THE STUDY OF SINGLE PHASE DIODE RECTIFIERS WITH HIGH POWER FACTOR AND LOW TOTAL HARMONIC DISTORTION

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PRANAVI CHOWDARI TELLA

Dr. NAZ E. ISLAM, Thesis Supervisor

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The undersigned, appointed by the Dean of the Graduate School, have examined the thesis entitled

THE STUDY OF SINGLE PHASE DIODE RECTIFIERS WITH HIGH POWER FACTOR AND LOW TOTAL HARMONIC DISTORTION

Presented by **Pranavi Chowdari Tella**,

A candidate for the degree of Master of Science,

And hereby certify that, in their opinion, it is worthy of acceptance.

Dr. Naz E. Islam, Associate Professor, Dept. of Electrical and Computer Engineering

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Dr. Guilherme DeSouza, Assistant Professor, Dept. of Electrical and Computer Engineering

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Dr. H. R. Chandrasekhar, Professor, Dept. of Physics and Astronomy

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LIST OF ACRONYMS

AC…………………..Alternating Current

CMOS………………Complementary metal–oxide–semiconductor

DC…………………..Direct Current

EMI………………... Electromagnetic Interference

GTO…………………Gate Turn-off Thyristor

IGBT………………...Insulated Gate Bipolar Transistor

MOSFET…………….Metal Oxide Semiconductor Field Effect Transistor

PF……………………power factor

PFC…………………..Power Factor Correction

PU……………………Per unit

PWM…………………Pulse Width Modulation

RMS………………….Root Mean Square

THD………………….Total Harmonic Distortion

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THE STUDY OF SINGLE PHASE DIODE RECTIFIERS WITH HIGH POWER FACTOR AND LOW TOTAL HARMONIC DISTORTION

Pranavi Chowdari Tella

Dr. Naz E. Islam, Thesis Supervisor

ABSTRACT

The mains current in an ac/dc converter contains periodic current pulses due to the action of rectifier and output filter capacitor. The high current peaks cause harmonic distortion of the supply current and low power factor. This results in a poor power quality, voltage distortion, poor power factor at input ac mains, slowly varying rippled dc output at load end and low efficiency. Many input wave shaping methods have been proposed to solve the problem of poor power factor which can be classified as active and passive methods. The main focus of this study is to review various existing wave shaping methods in terms of their efficiency, total harmonic distortion and power factor. Among the passive wave shaping techniques, the improved passive current wave shaping method and the novel method are analyzed and are simulated in ORCAD software. The active method which uses a MOSFET switch driven by the rectangular pulses of continuously varying duty cycle over a period of supply voltage is analyzed. The relevant theoretical design parameters and the simulated results are presented.

CHAPTER 1: INTRODUCTION

1.1 Aim of the work and research Goals

Single phase diode rectifiers are widely used for industrial applications. Many conventional switching power supplies in data processing equipment and low power motor drive systems operate by rectifying the input ac line voltage and filtering with large electrolytic capacitors. The capacitor draws current in short pulses. This introduces several problems including reduction in the available power and increased losses. This process involves both nonlinear and storage elements and results in the generation of harmonics in the line current. The non linear characteristics of loads such as televisions, computers, faxes and variable speed motor drives used in air-conditioning have made harmonic distortion a common occurrence in electrical distribution systems. However when operating in large numbers, the cumulative effect of these loads have the capability of causing serious harmonic distortions. This results in a poor power quality, voltage distortion, poor power factor at input ac mains, slowly varying rippled dc output at load end and low efficiency.

Further the input current has narrow pulses which in turn increase its r.m.s value. Buildings with large number of computers and data processing equipment also experience large neutral currents rich in third harmonic currents. Therefore the reduction in input current harmonics and the improvement of power factor operation of motor drives and switching power supplies is necessary from energy saving point of view. Many input wave shaping methods have been proposed to solve the problem of poor power factor which can be classified as active and passive methods. In general active methods have disadvantage of being difficult to implement, expensive and less reliable. These disadvantages are eliminated by the use of passive wave shaping methods. Among the passive wave shaping methods, the improved passive current wave shaping method [3] is superior to all others in reducing total harmonic distortion and improving power factor to near unity.

The passive techniques which introduce a filtering stage consisting of inductors and/or capacitors that reduce the amplitude of low frequency harmonics are attractive for their simple design, less cost and are more reliable. On the other hand, active techniques use a high frequency converter that shapes the input current to almost sinusoidal waveform with small harmonic content. The active techniques proposed so far are satisfactory to some extent but the design complexity and the cost of additional circuitry is often found to be unacceptable for low power applications.

The aim of this research work is to investigate the need for PFC circuits including identifying new applications that help reduce harmonic currents and to review the existing power factor correction circuits and analyzing them in terms of their efficiency and total harmonic content in the input current. The focus is to investigate methods to improve power factor, improve efficiency and reduce total harmonic distortion. Thus the overall objective of this thesis is to review the existing methods that reduce the total harmonic distortion, obtain high power factor and to increase the overall system efficiency.

The analysis of single phase diode rectifiers in this study are based on the following assumptions.

- The ac source is considered to be ideal and the local voltage is assumed to be ripple free and the load is assumed to be purely resistive

- Ideal filter components i.e. the losses in the inductor, capacitor and the bridge rectifier are neglected.
- The filter capacitance is assumed to be such a large value that the output voltage is ripple free constant dc voltage.
- All switching power devices are considered to be ideal and the forward voltage drop and reverse leakage currents of diodes are neglected.

1.2 Introduction to power electronics

1.2.1 Power electronics industry

Utility systems usually generate, transmit and distribute power at a fixed frequency such as 50 Hz or 60 Hz, while maintaining a reasonably constant voltage at the consumer terminal. The consumer may use different electronic or electrical products which consumes energy from a DC or AC power supply which converts the incoming AC in to required form. In the case of products or systems running on AC, the frequency may be the same, higher, lower or variable compared to the incoming frequency. Often power needs to be controlled with precision. A power electronics system interfaces between the utility system and the consumer load to satisfy this need.

The core of most power electronic apparatus consists of a converter using power semi conductor switching devices that works under the guidance of control electronics. The converters can be classified as rectifier (AC-to-DC converter), inverter (DC-to-AC converter), DC-to-DC converter or an AC power controller (running at the same frequency) etc. Often conversion is a hybrid type that mixes more than one basic conversion process. The motivation for using switching devices in a converter is to increase the conversion efficiency to a very high value. In a few situations of power electronic systems, the power semiconductors devices are used in the linear mode too, even though due to the reasons of efficiency it is getting more and more limited. Power electronics can be described as an area where anything from a few watts to over several hundred megawatt order powers are controlled by semiconductor control elements which consume only few microwatts to milliwatts in most areas.

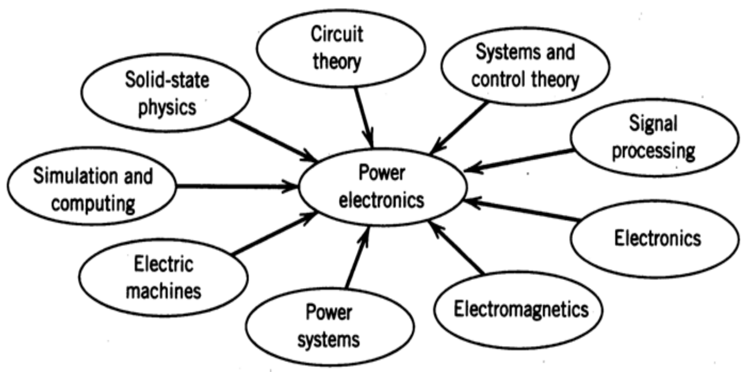

Fig 1.1: Interdisciplinary nature of power electronics [4]

1.2.2 Power conversion electronics

Power conversion electronics can be described as a group of electrical and electronic components arranged in the form of an electric circuit or a group of circuits for purpose of modifying or controlling electric power from one form to another. For example, power conversion electronics is employed to provide extremely high voltages to picture tubes to display the courses of aircraft approaching in airport.

In another example, power conversion electronics is employed to step up low voltage from a battery to the high voltage required by a vacuum fluorescent display to allow paramedics to display a victim's heartbeat on the screen. This also allows paramedics to gain information which may save the patient's life. Twenty years ago, power conversion was in its infancy, high efficiency switch mode power supplies were a laboratory curiosity, not a production line reality. Complex control functions such as precision control of stepper motors for robotics, micro electronics for implanted pacemakers and harmonic- free switch mode power supplies, were not economically achievable with the limited capabilities of semi conductor components.

1.2.3 Power electronic system

Most power electronic systems consist of two major modules: (1) The power stage (forward circuit) and (2) the control stage (feedback circuit).

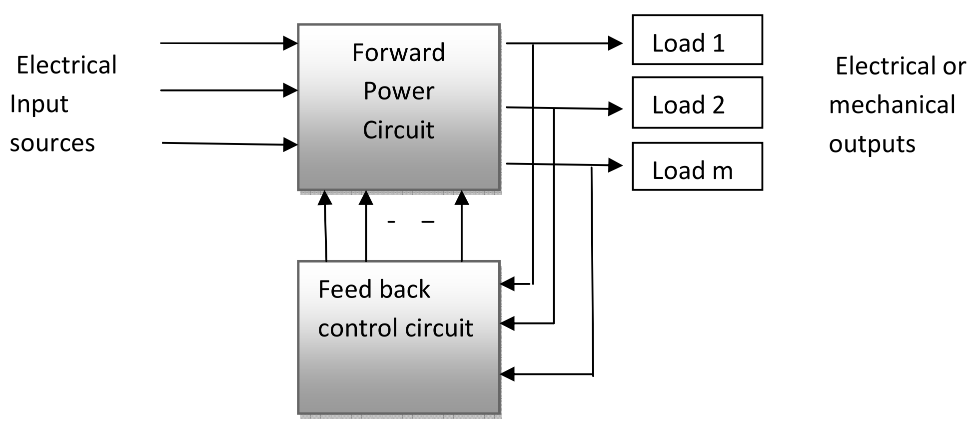

Fig 1.2: simplified block diagram for a power electronic system.

The power stage handles the power transfer from the input to the output and the feedback circuit controls the amount of power transferred to the output. A generalized block diagram of a power electronic system with n sources and m loads is given in fig 1.2 where the electrical inputs are sources like voltage, current or angular frequency and the output signals are voltages, currents or angular frequency. P_{in} (t) is the total instantaneous input power in watts. P_{out} (t) is the total instantaneous output power in watts. The efficiency, η, is defined as follows:

$$\eta = \frac{Pout}{Pin} * 100\ \% \qquad (1)$$

Fig 1.2 shows the detailed description of a block diagram for power electronic input system with electrical and mechanical output loads. The main function of a power electronic circuit is to process energy from a given source to a required load. The function of the power converter stage is to perform the actual power conversion and processing of the energy from the input to the output by incorporating a matrix of power switching devices. The control of the output power is carried out through control signals applied to these switching devices.

Broadly speaking, power conversion refers to the power electronic circuit that changes one of the following: voltage form (ac or dc), voltage level (magnitude), voltage frequency (line or otherwise), voltage wave shape (sinusoidal or non-sinusoidal such as square, triangle or saw tooth), or voltage phase (single or three phase). There are four conversion circuits that are used in the majority of today's power electronic circuits.

a. Rectification (ac-to-dc)
b. Inversion (dc-to-ac)
c. Cycloconversion (ac-to-ac, different frequencies) or ac controllers (ac-to-ac same frequency)
d. Conversion (dc-to-dc)

1.2.4 Semiconductor components

In modern power electronics apparatus, there are essentially two types of semiconductor elements: the power semiconductors that can be defined as the muscle of the equipment, and micro electronic control chips, which provide the control and intelligence. In most situations operations of both are digital in nature. One manipulates large power up to mega or gigawatts, the other handles power only on the order of microwatts to milliwatts.

Until the 1970's, power semiconductor technology was based exclusively upon bipolar devices, which were first introduced commercially in the 1950s. The most important devices in this category are the p-i-n power rectifier, the bipolar transistor, and the conventional power thyristor. The growth in the ratings of these devices was limited by the availability of high purity silicon wafers with large wafer diameter, and their maximum switching frequency was limited by minority carrier life time control techniques.

In the 1980s another bipolar device, the gate Turn-Off thyristor (GTO), became commercially available with the ratings suitable for high power applications. Its ability to turn-on and turn-off large current levels under gate control eliminated the commutation circuits required for conventional thyristors, thus reducing size and weight in traction applications, etc. Although these bipolar devices have been exclusively used for power electronic applications, a fundamental drawback that has limited their performance is the current controlled output characteristics of these devices. This characteristic has necessitated the implementation of high power systems with powerful discrete control circuits, which are larger in size and weight.

In the 1970s, the first power Metal-Oxide-Semiconductor Field Effect Transistor (MOSFETS) became commercially available. Their evolution represents the convergence of power semiconductor technology with main stream CMOS integrated circuit technology for the first time. Subsequently, in the 1980s, the Insulated Gate Bipolar Transistor (IGBT) became commercially available.

The MOSFET and IGBT require negligible steady state control power due to their Metal-Oxide-Semiconductor (MOS) gate structure. This feature has made them extremely convenient for power electronic applications resulting in a rapid growth in the percentage of their market share for power transistors.

The ratings of the power MOSFET and IGBT have improved rapidly in the recent years, resulting in their overtaking the capability of bipolar power transistors. However the physics of operation of these devices limits their availability to handle high current levels at operating voltages in excess of 2000 volts. Consequently, for high power systems, such as traction (electric locomotives and trams) and power distribution, bipolar power devices, namely the thyristor and GTO, are the best commercially available components today.

The development of the insulated gate power devices discussed above has reduced the power required for controlling the output transistors in systems. The relatively small (less than an ampere) currents at gate drive voltages of less than 15 volts that are needed for these devices can be supplied by transistors that can be integrated with CMOS digital and bipolar analog circuitry on the monolithic silicon chip. This led to the advent of smart power technology in the 1990s.

Smart power technology provides not only the control function in systems but also serve to provide over-current, over-voltage, and over-temperature protection, etc. At lower power levels, it enables the implementation of an entire subsystem on a monolithic chip. In systems such as automotive electronics or multiplex bus networks and power supplies for computers with low operating voltages (below 100 volts), the power MOSFET provides the best performance. In systems such as electric trams and locomotives, the GTO is best commercially available component. In the near future, MOS gated thyristor structures are likely to replace the GTO.

