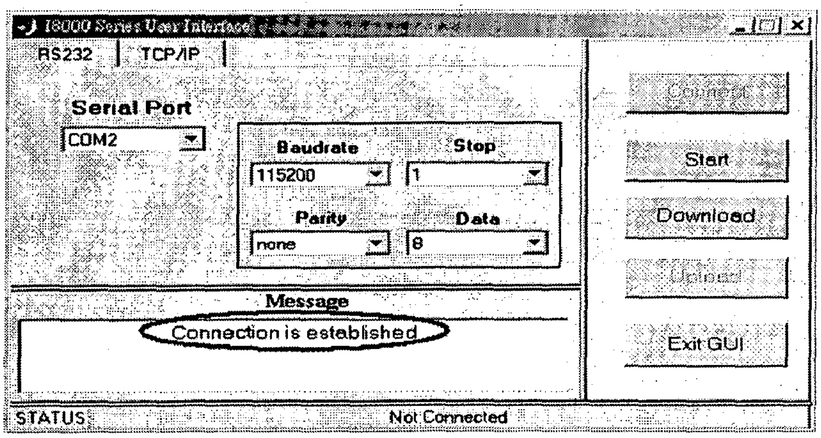
In RS232 mode, please follow steps to download the program to the I-8xx8 target system for application:

Step 1: Turn on the I8xx8 control system and **set I8xx8 control system in OS mode - it means that you must accomplish the step1 to step3 of Appendix A** before you download your program.

Step 2: Enter **gui8000** command at the MATLAB prompt and the GUI dialog box appears.

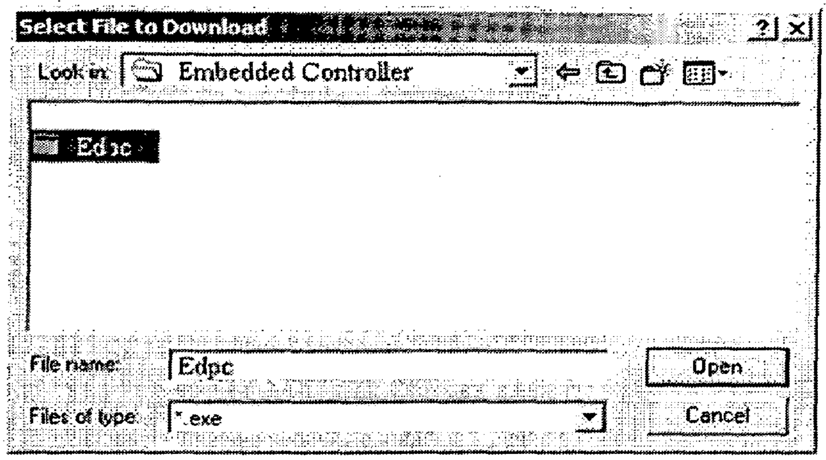
Step 3: Select the serial port you use in the PC to connect to the I8xx8 control system. Then set *Baud rate*, *Parity*, *Data bits*, *Stop bit* as '115200, none, 8, 1'. The default baud rate of the I8xx8 control system is 115200.

Step 4: Close 7188xw.exe first and then click the *Connect* button. If the connection is successful, the message, "Connection is established' on the dialog box", will show up.

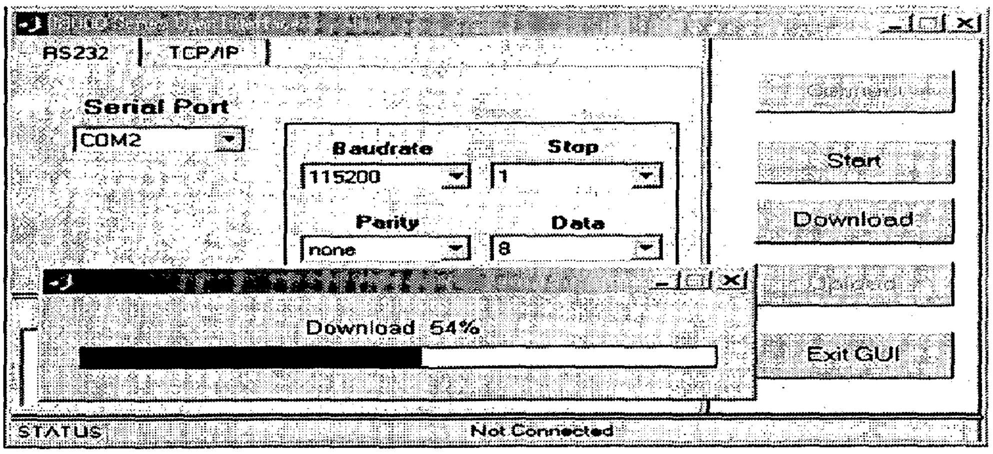


Step 5: Now it's time to download your program. Click the *Download* button and the *Select File to Download* dialog box appears. Select the file you want to download to the

I8xx8 control system and press the OK button to close the dialog box and then the download process starts.



Step 6: On the dialog box that appears, you can see the progress of program downloading. Then you can click the *Start* button to run your control program after the progress of program downloading was finished.



Step 7: After you execute the program successfully, then you can click the *Upload* button to collect the data from the I8xx8 control system, and data will be saved in a file whose name is the filename you assigned in the Data To File dialog box. This data file will be placed in the current working directory.

Step 8: Click the *Exit* button or X on the right-upper corner to close the GUI dialog box.