1.2.5 Applications of power electronics

Power electronics covers a wide range of residential, commercial, and industrial applications, including computers, transportation, aircraft/aerospace, information processing, telecommunications, and power utilities. Broadly speaking, these applications may be classified in to three categories:

Electrical applications:

Power electronics can be used to design ac and dc regulated power supplies for various electronic equipment, including consumer electronics, instrumentation devices, computers, aerospace, and uninterruptable power supply (UPS) applications. Power electronics is also used in the design of distributed power systems, electric heating and lighting control, power factor correction, and static var compensation.

Electromechanical applications:

Electromechanical conversion systems are widely used in industrial, residential, and commercial applications. These applications include ac and dc machine tools, robotic drives, pumps, textile and paper mills, peripheral drives, rolling mill drives, and induction heating.

Electrochemical applications:

Electrochemical applications include chemical processing, electroplating, welding, metal refining, production of chemical gases and fluorescent lamp ballasts. Table

1.1[4] gives other power electronics applications in residential, commercial, industrial, transportation, utility systems, aerospace and telecommunication fields.

Table 1.1: Power electronics applications

(a) *Residential*	(d) *Transportation*
Refrigeration and freezers	Traction control of electric vehicles
Space heating	Battery chargers for electric vehicles
Air conditioning	Electric locomotives
Cooking	Street cars, trolley buses
Lighting	Subways
Electronics (personal computers, other entertainment equipment)	Automotive electronics including engine controls
(b) *Commercial*	(e) *Utility systems*
Heating, ventilating, and air conditioning	High-voltage dc transmission (HVDC)
Central refrigeration	Static var compensation (SVC)
Lighting	Supplemental energy sources (wind, photovoltaic), fuel cells
Computers and office equipment	Energy storage systems
Uninterruptible power supplies (UPSs)	Induced-draft fans and boiler feedwater pumps
Elevators	(f) *Aerospace*
(c) *Industrial*	Space shuttle power supply systems
Pumps	Satellite power systems
Compressors	Aircraft power systems
Blowers and fans	(g) *Telecommunications*
Machine tools (robots)	Battery chargers
Arc furnaces, induction furnaces	Power supplies (dc and UPS)
Lighting	
Industrial lasers	
Induction heating	
Welding	

1.2.6 Future trends in power electronics:

It is hard to predict the direction of future research in the field of power electronics, or any field for that matter. However, based on today's research and teaching activities in power electronics, which are driven by market demands, energy conservation, and cost reduction, it is possible to identify some possible short-term future research activities in power electronics:

- Continued technological improvement of high-power and high-frequency semiconductor devices.

- Continued development of power electronic converter topologies to attain further size and reduction with increased efficiency and performance
- Improvement in the design of driver circuits for switching devices
- Improvements in control techniques, including optimal and adaptive control
- Integration of power and control circuitry on “smart power” ICs and further development of application-specific modules
- Distributed power system (DPS) approach in applications such as VLSI mainframe computers, military VHSIC systems, and telecom switching equipment
- Power factor correction techniques and EMI reduction
- Additional applications of power electronics in Flexible AC Transmission Systems (FACTS)

As power electronics becomes cheaper, it will extend in to various new industrial, residential, aerospace, and telecommunications applications. Based on the growth of power electronics in recent years, future growth can be projected even greater. As long as we continue to seek improved standards, of living, our quest for cheap and environmentally clean energy will continue. Power electronics will be used widely to address energy conversion and conversion efficiency. It has been reported that energy savings of more than 20% could be achieved with the help of power electronics. The role of power electronics will be greater as it becomes cheaper and more devices and systems become available. The challenge of power electronic circuit engineers is to keep developing new and optimal topologies to match market applications, and the challenge for power device engineers is to come up with new devices that can be used in these topologies.

1.3 Review of switching concepts and power semiconductor devices

Power semiconductor devices represent the heart of modern power electronics, with two major desirable characteristics guiding their development:

1. Switching speed (turn-on and turn-off times)
2. Power handling capabilities (voltage-blocking capability and current-carrying capability)

Improvements in semiconductor processing technology as well as in manufacturing and packaging techniques have allowed the development of power semiconductor devices for high voltage and high current ratings and fast turn-on and turn-off characteristics. The availability of different devices with different switching speeds, power handling capabilities, sizes, costs, and other factors makes it possible to cover many power electronic applications, so that trade-offs must be made when it comes to selecting power devices.

1.3.1 Need for switching in power electronic devices

There are many circuits that can perform energy conversion without switches, such as linear regulators and power amplifiers. However, the need for semiconductor devices to perform conversion functions is very much related to the converter efficiency. In power electronic circuits, the semiconductor devices are generally operated as switches, either in on-state or off-state. This is unlike in the case of power amplifiers and linear regulators, where semiconductors operate in the linear mode. As a result a very large amount of money is lost within the power circuit before the processed energy reaches the output. The need to use semiconductor switching devices in power electronic circuits is based on their ability to control and manipulate very large amounts of power from the input to the output with relatively very low power dissipation in the switching device, resulting in very high efficiency power electronic system.

Efficiency is very important figure of merit and has significant implication on the overall performance of the system. A low efficiency power system means that large amounts of power are being dissipated in the form if heat with one or more of the following implications.

1. The cost of energy increases due to increased consumption.
2. Additional design complications might be imposed, especially regarding the design of device heat sinks
3. Additional components such as heat sinks increase the cost, size, and weight of the system, resulting in low power density.
4. High power dissipation forces the switch to operate at low switching frequencies, resulting in limited bandwidth and slow response, and most important the size and weight of magnetic components (inductors and transformers) and capacitors remain large. Therefore it is always desirable to operate switches at very high frequencies.
5. Component and device reliability is reduced.

It has been proved from ages that switching is the best way to achieve high efficiency. However electronic switches are superior to the mechanical switches because of their high speed and power-handling capabilities as well as their reliability. Because of the nature of switch currents and voltages, high order harmonics are normally generated in the system. Moreover, depending on the device type and power electronic circuit topology used, driver circuit control and circuit protection can significantly increase the complexity of the system and its cost.

Ideal switch:

It is always desirable to have power switches perform near as possible to the ideal case. For a semiconductor device to operate as an ideal switch, it must possess the following features.

1. No limit on the amount of current (known as forward or reverse current) that the device can carry when in the conduction state (on-state)
2. No limit on the amount of device voltage (known as forward or reverse blocking voltage) when the device is in non conduction state (off-state)
3. No limits on the operating speed of the device when it changes state that means zero rise and fall times
4. Zero on-state voltage drop when in conduction state and infinite off-state resistance that means zero leakage current when in the non conduction state.

Practical switch:

The practical switch has the following switching and conduction characteristics

1. Limited power-handling capabilities, i.e., limited conduction current when the switch is in the on-state and limited blocking voltage when switch is in off-state
2. Limited switching speed, caused by finite turn-on and turn-off times, which limits the maximum operating frequency of the device
3. Finite on-state and off-state resistances, i.e., the existence of forward voltage drop in the on-state, and reverse leakage current flow in the off-state

4. Because of the characteristics 2 and 3, the practical switch experiences power losses in the on and off states (known as conduction loss) and during switching transitions (known as switching loss)

1.3.2 Available semiconductor switching devices

There are two broad families of power devices available.

1. Bipolar and unipolar devices
2. Thyristor based devices

The available bipolar and unipolar devices are power diodes, bipolar junction transistors (BJTs), insulated gate bipolar transistors (IGBTs), metal oxide semiconductor field effect transistors (MOSFETs). The thyristor based devices available are silicon-controlled rectifier (SCRs), gate turn-off (GTO) thyristors, triode ac switches (triacs), static induction transistors (SITs) and thyristors (SITHs), mos-controlled thyristors (MCTs). The types of power diodes and the types of power transistors are discussed in the following sections.

1.3.3 Types of power diodes

Diodes are classified according to their reverse recovery characteristics. The three types of power diodes are as under:

General purpose diodes:

These diodes have relatively high reverse recovery time, of the order of about 25µs. Their current rating varies from 1A to several thousand amperes and the range of voltage rating is from 50V to about 5kV. Applications of power diodes of this type include battery charging, electric traction, electroplating, welding and uninterruptible power supplies (UPS).

Fast recovery diodes

The diodes with low reverse recovery time, of about 5µs or less, are classified as fast-recovery diodes. These are used in choppers, commutation circuits, switched mode power supplies, induction heating etc. Their current rating varies from about 1A to several thousand amperes and voltage ratings from 50V to about 3kV.

Schottky diodes:

These classes of diodes use metal to semiconductor junction for rectification purposes instead of pn-junction. Schottky diodes are characterized by very fast recovery time and low forward voltage drop. Rectified current flow is by majority carriers only and this avoids the turn-off delay accompanied with minority carrier recombination. Their reverse voltage ratings are limited to about 100V and forward current ratings vary from 1A to 300A. Applications of schottky diodes include very high-frequency instrumentation and switching power supplies.

1.3.4 Types of power transistors

Power diodes are uncontrolled devices. In other words their turn-on and turn-off characteristics are not under control. Power transistors, however, possess controlled characteristics. These are turned on when a current signal is given to base or control terminal. The transistor remains in the on-state so long as the control signal is present. When this control signal is removed, a power transistor is turned off.

Bipolar junction transistors and monolithic Darlingtons

The circuit symbol for an NPN BJT is shown in the fig 1.3a, and its steady state i-v characteristics are shown in fig 1.3b. As shown in the i-v characteristics, a sufficiently large base current (dependent on the collector current) results in a device being fully on. This requires that the control circuit provide a base current that is sufficiently large so that $I_B > \frac{Ic}{hfe}$ (2)

where h_{fe} is the dc current gain of the device.

The on-state voltage $V_{CE\ (sat)}$ of the power transistors is usually in the 1-2V range, so that the conduction power loss in the BJT is quite small. The idealized i-v characteristics of the BJT operating as a switch are shown in fig 1.3 c

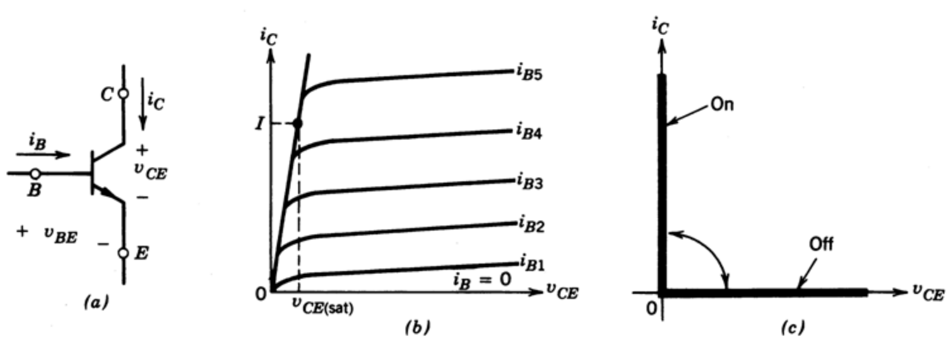

Fig 1.3 (a) symbol of BJT (b) i-v characteristics (c) idealized characteristics [4]

Bipolar junction transistors are current controlled devices, and the base current must be supplied continuously to keep them in on-state. The current gain h_{fe} is usually only 5-10 in high power transistors, and so these devices are sometimes connected in a Darlington or triple Darlington configuration as shown in fig 1.4a and b, to achieve a larger current gain. Some disadvantages accrue in this configuration including slightly higher over all $V_{CE(sat)}$ values and slower switching speeds.

Whether in single units or made as a Darlington configuration on a single chip [a monolithic Darlington (MD)], BJTs have significant storage time during the turn-off transition. Typical switching times are in the range of a few hundred nanoseconds to a few micro seconds

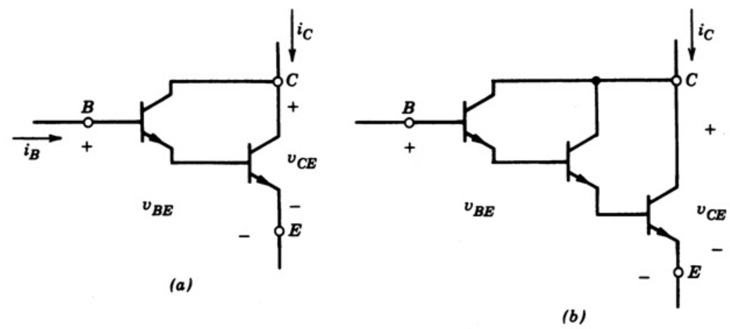

Fig 1.4: Darlington configurations (a) Darlington (b) triple Darlington [4]

Including MDs, BJTs are available in voltage ratings up to 1400V and current ratings of a few hundred amperes. In spite of a negative temperature coefficient of on-state resistance, modern BJTs fabricated with a good quality control can be paralleled provided that care is taken in the circuit layout and that some extra current margin is provided, that is, where theoretically four transistors in suffice based on equal current sharing, five may be used to tolerate a slight current imbalance [4].

Metal-Oxide-Semiconductor field Effect Transistors

The circuit symbol of the n channel MOSFET is shown in fig 1.5(a). It is a voltage controlled device, as indicated by the i-v characteristics as shown in fig 1.5(b). The device is fully on and approximates a closed switch when the gate-source voltage is below the threshold value, $V_{GS(th)}$. The idealized characteristics of the device operating as a switch are shown in fig 1.5(c).

MOSFETs require the continuous application of a gate-source voltage of the appropriate magnitude in order to be on-state. No gate current flows except during transitions from on to off or vice versa when the gate capacitance is being charged or discharged. The switching times are very short, being in the range of a few tens of nanoseconds to a few hundred nanoseconds depending on the device type.

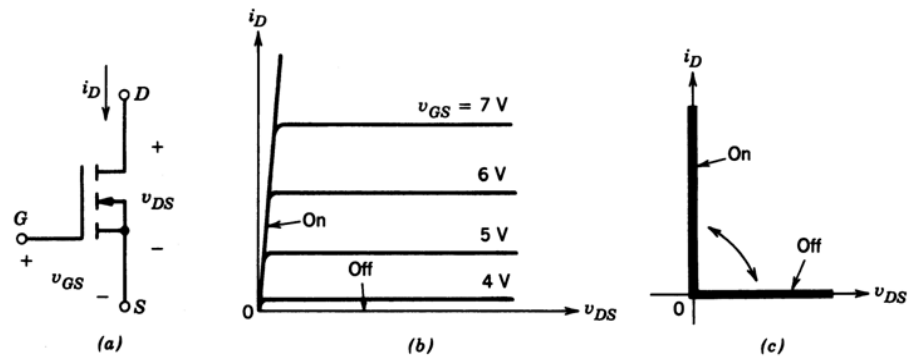

Fig 1.5 N-channel MOSFET(a) symbol (b) i-v characteristics (c) idealized characteristics [4]

However, because of their fast switching speed, the switching losses can be small. MOSFETs are available in voltage ratings in excess of 1000 V but with small current ratings and with up to a 100 A at small voltage ratings. The maximum gate source voltage is +20 or -20, although MOSFETs that can be controlled by 5 V signals are available [4].

Insulated gate bipolar transistors

The circuit symbol for an IGBT is shown in fig 1.6(a) and its i-v characteristics are shown in fig 1.6(b). The IGBTs have some of the advantages of the MOSFET and the BJT. Similar to MOSFET, the IGBT has a high impedance gate, which requires only a small amount of energy to switch the device. Like the BJT, the IGBT has a small on-state voltage even in devices with large blocking voltage ratings (for example, Von is 2-3 V in a 1000 V). IGBTs have turn-on and turn-off times on the order of 1 μs and are available in module ratings as large as 1700 V and 1200 A. Voltage ratings of up to 2-3 kV are projected [4].

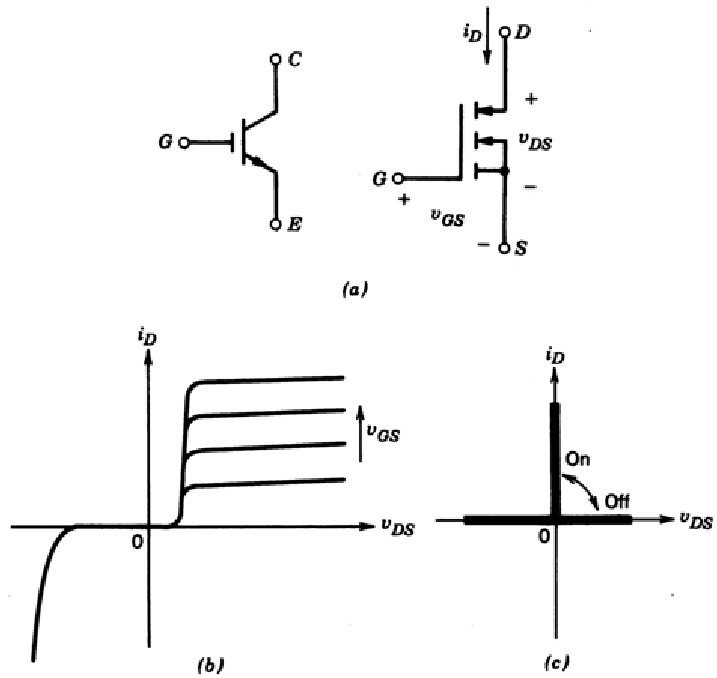

Fig 1.6: IGBT (a) symbol (b) i-v characteristics (c) idealized characteristics[4]

All the available switches are compared in terms of their power capability and their switching speed and are tabulated in table 1.2.

Table 1.2: Comparison chart of the power transistors

Controllable switch	Power capability	Switching speed
BJT	MEDIUM	MEDIUM
MOSFET	LOW	FAST
GTO	HIGH	SLOW
IGBT	MEDIUM	MEDIUM
MCT	MEDIUM	MEDIUM

1.4 Basic power factor and harmonic concepts

Harmonics are an increasing problem in electric power systems because of the expanding demand of nonlinear load such as power electronic equipment. Harmonics can cause a number of unwanted effects. Electric utility transmission and distribution equipment may be adversely affected by ac line harmonics which may cause higher transformer loss, capacitor failure or failure of protective relay operation. Sensitive electronic loads also may malfunction when connected to an ac line which has severe harmonics. Another concern is interference with communication circuits. The power line harmonics current can be coupled in to the communication circuits by either induction or direct conduction.

Major sources of harmonics in utility or industrial systems include rectifiers, motor drives, UPS and Arc furnaces. For this research, the harmonics due to rectifier loads are considered and analyzed. The wide spread application of power electronics is resulting in an increasing number of electrical load which include rectifiers to produce dc power. Inverter motor drives, uninterruptible power supplies and computer power supplies generally have rectifier inputs. The most common ac to dc converter used in power electronics is single phase diode rectifier.

1.4.1 Harmonics:

A harmonic is defined as a sinusoidal component of a periodic wave having a frequency that is an integral multiple of the fundamental frequency. We define harmonics as voltages or currents at frequencies that are a multiple of the fundamental frequency. In most systems, the fundamental frequency is 60 Hz. Therefore, harmonic order is 120 Hz, 180 Hz, 240 Hz and so on. (For European countries with 50 Hz systems, the harmonic order is 100 Hz, 150 Hz, 200 Hz, etc.)We usually specify these orders by their harmonic number or multiple of the fundamental frequency.

For example, a harmonic with a frequency of 180 Hz is known as the third harmonic (60x3 = 180). In this case, for every cycle of the fundamental waveform, there are three complete cycles of the harmonic waveforms. The even multiples of the fundamental frequency are known as even-order harmonics while the odd multiples are known as the odd-order harmonics.

Effects of harmonics:

The biggest problem with harmonics is voltage waveform distortion. We can calculate a relationship between the fundamental and distorted waveforms by finding the square root of the sum of the squares of all harmonics generated by a single load, and then dividing this number by the nominal 60 Hz waveform value. We can do this by a mathematical calculation known as a Fast Fourier Transform (FFT) theorem. This calculation method determines the total harmonic distortion (THD) contained within a nonlinear current or voltage waveform. Electronic equipment generates more than one harmonic frequency. For example, computers generate 3rd, 9th, and 15th harmonics. These are known as triplen harmonics. They are of a greater concern to engineers and building designers because they do more than distort voltage waveforms. They can overheat the building wiring, overheat transformer units, and cause random end-user equipment failure.

Harmonics can cause overloading of conductors and transformers and overheating of utilization equipment such as motors. Triplen harmonics can especially cause overheating of neutral conductors on 3-phase, 4-wire systems. While the fundamental frequency and even harmonics cancel out in the neutral conductor, odd-order harmonics are additive. Even in a balanced load condition, neutral currents can reach magnitudes as high as 1.73 times the average phase current. This additional loading creates more heat, which breaks down the insulation of the neutral conductor. In some cases, it can break down the insulation between windings of a transformer. In both cases, the result is a fire hazard. But this potential damage can be diminished by using sound wiring practices.

1.4.2 Power Factor

Power factor (PF) is defined as the ratio of the real power (P) to apparent power (S), or the cosine (for pure sine wave for both current and voltage) that represents the phase angle between the current and voltage waveforms (Fig 1.7). The power factor can vary between 0 and 1, and can be either inductive (lagging, pointing up) or capacitive (leading, pointing down). In order to reduce an inductive lag, capacitors are added until PF equals 1. When the current and voltage waveforms are in phase, the power factor is 1 ($\cos(0°) = 1$). The whole purpose of making the power factor equal to one is to make the circuit look purely resistive (apparent power equal to real power).

Real power (watts) produces real work; this is the energy transfer component (example electricity-to-motor rpm). Reactive power is the power required to produce the magnetic fields (lost power) to enable the real work to be done, where apparent power is considered the total power that the power company supplies, as shown in Figure 1.7. This total power is the power supplied through the power mains to produce the required amount of real power.

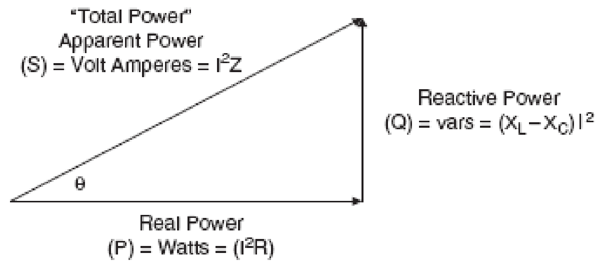

Fig 1.7: Power factor triangle (lagging) [31]

The previously-stated definition of power factor related to phase angle is valid when considering ideal sinusoidal waveforms for both current and voltage; however, most power supplies draw a non-sinusoidal current. The purpose of the power factor correction circuit is to minimize the input current distortion and make the current in phase with the voltage.

When the power factor is not equal to 1, the current waveform does not follow the voltage waveform. This result not only in power losses, but may also cause harmonics that travel down the neutral line and disrupt other devices connected to the line. The closer the power factor is to 1, the closer the current harmonics will be to zero since all the power is contained in the fundamental frequency.

1.4.3 Causes of inefficiencies

One problem with switch mode power supplies (SMPS) is that they do not use any form of power factor correction and that the input capacitor C_{in} (shown in Figure 1.8) will only charge when V_{in} is close to V_{Peak} or when V_{in} is greater than the capacitor voltage VC_{in}.

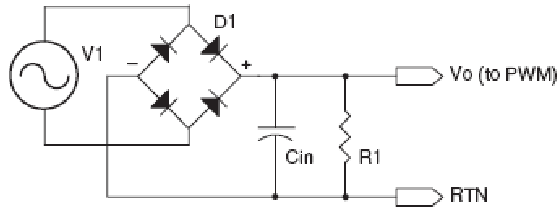

Fig 1.8: SMPS input without PFC [31]

If C_{in} is designed using the input voltage frequency, the current will look much closer to the input waveform, however, any little interruption on the mainline will cause the entire system to react negatively. In saying that, in designing a SMPS, the hold-up time for C_{in} is designed to be greater than the frequency of V_{in}, so that if there is a glitch in V_{in} and a few cycles are missed, C_{in} will have enough energy stored to continue to power its load.

As previously stated, C_{in} will only charge when V_{in} is greater than its stored voltage, meaning that a non-PFC circuit will only charge C_{in} a small percentage of the overall cycle time. After 90 degrees (Fig 1.9), the half cycle from the bridge drops below the capacitor voltage (VC_{in}); which back biases the bridge, inhibiting current flow into the capacitor (via V_{in}). Notice how big the input current spike of the inductor is. All the circuitry in the supply chain (the wall wiring, the diodes in the bridge, circuit breakers, etc) must be capable of carrying this huge peak current.

During these short periods the C_{in} must be fully charged, therefore large pulses of current for a short duration are drawn from V_{in}. There is a way to average this spike out so it can use the rest of the cycle to accumulate energy, in essence smoothing out the huge peak current, by using power factor correction.

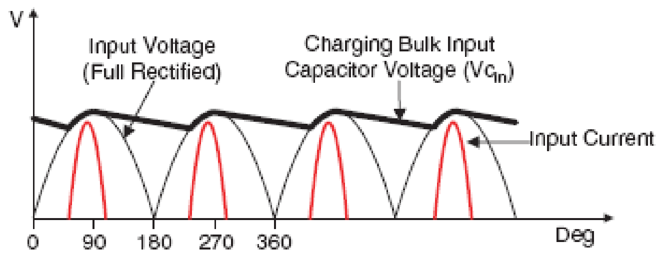

Fig 1.9: voltage and current waveforms in a simple rectifier circuit [31]

In order to follow V_{in} more closely and not have these high amplitude current pulses, C_{in} must charge over the entire cycle rather than just a small portion of it. Today's non-linear loads make it impossible to know when a large surge of current will be required, so keeping the inrush to the capacitor constant over the entire cycle is beneficial and allows a much smaller C_{in} to be used. This method is called power factor correction.

1.4.4 Need for power factor correction

The input stage of any AC-DC converter comprises of a full-bridge rectifier followed by a large filter capacitor. The input current of such a rectifier circuit comprises of large discontinuous peak current pulses that result in high input current harmonic distortion. The high distortion of the input current occurs due to the fact that the diode rectifiers conduct only for a short period. This period corresponds to the time when the mains instantaneous voltage is greater than the capacitor voltage. Since the instantaneous mains voltage is greater than the capacitor voltage only for very short periods of time, when the capacitor is fully charged, large current pulses are drawn from the line during this short period of time.

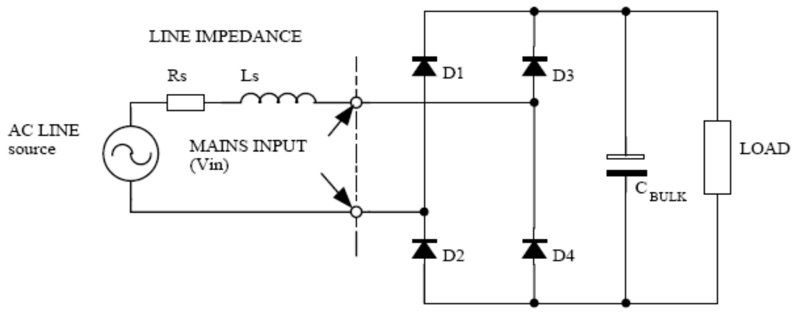

Fig 1.10: Schematic diagram of a single phase diode rectifier with capacitor filter circuit [33]

Fig 1.10 shows the schematic of a typical single phase diode rectifier filter circuit while Fig 1.11 shows the typical simulated line voltage and current waveforms. The typical input current harmonic distortion for this kind of rectification is usually in the range of 55% to 65% and the power factor is about 0.6 [5]. The actual current wave shape and the resulting harmonics depend on the line impedance.

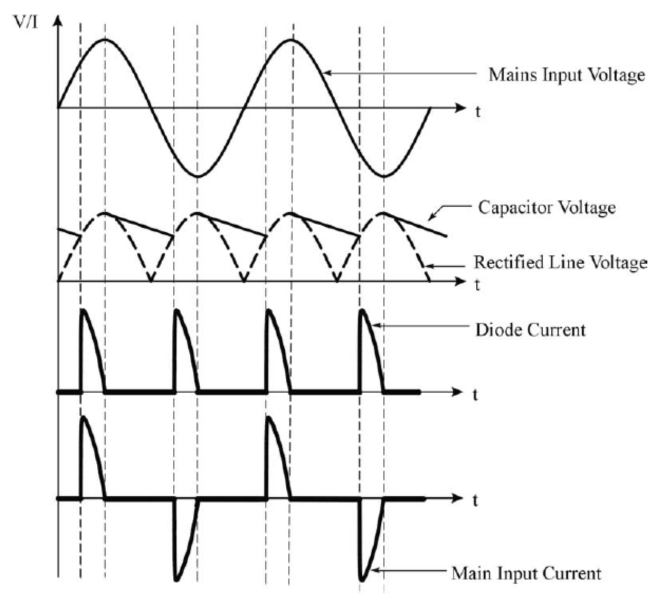

Fig 1.11: Typical line current and voltage waveforms [33]

Conventional AC rectification is thus a very inefficient process, resulting in waveform distortion of the current drawn from the mains. A circuit similar to that shown in fig 1.10 is used in most mains-powered AC-DC converters. At higher power levels (200 to 500 watts and higher) severe interference with other electronic equipment may become apparent due to these harmonics sent into the power utility line. Another problem is that the power utility line cabling, the installation and the distribution transformer, must all be designed to withstand these peak current values resulting in higher electricity costs for any electricity utility company.

Thus, summarizing, conventional AC rectification has the following main disadvantages:

- It creates harmonics and electromagnetic interference (EMI).
- It has poor power factor.
- It produces high losses.
- It requires over-dimensioning of parts.
- It reduces maximum power capability from the line.

1.5 Simulation environment

To successfully meet project goals, PCB designers and electrical engineers need powerful, intuitive, and integrated technologies that work seamlessly across the entire PCB design flow. Cadence OrCAD solutions offer fully integrated front-end design, analog/signal integrity simulation, and place-and-route technologies that boost productivity and shorten time to market.

OrCAD Capture provides fast and intuitive schematic design entry for PCB development or analog simulation using PSpice. The component information system (CIS) integrates with it to automatically synchronize and validate externally sourced part data. Easy-to-use and powerful, Cadence OrCAD Capture is the most widely used schematic design solution, supporting both flat and hierarchal designs from the simplest to the most complex. Seamless bi-directional integration with OrCAD PCB Editor enables data synchronization and cross-probing/placing between the schematic and the board design. OrCAD Capture allows designers to back annotate layout changes, make gate/pin swaps, and change component names or values from board design to schematic using the feedback process. It also comes with a large library of schematic symbols and can export netlists in a wide variety of formats.

OrCAD Capture CIS integrates the OrCAD Capture schematic design application with the added capabilities of a component information system (CIS). CIS allows designers to search, identify, and populate the design with preferred parts. With easy access to component databases and part information, designers can reduce the amount of time spent researching needed parts.

Features and benefits

- Boosts schematic editing efficiency of complex designs through hierarchical and variant design capabilities
- Integrates with a robust CIS that promotes the use of preferred, current parts to accelerate the design process and reduce project costs
- Provides access to more than two million parts with Cadence Active Parts, offering greater flexibility when choosing design components

The single phase power factor correction circuits designed with the given specifications are drawn using OrCAD capture Design entry CIS tool in Cadence software. The elements used in the circuits and their respective pspice libraries are tabulated and are included in the appendix. The data sheets of the major elements used in the active power factor correction circuits are included in the appendix.

CHAPTER 2: LITERATURE REVIEW

The power factor correction (PFC) technique has been gaining increasing attention in power electronics field in recent years. For the conventional single-phase diode rectifier, a large electrolytic capacitor filter is used to reduce dc voltage ripple. This capacitor draws pulsating current only when the input ac voltage is greater than the capacitor voltage, thus the THD is high and the power factor is poor. To reduce THD and improve power factor, passive filtering methods and active wave-shaping techniques have been explored.

Traditionally, the conversion of ac power to dc power has been done by using a diode rectifier and a large electrolytic dc capacitor connected to the rectifier output as shown in the fig 2.1. Such a conversion approach has the disadvantage of generating pulsed ac line currents drawn from the ac distribution network. The non ideal character of these input currents creates a number of problems for the power distribution network and for other electrical apparatus in the vicinity of the rectifier. This approach has many disadvantages, including

- High-input current harmonic components.
- Low rectifier efficiency because of large rms value of the input current.
- Input ac mains voltage distortion because of the associated peak currents.
- Maximum input power factor of approximately 0.50 while a larger filter inductor is required for a high-input power factor.

Many input current wave shaping methods have been proposed to overcome above disadvantages, which can broadly classify as active, passive and hybrid methods. In the past, designers have used three passive wave shaping methods to improve the input power factor and reduce total harmonic distortion THD of conventional ac-to-dc rectifiers [12]. Input passive filter method, resonant passive input filters method and Ferro resonant transformer method

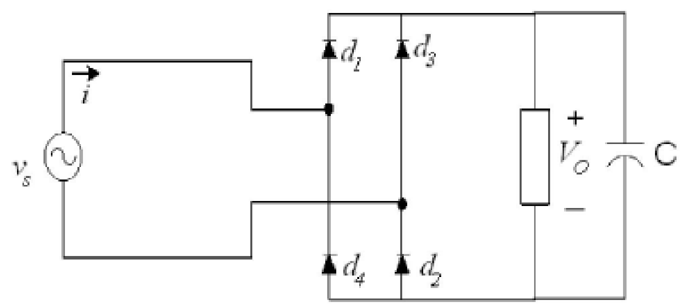

Fig 2.1 Conventional single phase ac-dc diode rectifier topology [14]

In the later years a new classification presented include passive, active and hybrid methods. Also, the past classification for passive techniques is not reasonable after all these methods, which is connected to the input, output and input\output sides. Many passive techniques (i.e. circuits using only inductors and capacitor) are available to improve power factor PF and reduce the levels of harmonics for single-phase rectifier, including the connection of series supply reactor, tuned series harmonic filter, tuned parallel harmonic filter. In these methods the power factor is improved and harmonic distortion is reduced in comparison with conventional topology. Among the passive wave shaping methods proposed earlier, the novel method (fig 2.2) proposed by P.D.Ziogas [5] in 1990 is superior to others in reducing the input current harmonics and improving the input power factor. The novel method can efficiently improve the power factor, however, the further improvement of the input power factor is difficult to achieve, and the input current's total harmonic distortion is still high, which is the main disadvantage of the novel topology. This novel method proposed by P.D. Ziogas [5] in 1990 (Fig 2.2) uses an input Lr-Cr parallel resonant tank to remove the third harmonic component from the input current. The input power factor increases because the third harmonic component is the main reason of the low input power factor. The advantages of the Ziogas method over the conventional method include: (i) low input current THD (ii) higher input power factor, and (iii) increase in the efficiency of the rectifier

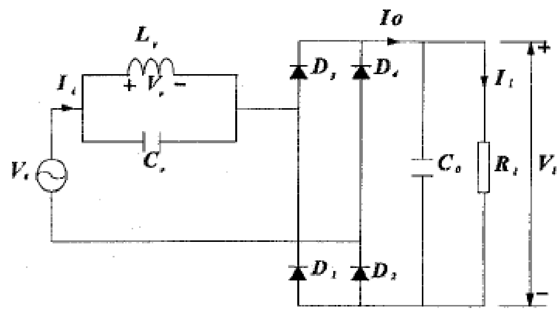

Fig 2.2 Novel single phase ac-dc rectifier topology [6]

In novel method, a single phase rectifier is designed for 5KW load specification from a 208 rms, single phase source with 60 Hz frequency. The power factor is found to be 0.957 which is better than 0.623, the power factor of conventional topology for the same specifications. The total harmonic distortion for the conventional method is 116% which is highly undesirable. There is a drastic drop down of the total harmonic distortion levels from the conventional topology to the novel method. The total harmonic distortion for the novel method is found to be 20%.

To overcome the disadvantage of still high total harmonic distortion associated with the novel method and to further improve the power factor, a capacitor C_b is placed in parallel between the parallel resonant tank and the rectifier bridge as shown in fig 2.3, which could compensate the reactive power and absorb the distortion power. This method is named as improved passive wave shaping method by Yanchao in 1996 [6]. Presenting the rather small impedance to the higher order harmonics, the capacitor C_b serves the function of filtering out these components. As a result the improved method has a better filter feature and the higher input power factor than the novel method. For a designed L_r and C_r values, C_b is selected such that the input power factor at rated output power reaches its peak value. In improved method [6], the single phase rectifier is designed for 5KW load specification from a 220v r.m.s with 5% output voltage ripple and its frequency is 50 Hz. The power factor is found to be 0.9852 and the total harmonic distortion is decreased from 20% to 14.9%.

The advantages of the improved method over novel method include:

1. Lower the input current total harmonic distortion due to significant filter feature of capacitor C_b
2. Higher input power factor,
3. Increased efficiency of the rectifier.

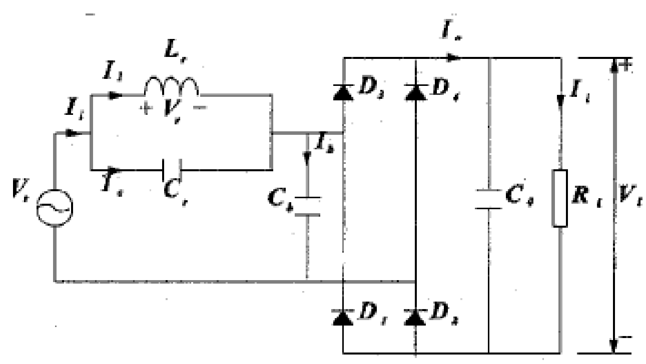

Fig 2.3 improved passive wave shaping method [6]

The passive methods are bulky and fail to provide satisfactory results. The active methods using high frequency switching technique to shape the input current are much preferred. There are also some disadvantages associated with active wave shaping methods. The disadvantages includes being difficult to implement, expensive and less reliable.

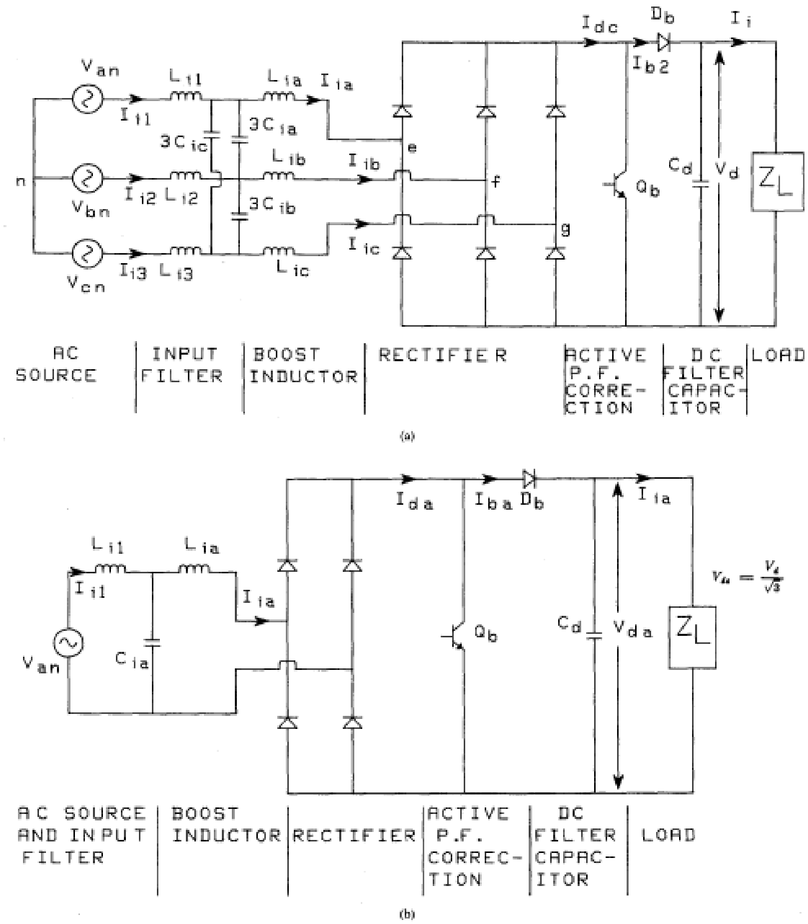

Fig 2.4(a) Active power factor correction technique for three phase diode rectifiers (b) Single phase equivalent circuit of (a) [13]

In 1991, a novel active power factor correction method for power supplies with three phase front end diode rectifiers (fig 2.4) is proposed and analyzed by A.R.Prasad and P.D.Ziogas. The implementation of this method requires the use of an additional single switch boost chopper. The combined front end converter draws sinusoidal ac currents from the ac source with nearly unity power factor while operating at a fixed switching frequency. In this study they also found that when active input power factor correction stage is also used to regulate the dc bus voltage, the converter performance can improve substantially. These improvements include component count reduction, simplified input synchronization logic requirements, and smaller reactive components. In this method the rectifier was designed for 1KW rated power with 50 V rms source voltage at 60 Hz frequency and the boost switching frequency was 24 KHz. This method does not deal with total harmonic distortion but the power factor is near unity.

Based on the analysis of the novel active power factor correction of three phase diode rectifiers by A.R.Prasad and P.D.Ziogas[13], M.A. Khan in 2007 [14] designed a single phase rectifier with switching on AC side for high power factor and low total harmonic distortion. This method uses a single MOSFET switch on the ac side to provide alternative path for input current to flow and hence make it continuous. The rectifier is connected to the ac mains through a series combination of inductor and capacitor, which keeps the input current smooth and in phase with the supply voltage. The simulated results revealed that the total harmonic distortion is below 2% with overall efficiency of 90%.

The single phase rectifier circuit was designed for 220 V rms source with 50 Hz frequency at 1KW load specification and several combinations of L and C at various switching frequencies are used to calculate the efficiencies and the percentage of total harmonic distortions. It was found that for the above specifications with the combination of 50 mH inductance and 206 μf the efficiency was found to be 91.12% and the total harmonic distortion is 2.8%. The single phase rectifier with switching on AC side is shown in fig 2.5.

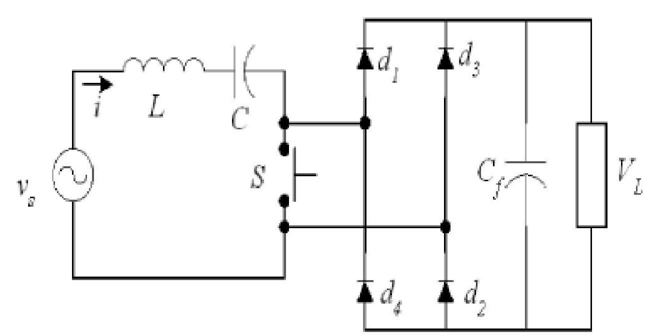

Fig 2.5 proposed scheme of single phase rectifier with switching on AC side [14]

CHAPTER 3: SINGLE PHASE POWER FACTOR CORRECTION- A REVIEW

Most of the applications that require ac-dc power conversion need the output dc voltage to be well regulated with good steady state and transient performance. The rectifier with filter capacitor is cost effective but it severely deteriorates the quality of the supply there by affecting the performance of other loads connected to it besides causing other problems. Since mid 1980's power electronics engineers have been developing new approaches for better utility interface, to meet these imposed standards. These new circuits have been collectively called power factor correction (PFC) circuits.

Reducing the input current harmonics to meet the agency standards implies improvement of power factor as well. Several techniques for power factor correction and harmonic reduction have been reported and a few of them have gained greater acceptance over the others. Commercial IC manufacturers have introduced control ICs in the market for the more popular techniques. In this chapter, the developments in the field of single-phase PFC are reviewed.

3.1 Single phase diode bridge rectifier

A single phase diode rectifier is an uncontrolled rectifier which is used to convert alternating current to direct current. A commonly used single-phase rectifier is shown in the fig 3.1. A large filter capacitor is connected on the dc side. The utility supply is modeled as a sinusoidal voltage source V_s in series with its internal impedance, which in practice is primarily inductive. Therefore it is represented by L_S. To improve the line-current waveform, an inductor may be added in series on the ac side, which will increase the value of L_S. The objective of this section is to thoroughly analyze the operation of this circuit.

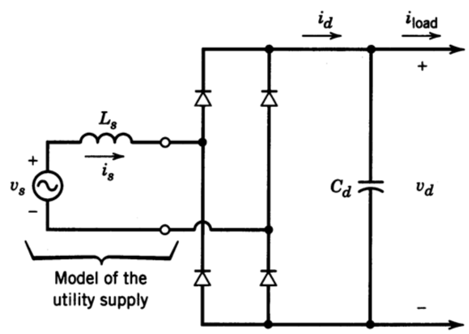

Fig 3.1 single phase diode bridge rectifier [4]

Idealized circuit with L_S =0

As a first approximation to the single phase diode rectifier circuit in fig 3.1, we will assume L_S to be zero and replace the dc side of the rectifier by a resistance R or a constant dc current source i_d, as shown in the fig 3.2 a and b.

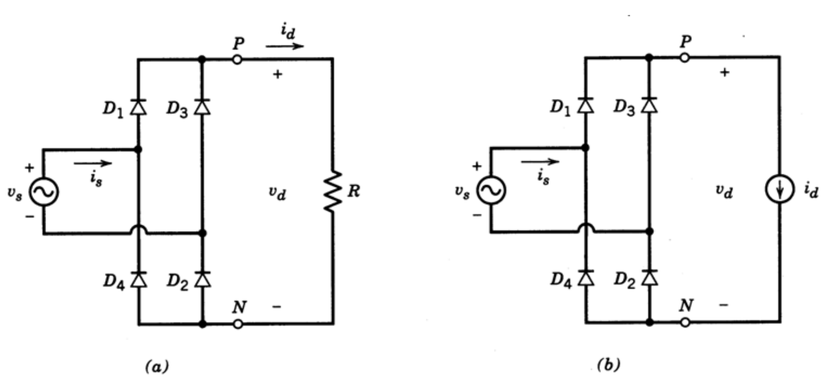

Fig 3.2 idealized circuit with Ls=0 [4]

The circuit in fig 3.2 is redrawn in fig 3.3, which shows that this circuit consists of two groups of diodes: top group with diodes 1 and 3 and bottom groups with diodes 2 and 4. It is easy to see the operation of each group of diodes with L_s =0. The current i_d flows continuously through one diode of the top group and one diode in the bottom group.

In the top group the cathodes of the two diodes are at common potential. Therefore the diode with its anode at the higher potential will conduct i_d. That is, when the voltage V_s is positive, diode 1 will conduct the current i_d and the voltage V_s will appear as a reverse-bias voltage across diode 3. When voltage V_s goes negative, the current i_d shifts (commutates) instantaneously to diode 3 since L_s=0. A reverse bias voltage appears across diode 1. In the bottom group, the anodes of the two diodes are at common potential. Therefore, the diode with its cathode at the lowest potential will conduct the current i_d. That is, when V_s is positive, diode 2 will carry the current i_d and voltage V_s will appear as reverse-bias voltage across diode 4. When the supply voltage V_s goes negative, the current i_d instantaneously commutates to diode 4 and a reverse-bias voltage appears across diode 2.

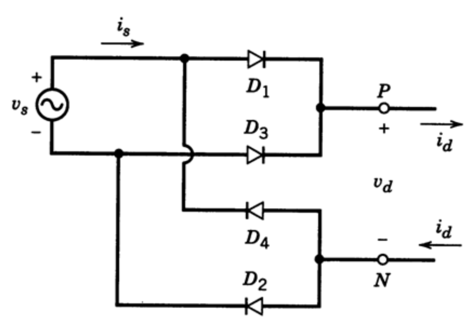

Fig 3.3: redrawn rectifier in fig.3.2 [4]

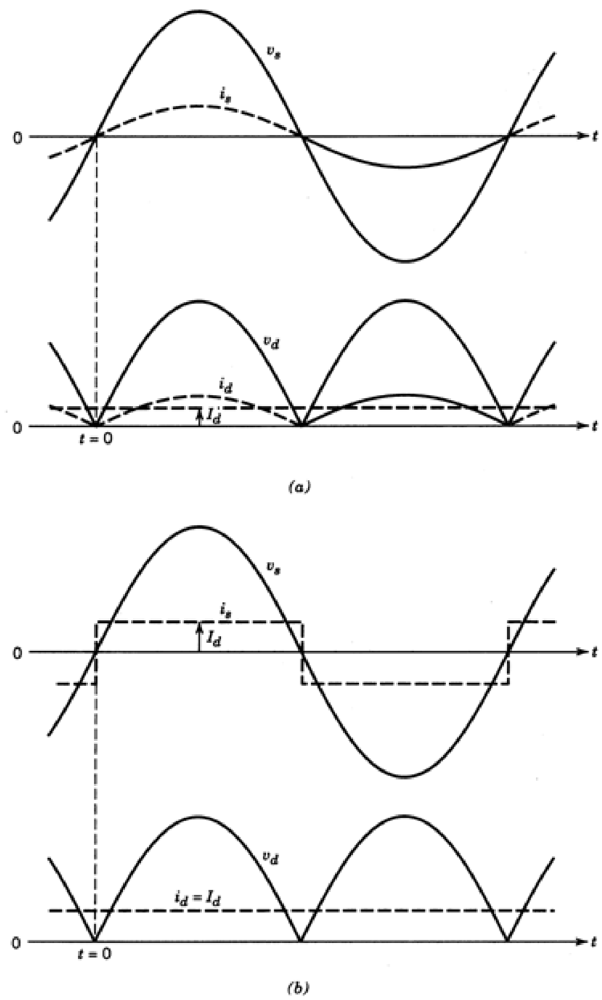

Fig 3.4 wave forms of the circuit in fig 3.2 a and b [4]

3.2 Conventional single phase ac-dc utility interface

The rectifier with filter capacitor is called a conventional ac-dc utility interface. The filter capacitor reduces the ripples present in the output voltage. Although a filter capacitor significantly suppresses the ripple from the output voltage, it introduces distortions in the input current and draws current from the supply discontinuously, in short pulses. This introduces several problems including reduction of available power and increased loss.

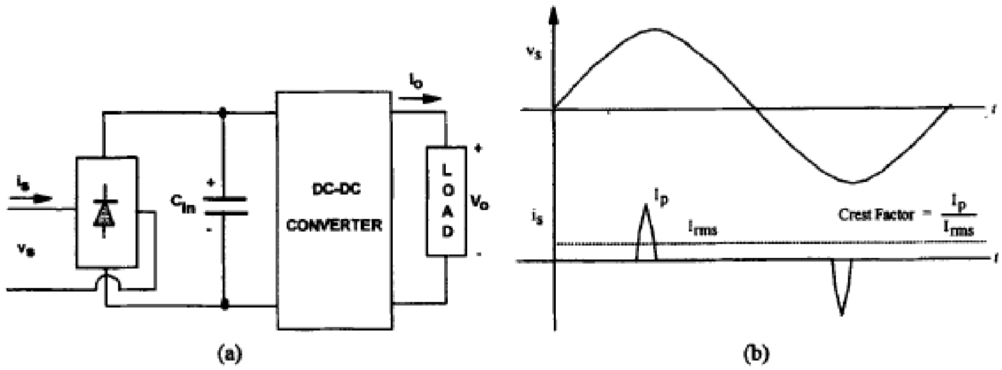

Fig 3.5 conventional utility interface [15]

3.2.1 Utility issues

Problems of conventional interface: The large harmonic content and the consequent poor PF of operation of the conventional rectifier--capacitor type interface causes several problems to the utility supply. Some of them are listed below [1-4]

(i) Due to harmonic components - Because of the non-zero source impedance in the utility supply, the harmonic currents flowing through the conventional ac-dc utility interface will cause a distortion in the voltage waveform at the point of common coupling to other loads. This may cause malfunction of power system protection, other loads and also metering devices. Besides voltage waveform distortion, harmonic components may also cause the problems of overheating of neutral line, distribution transformers and distribution lines, interference with communication and control signals, over voltages due to resonance conditions.

(ii) Due to poor PF - Poor power factor of operation implies ineffective use of the volt-ampere ratings of the utility equipment such as transformers, distribution lines and generators. Also, it places a restriction on the total equipment load that can be connected to a typical home or office wall-plug with specified maximum r.m.s current rating.

3.2.2 Desirable features of a power factor correction techniques

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:

(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.

Others: Mechanical and Electrical features

(1) Galvanic isolation between input and output.

(2) High power conversion efficiency.

(3) Hold-up time if required.

(4) Universal input voltage operation (85 V- 270 V ac r.m.s).

(5) Low part count.

(6) Smaller size and weight.

(7) Low cost.

3.3 Passive power factor correction

The power line disturbances caused by the proliferation of phase controlled and diode rectifier circuits were of concern even in late 70s [3][11]. The definition of power factor for nonlinear circuits and passive techniques for improving it are presented in an early literature [11]. Currently, passive techniques remain attractive for low power PFC applications [19]. It has been reported [19] that power factor as high as 0.98 can be achieved using passive PFC techniques. The following sub-sections discuss a few of the passive PFC circuits.

3.3.1 Inductive filter

Figure 3.6 shows a diode rectifier circuit with an inductor inserted between the output of the rectifier and the capacitor. The inclusion of the inductor results in larger conduction angle of the current pulse and reduced peak and r.m.s values. For low values of inductance the input current is discontinuous and pulsating. However, it is shown [11] that even for infinite value of the inductance; the PF cannot exceed 0.9 for this kind of arrangement.

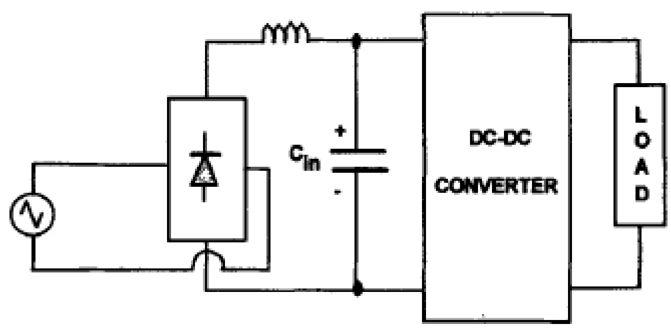

Fig 3.6: conventional rectifier circuit with inductive filter [15]

In the scheme shown in figure 3.7, a small filter capacitor C_s is connected across the input terminals of the circuit. The line inductance (not shown in figure 3.7) and C_s forms the first stage LC filter. Therefore higher order harmonics of the line frequency will undergo greater attenuation (typically 80 dB) resulting in better harmonic performance. It is reported [12] that even for a relatively small value of the inductance; PF of 0.86 is attainable, a considerable improvement over the no-capacitance case.

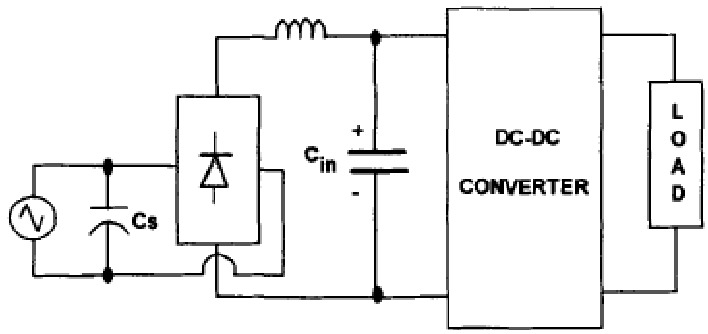

Fig 3.7: rectifier circuit with input capacitance Cs [15]

3.3.2 Resonant input filter

Figure 3.8 shows the series filter arrangement for power factor correction [13], which results in good power factors as high as 0.94. Thus, harmonic performance is also good. This circuit arrangement is popularly used in applications where the supply frequency is high. The disadvantage with this type of arrangement is the use of large size of elements and large r.m.s currents in the both filter capacitors

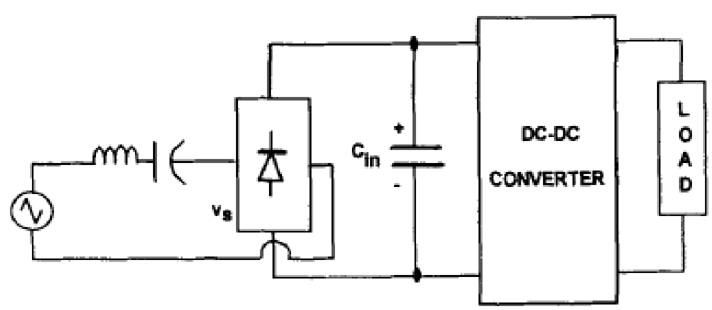

Fig 3.8: rectifier circuit with series resonant input filter [15]

Some authors [13][6], suggest the use of parallel resonant filter (see figure 3.9) for PF improvement. With this arrangement power factor close to 0.95 is achieved. The filter is tuned to offer very high impedance to the third harmonic component (the most predominant). The high value parallel resistor is added to damp out circuit oscillations.

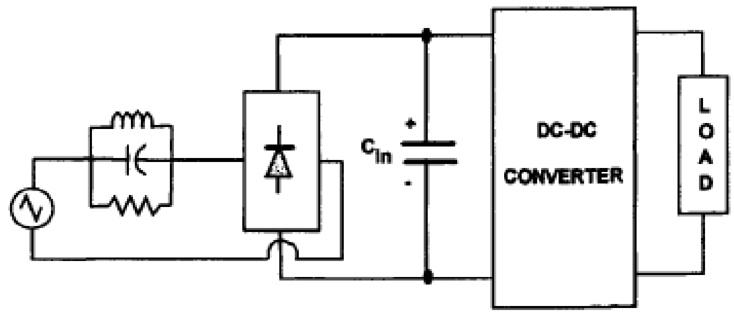

Fig 3.9: rectifier with parallel resonant filter [15]

3.4 Active power factor correction

The active PFC technique, which involves the shaping of the line current using switching devices such as MOSFETs (metal oxide semiconductor field effect transistors) and IGBTs (insulated gate bipolar junction transistors), is a result of advances in power semiconductor devices and microelectronics.

For low and medium power ranges up to a few kilowatts (<5 kW), MOSFETs are by far the popular choice for PFC because of their switching speed, ease of driving and ruggedness. BJTs and more recently IGBTs are used for high voltage medium power applications which MOSFETs are unable to contend with owing to their large on-state resistances.

For achieving good input current wave shaping using active techniques, typically the switching frequency should be at least an order of magnitude greater than 3 kHz (= 50 x 60 Hz = 50 th harmonic of line frequency). With modern advances in MOSFETs and IGBTs, this is feasible.

One of the recent active power factor correction methods to be discussed in the present work is the single phase rectifier circuit with switching on AC side for high power factor and low total harmonic distortion proposed by M.A. Khan [14] which uses a MOSFET switch on the AC side to provide alternative path for the input current to flow and hence makes it continuous.

The rectifier is connected to the ac mains through a combination of inductor and capacitor in series, which keeps the input current smooth and in-phase with the supply voltage. The input filter circuit constitutes a series resonant circuit in which the resonance condition is satisfied to calculate the inductance and capacitance values.

3.5 Design analysis

The design analysis for this research work is carried out for the following design specifications in which V_{base} is base voltage and P_{base} is base power. P_{in} and P_{out} are input and output power respectively. I_{base} is the input base current, Z_{base} is the base impedance, V_{out} is the output voltage, X_L is the inductive reactance and ω is the angular frequency.

A single phase bridge rectifier is designed for 1 KW load specification from a 115 V r.m.s, 60 Hz single phase source. The output voltage of 220 V_{dc} requires a minimal boosting.

Using Per unit values to simplify calculations, we get

V_{base} = 115 V = 1.0 pu

P_{base} = 1 kW = 1.0 pu

Assuming zero switching losses, $P_{in} = P_{out}$ = 1.0 pu

This yield

$I_{base} = P_{base} / V_{base}$ = 1K/ 115 = 8.695 A

$Z_{base} = V_{base} / I_{base}$ = 115/8.695 = 13.22 Ω

V_{out} = 220/ 115 = 1.91 pu

$I_{out} = P_{base} / V_{out} = 1K/220 = 4.54$ A

For the given design specifications, the output current is 4.545 A and therefore the output resistance R_L is 1000/ (4.545*4.545) = 48.4 Ω

Input resonant filter parameters

Input inductor L, may be determined by knowing the switching frequency f_s i.e., 2KHz. To obtain an input current ripple of < 1%, find L by

$I_{2\,KHz} = (0.01)\,(I_{60Hz}) = 0.01$ pu

$X_L = \omega L = V_n / I_n$

$X_{in} = n\omega L = n\,X_L$

Letting $n = f_s / f = 2K / 60 = 33.33$

Assuming $V_n = 1.0$ pu

$(33.33)\,X_L = 115/\,(8.65)(0.01)$

$X_L = 39.88$

$L = X_L / \omega = 105$ mH

I have chosen L = 100 mH to ensure a minimum ripple in the input current

If a series resonant filter is introduced at the input end of the single phase rectifier. The capacitance C is chosen such that the resonance condition is satisfied.

$\omega = 1/\sqrt{LC}$ Where $\omega = 2*\prod *$ frequency. So the value of C = 70 µf

Output capacitance

When the instantaneous voltage V_s is higher than capacitor voltage V_c, the diodes (D1 & D2 or D3 & D4) will conduct. The capacitor is charged from supply. If the instantaneous voltage Vs falls below the instantaneous capacitor voltage V_c, the diodes (D1 & D2 or D3 & D4) are reverse biased. The capacitor c discharges through the load resistance R.

The capacitor voltage varies between $V_c(min)$ & $V_c(max)$. Let t_1 is the charging time & t_2 is the discharging time of capacitor.

Let us assume that t_1 is the charging time and t_2 is the discharging time of the capacitor C_e. The equivalent circuit during charging is shown in for 3.10 (c)

The capacitor voltage charges to almost instantaneously to the peak value of the supply voltage Vs.

The capacitor C_e is charged to peak supply voltage V_m. So that $V_C\,(t=t_1) = V_m$

Fig 3.10(d) shows an equivalent circuit during discharging. The capacitor discharges exponentially through R.

$$\frac{1}{C_e}\int i_L\, dt + v_c(t = 0) + Ri_L = 0$$

Which with an initial condition $V_C\,(t=0) = V_m$, gives the discharging current as

$$i_L = \frac{V_m}{R}\, e^{-t/RC_e}$$

The output (or capacitor) voltage V_L during the discharging period can be found from

$$v_L(t) = Ri_L = V_m e^{-t/RC_e}$$

The peak-to-peak ripple voltage $V_{r\,(pp)}$ can be found from

$$V_{r(pp)} = v_L(t = t_1) - v_L(t = t_2) = V_m - V_m e^{-t_2/RC_e} = V_m(1 - e^{-t_2/RC_e})$$

Since $e^{-x} = 1$-x. the above equation can be simplified to

$$V_{r(pp)} = V_m\left(1 - 1 + \frac{t_2}{RC_e}\right) = \frac{V_m t_2}{RC_e} = \frac{V_m}{2fRC_e}$$

Therefore the average load voltage V_{dc} is given by

$$V_{dc} = V_m - \frac{V_{r(pp)}}{2} = V_m - \frac{V_m}{4fRC_e}$$

Thus the rms output voltage V_{ac} can be found approximately from

$$V_{ac} = \frac{V_{r(pp)}}{2\sqrt{2}} = \frac{V_m}{4\sqrt{2}\,fRC_e}$$

The ripple factor RF can be found from

$$\mathrm{RF} = \frac{V_{ac}}{V_{dc}} = \frac{V_m}{4\sqrt{2}\,fRC_e}\,\frac{4fRC_e}{V_m(4fRC_e - 1)} = \frac{1}{\sqrt{2}\,(4fRC_e - 1)}$$

This can be solved for Ce

$$C_e = \frac{1}{4fR}\left(1 + \frac{1}{\sqrt{2}\,\mathrm{RF}}\right)$$

The value of Ce should be designed such that there is a very minimum ripple factor to get ripple free output. With the above specifications I have chosen value of Ce to be 60 mf to ensure the ripple factor is 0.1%

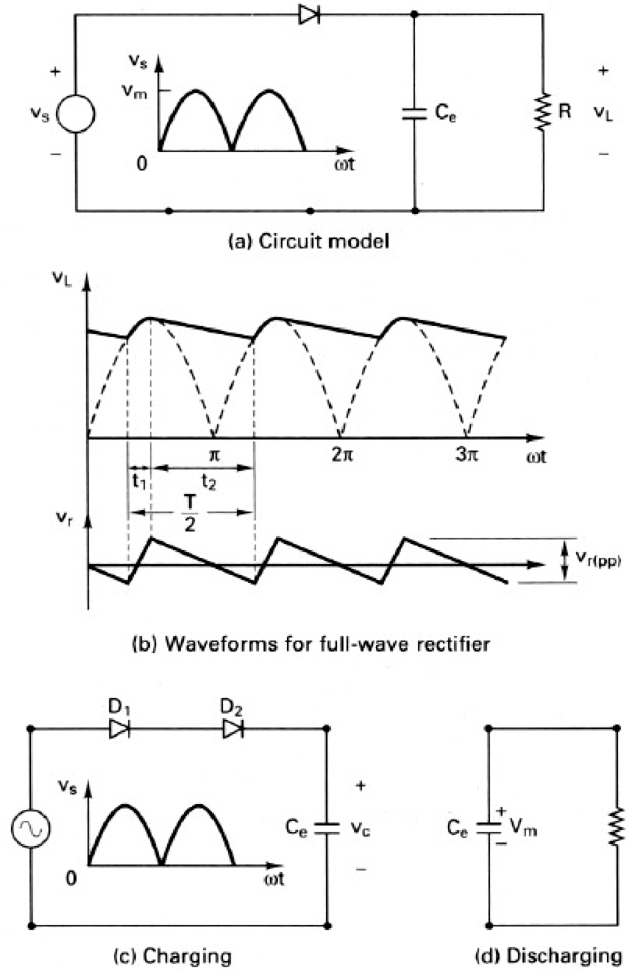

Fig 3.10: single phase bridge rectifier with C filter

CHAPTER 4: SIMULATION RESULTS AND DISCUSSION

In the present work, 5 different input current wave shaping circuits are considered and designed for 1 KW load specification from a 115 V rms, 60 Hz single phase source. The designed circuits are simulated using OrCAD software and the graphs are plotted. The input current total harmonic distortion, power factor and their efficiencies are calculated and tabulated. The comparison charts are plotted with the tabulated values. The 5 designed circuits are

1. Conventional rectifier with filter capacitor
2. Novel passive wave shaping method for a single phase diode rectifier
3. Rectifier circuit with series input resonant filter
4. Improved passive wave shaping method for a single phase diode rectifier
5. Single phase diode rectifier with switching on AC side

The following discussion includes the output result of each simulated prototype and their calculated input current total harmonic distortion, power factor and efficiency. All the methods are compared in terms of their efficiency, power factor and total harmonic distortion. Relevant discussion is carried out for each simulated prototype and the conclusions drawn from the simulated circuits are presented in chapter 5. Sample calculation is also presented in appendix A (with all the relevant expressions that are used to find the required parameters). The list of materials used in the prototypes is included in appendix B.

4.1 Conventional rectifier with filter capacitor

Fig 4.1 shows the simulated prototype of a conventional rectifier with filter capacitor.

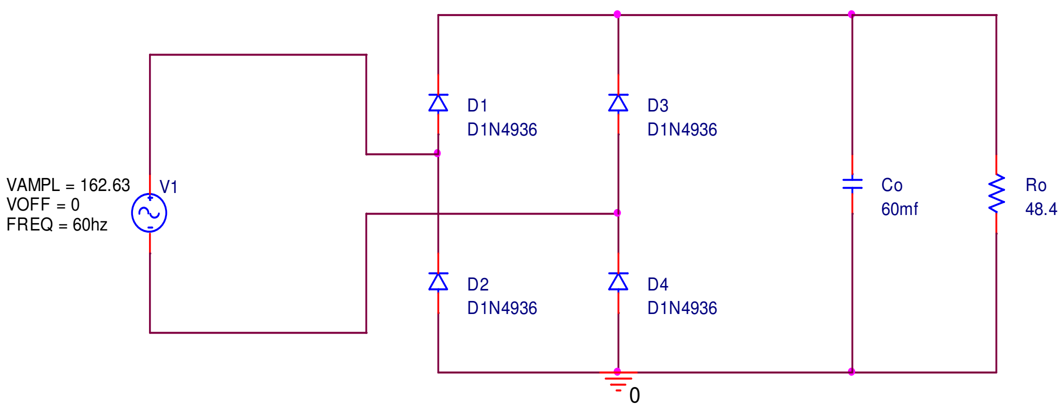

Fig 4.1 conventional single phase diode rectifier with filter capacitor

The output filter capacitance C_e (Co) is calculated by using the formula

$$C_e = \frac{1}{4fR}\left(1 + \frac{1}{\sqrt{2}\,RF}\right)$$

Here f is the supply frequency which is 60 Hz. R is the output resistance and RF is called the ripple factor. To get a minimum ripple factor of less than 0.1% I have chosen the output capacitance to be 60 mf.

The circuit is simulated using OrCAD and input current with respect to input voltage waveform is plotted in graph as shown in the figure 4.2. The Fourier components of transient response I (V_V1) are tabulated in table 4.1

DC COMPONENT = -3.676838E-03

Table 4.1 Fourier components of transient response of input current of fig 4.1

Harmonic Number	Frequency (Hz)	Fourier component	Normalized component	Phase (deg)	Normalized phase (deg)
1	6.000E+01	6.529E+00	1.000E+00	3.677E+01	0.000E+00
2	1.200E+02	2.529E-02	3.873E-03	-1.322E+02	-2.057E+02
3	1.800E+02	6.303E+00	9.653E-01	-6.967E+01	-1.800E+02
4	2.400E+02	4.492E-02	6.879E-03	1.193E+02	-2.779E+01
5	3.000E+02	5.869E+00	8.988E-01	-1.760E+02	-3.598E+02
6	3.600E+02	5.792E-02	8.871E-03	3.607E+00	-2.170E+02
7	4.200E+02	5.262E+00	8.059E-01	7.784E+01	-1.795E+02
8	4.800E+02	6.347E-02	9.721E-03	-1.168E+02	-4.110E+02
9	5.400E+02	4.531E+00	6.940E-01	-2.805E+01	-3.590E+02
10	6.000E+02	6.424E-02	9.839E-03	1.170E+02	-2.507E+02

Total harmonic distortion = 1.694413E+02 percent

The calculated power factor and efficiencies are

- Total harmonic distortion (THD) = 169 %
- Power factor (PF) = 0.4071
- Efficiency (η) = 66.6 %

Discussion:

From the calculated values it is clear that the total harmonic distortion is 169% which is very high and it needs to be reduced and that is achieved in the proceeding methods. We can observe a significant change as we move on from one method to the other. The efficiency is very poor which means that the passive methods should be accompanied by some other methods to improve the efficiency. The input current is in the form of short pulses which is highly undesirable as shown in the fig 4.2.

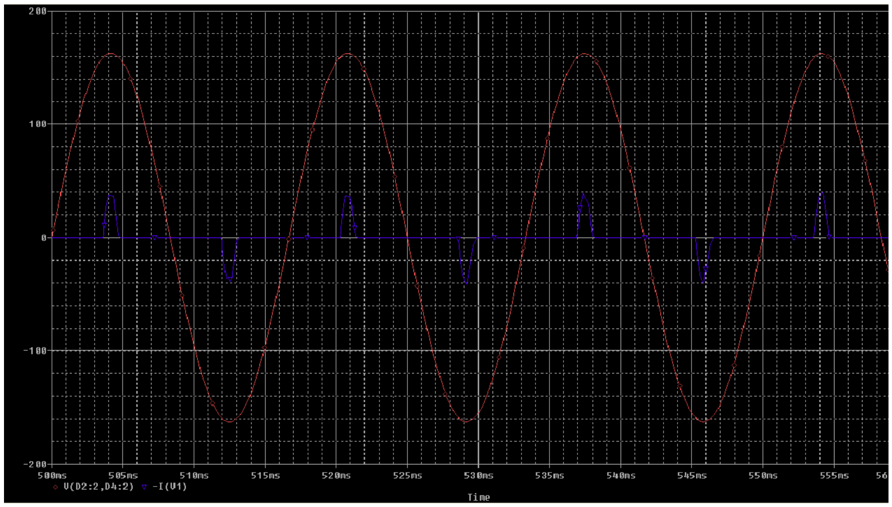

Fig 4.2: input current waveform with respect to the input voltage of fig 4.1

Due to the high total harmonic distortion and poor efficiency the use of the conventional single phase diode rectifier with a filter capacitor the use of these circuits are limited to low power applications accompanied with some other power factor correction schemes.

This method has the disadvantage of high input current harmonic component, low power factor, the maximum value of which to deliver 1.0 pu power is only about 0.4071 and low conversion efficiency.

4.2 Novel passive wave shaping method of a diode rectifier

The simulated prototype of a single phase diode rectifier using novel passive wave shaping method is shown in the fig 4.3. In this method a parallel resonant circuit is introduced at the input end. The values of the inductor and capacitor are calculated using the analysis discussed below for the 1 KW load specification, 115 V r.m.s and 60 Hz supply.

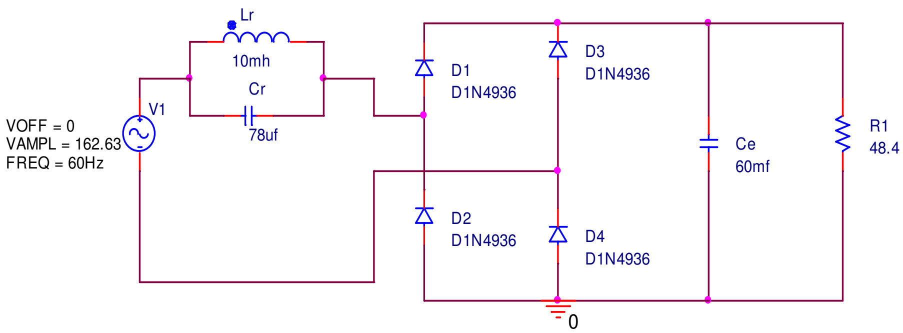

Fig 4.3: single phase diode rectifier using novel passive wave shaping method

Input Filter Analysis:

The nth harmonic component of the equivalent impedance of the input parallel resonant filter is given by

$$Z_n = \frac{nX_{L_r} * \frac{X_{C_r}}{n}}{jnX_{L_r} - j\frac{X_{C_r}}{n}}$$

where X_{Lr} is the impedance of the input resonant inductor L, at fundamental frequency, and X_{cr} is the impedance of the input resonant capacitor Cr at fundamental frequency. From above equation, the third harmonic impedance of the input resonant filter becomes infinity (theoretically) when

$$3X_{L_r} = \frac{X_{C_r}}{3}$$

$$L_r = \frac{1}{9\omega^2 C_r}$$

where ω is the angular frequency of the input ac source E_i.

From the equation, for a selected value L= 10 mH, the calculated value of C is 78μf.

The Fourier components of transient response of I (V_V1) are tabulated in table 4.3

DC COMPONENT = 2.068956E-01

Table 4.2 Fourier components of transient response of input current of fig 4.3

Harmonic Number	Frequency (Hz)	Fourier component	Normalized component	Phase (deg)	Normalized phase (deg)
1	6.000E+01	3.020E+00	1.000E+00	4.668E+01	0.000E+00
2	1.200E+02	2.264E-01	7.497E-02	-2.401E+01	-1.174E+02
3	1.800E+02	2.798E-01	9.265E-02	-3.394E+00	-1.434E+02
4	2.400E+02	6.070E-02	2.010E-02	3.620E+01	-1.505E+02
5	3.000E+02	1.063E+00	3.521E-01	5.087E+01	-1.825E+02
6	3.600E+02	6.216E-02	2.059E-02	-5.691E+01	-3.370E+02
7	4.200E+02	4.385E-01	1.452E-01	4.164E+01	-2.851E+02
8	4.800E+02	6.601E-02	2.186E-02	-3.784E+00	-3.772E+02
9	5.400E+02	5.237E-01	1.734E-01	4.035E+01	-3.797E+02
10	6.000E+02	2.281E-02	7.553E-03	-3.759E+01	-5.044E+02

Total harmonic distortion = 4.366811E+01 percent

The calculated efficiency and power factor are

- Total harmonic distortion (THD) = 43.6%
- Power factor (PF) = 0.6287
- Efficiency (η) = 72.81%

Discussion:

The input total harmonic distortion is 43.6% which is better compared to the previous method but there is significant improvement in the power factor from 0.407 to 0.62. The efficiency is increased. But still the efficiency is poor. The novel method uses a parallel resonant circuit at the input side in order to remove third harmonic component from the input current. The power factor is improved because the third harmonic component is the main reason for the low power factor. The relevant input current and voltage waveform is plotted in fig 4.4 which shows that the distortion is still high. The calculated values shows that the efficiency is improved compared to previous methods.

The advantages of the novel method over previous methods are the improved power factor and the improved efficiency. The disadvantages of the novel method include non unity power factor and still there should be significant improvement in efficiency.

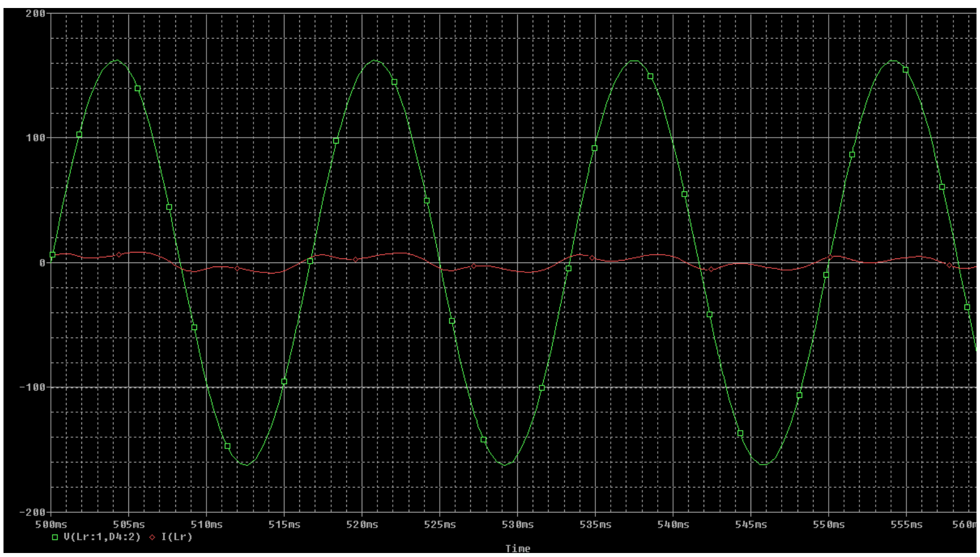

Fig 4.4: input current waveform with respect to the input voltage of fig 4.3

4.3 Rectifier circuit with series input resonant filter

The simulated prototype of a single phase diode rectifier with series input resonant filter is shown in the fig 4.5. The values considered in the prototype are calculated using the analysis discussed in chapter 3 for the 1 KW load and 115 V rms, 60 Hz source.

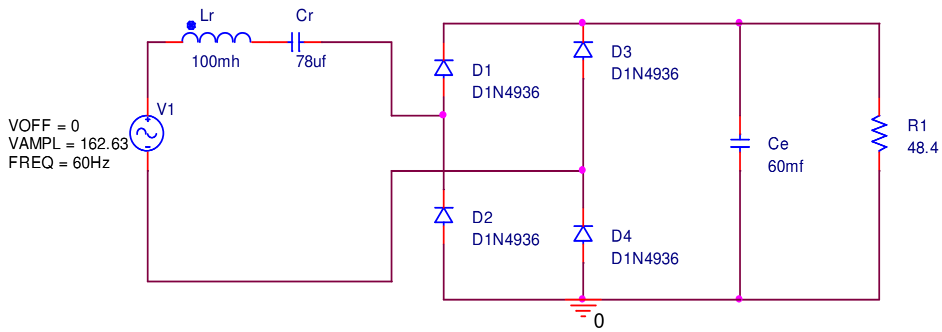

Fig 4.5: single phase diode rectifier circuit with series input resonant filter

The Fourier components of transient response I (V_V1) are tabulated in table 4.3

DC COMPONENT = 1.389064E-01

Table 4.3 Fourier components of transient response of input current of fig 4.5

Harmonic Number	Frequency (Hz)	Fourier component	Normalized component	Phase (deg)	Normalized phase (deg)
1	6.000E+01	5.438E+00	1.000E+00	1.734E+01	0.000E+00
2	1.200E+02	1.069E-01	1.966E-02	-4.992E+01	-8.460E+01
3	1.800E+02	4.914E-01	9.036E-02	1.778E+02	1.258E+02
4	2.400E+02	3.213E-02	5.909E-03	-3.326E+01	-1.026E+02
5	3.000E+02	1.734E-01	3.189E-02	-1.210E+02	-2.077E+02
6	3.600E+02	2.159E-02	3.970E-03	-1.596E+01	-1.200E+02
7	4.200E+02	9.734E-02	1.790E-02	-6.400E+01	-1.854E+02
8	4.800E+02	1.559E-02	2.868E-03	-1.153E+01	-1.502E+02
9	5.400E+02	6.386E-02	1.174E-02	-1.304E+01	-1.691E+02
10	6.000E+02	1.123E-02	2.066E-03	-6.794E-01	-1.741E+02

Total harmonic distortion = 1.004519E+01 percent

The calculated power factor and efficiency are

- Total harmonic distortion (THD) = 10 %
- Power factor (PF) = 0.9479
- Efficiency (η) = 61%

Discussion:

The input current total harmonic distortion is 10% which is very low and is desirable. The power factor is 0.9479 and our aim is to achieve unity power factor. The efficiency is very poor compared to the novel method. As low total harmonic distortion is achieved for this method which is better compared to the novel method. From the analysis discussed in chapter 3, the value of L is 100 mH to ensure a minimum ripple in the input current. I have chosen C= 78 μf instead of 70 μf as the input current is getting short circuited for C= 70 μf. That means that the resonance condition is not satisfied in this case. This makes the series resonant filter method ineffective unless a semiconductor switch on the input side is introduced which will improve efficiency and also unity power factor is achieved. The input current is plotted with respect to the input voltage which shows a major improvement in the input current wave shape compared to the waveform in fig 4.5

The advantages of this method over the conventional method are

1. Efficient circuit for input current wave shaping as the total harmonic distortion is 10% when compared to the novel method
2. Significant improvement in the power factor from 0.62 to 0.9479
3. Improvement in the efficiency

The disadvantages of this method are

2. The power factor needs to be improved to unity
3. Resonance condition is not achieved and should be accompanied with a power switch to improve its performance.

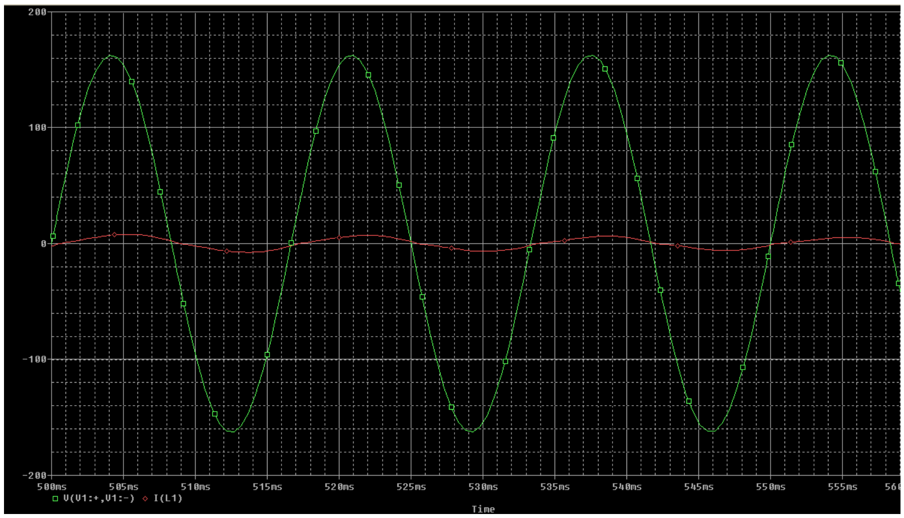

Fig 4.6: input current waveform with respect to the input voltage of fig 4.5

4.4 Improved passive wave shaping method of a diode rectifier

The simulated prototype of a single phase diode rectifier using improved passive wave shaping method is shown in the fig 4.7. To lower the input current THD of the diode rectifier with novel passive wave shaping, a capacitor C_b is placed parallel between the parallel resonant tank and the rectifier bridge, which compensate the reactive power and absorb the distortion power. Presenting the rather small impedance to the high order harmonics, the capacitor C_b will serve the function of filtering out these components. As a result the improved method has the better filter feature and the high input power factor than the novel method. The values of the inductor and capacitor are calculated using the analysis discussed below for the 1 KW load specification, 115 V rms, 60 Hz supply voltage source.

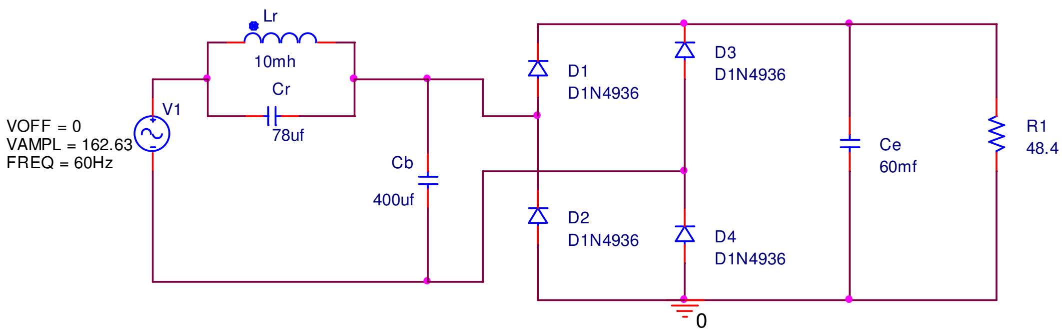

Fig 4.7: single phase diode rectifier using improved passive wave shaping method

The C_b values are chosen ranging from 100 µf (micro farads) to 10 mf (milli farads) and is selected such that the input power factor at rated output power reaches its peak value. The THD and PF are calculated for various values of C_b by simulating the circuit for each value of C_b .The calculated values are tabulated in table 4.4.

Table 4.4: Calculated power factor values of different values of capacitance C_b

C_b	THD	Power factor (PF)
100 µf	8.312	0.6405
200 µf	4.7675	0.8533
300 µf	3.55	0.9575
400 µf	2.62	0.9960
500 µf	2.071	0.9956
1 mf	0.99	0.807
5 mf	0.1437	0.59116
10 mf	2.614	0.5578

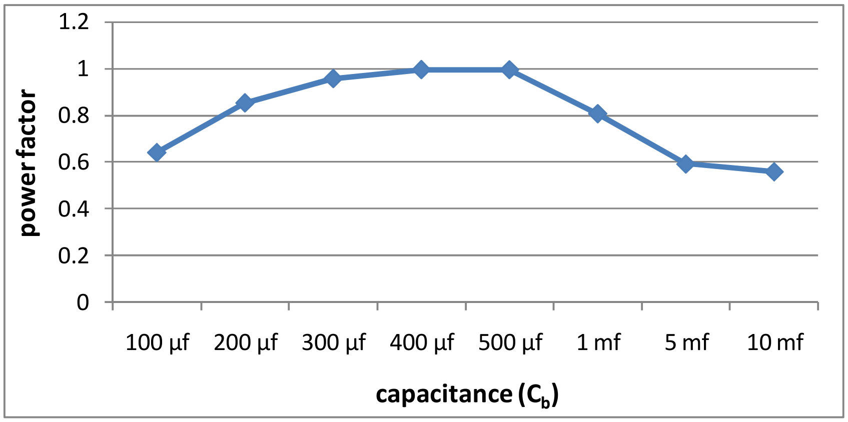

Fig 4.8: variation of power factor with respect to capacitance C_b

The Fourier components of transient response of I (V_V1) are tabulated in table 4.5

DC COMPONENT = 6.112578E-02

Table 4.5 Fourier components of transient response of input current of fig 4.7

Harmonic Number	Frequency (Hz)	Fourier component	Normalized component	Phase (deg)	Normalized phase (deg)
1	6.000E+01	6.425E+01	1.000E+00	4.958E+00	0.000E+00
2	1.200E+02	3.726E-01	5.800E-03	1.723E+02	1.624E+02
3	1.800E+02	3.477E-01	5.411E-03	1.338E+02	1.189E+02
4	2.400E+02	1.961E-02	3.051E-04	1.274E+02	1.076E+02
5	3.000E+02	8.960E-01	1.394E-02	-4.561E+01	-7.040E+01
6	3.600E+02	1.852E-01	2.882E-03	-1.747E+02	-2.044E+02
7	4.200E+02	1.114E+00	1.733E-02	1.445E+02	1.098E+02
8	4.800E+02	8.770E-02	1.365E-03	-2.082E+01	-6.048E+01
9	5.400E+02	6.833E-01	1.063E-02	-2.162E+01	-6.623E+01
10	6.000E+02	1.886E-01	2.936E-03	1.750E+02	1.254E+02

Total harmonic distortion = 2.626355E+00 percent

The calculated efficiency and power factor are

- Total harmonic distortion (THD) = 2.62%
- Power factor (PF) = 0.9960
- Efficiency (η) = 11.76%

Discussion:

The input total harmonic current distortion is reduced to 2.62% and there is a significant improvement in the power factor. But we can observe a decrease in the efficiency which means that this method is only a good input current wave shaping method and should be accompanied by another method to improve efficiency. The graph of input current shown in fig 4.9

The advantages of the improved method over the novel method are that the input current total harmonic distortion is low due to significant filter feature of the capacitor C_b and input power factor is high. The disadvantage associated with this method is poor efficiency and that needs to be improved.

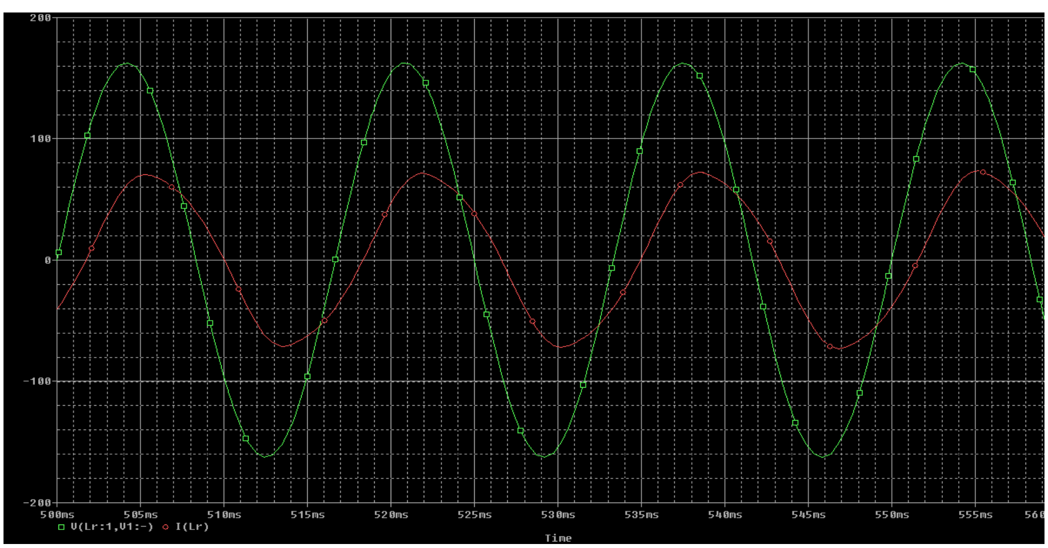

Fig 4.9: input current waveform with respect to the input voltage of fig 4.7

All the calculated values of total harmonic distortion, power factor and efficiencies of passive wave shaping methods are tabulated in table 4.6

Table 4.6 Calculated THD, PF and efficiencies of various passive methods

Passive wave shaping method	Total harmonic distortion (%)	Power factor (PF)	Efficiency (η %)
Conventional method	169.44	0.4071	66.6
Novel method	43.66	0.6287	72.81
Series resonant filter method	10	0.9479	61
Improved method	2.62	0.9960	11.76

The comparison charts of various passive wave shaping methods in terms of total harmonic distortion, power factor and efficiency are plotted. Fig 4.10 shows variation of total harmonic distortion for various passive wave shaping methods. From the fig 4.10 it is clear that the series resonant filter method has lower THD which is highly desirable.

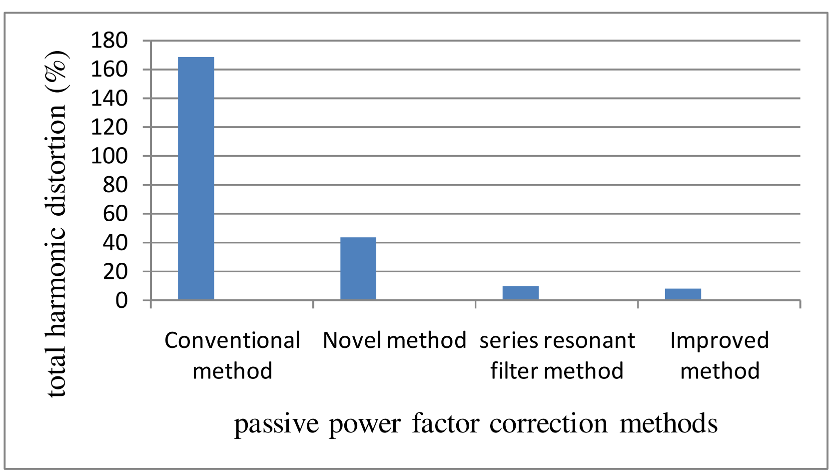

Fig 4.10 variation of total harmonic distortion of various passive methods

Fig 4.11 shows the variation of power factor for various passive wave shaping methods. From the fig 4.11 it is clear that the power factor is high for the improved method.

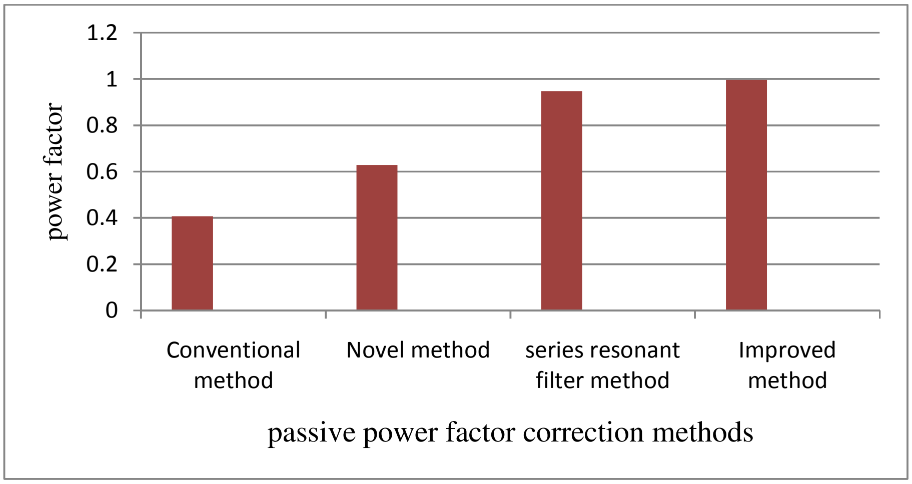

Fig 4.11 variation of power factor of various passive methods

Fig 4.12 shows the variation of efficiencies for various passive power factor correction methods. The efficiency is high for novel method. Fig 4.13 is the comparison chart of all the passive power factor correction methods

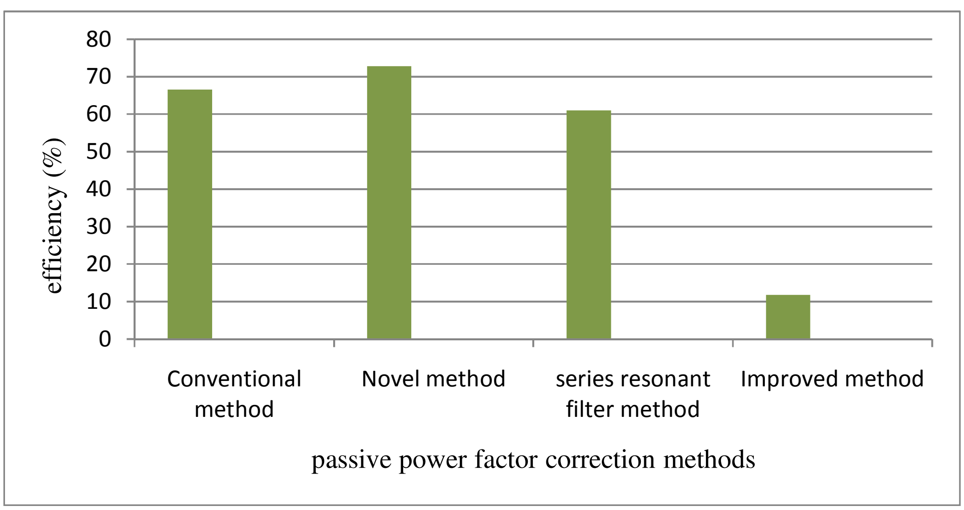

Fig 4.12 variation of efficiencies of various passive methods

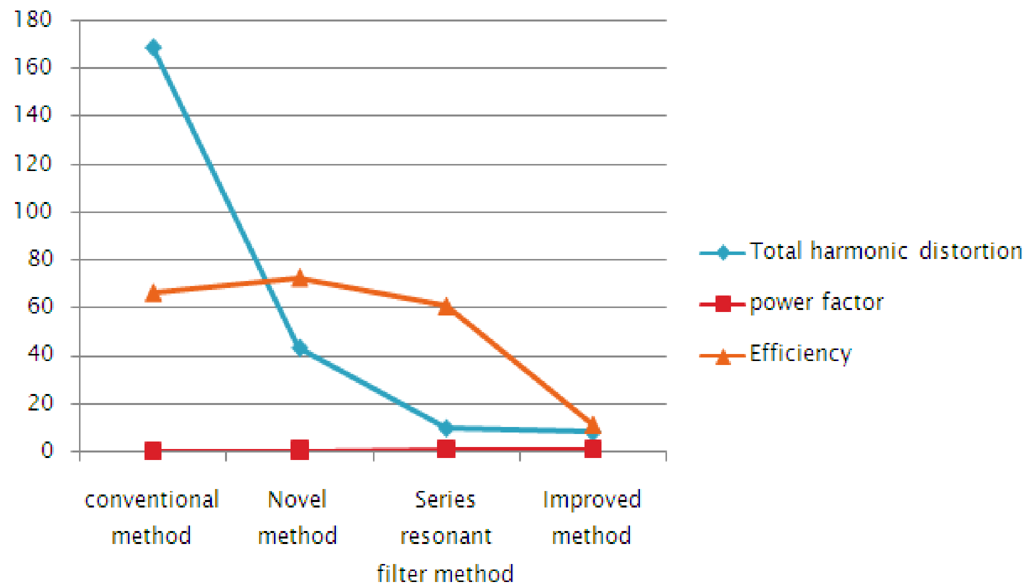

Fig 4.13 variation of THD, PF and Efficiencies of various passive power factor correction methods

Fig 4.13 shows the comparison graph of various passive wave shaping methods in terms of THD, PF and efficiencies. From the graph it is clear that the improved method has better PF and Low THD compared to other passive methods while the Novel method has highest efficiency compared to others.

4.5 single phase diode rectifier with switching on AC side

All the disadvantages associated with the series input resonant passive power factor correction methods are improved by using an active switch on the input side between the resonant circuit and the rectifier bridge. This method is called Active wave shaping method in the present work. The reason for using MOSFET switch is because of its high switching speed compared to other semiconductor switches. Table 1.2 shows the comparison of the properties of available semiconductor switches. The simulation proto type is shown in the fig 4.14. There are two stages in the prototype.

1. Power stage
2. Pulse width modulation control circuit and the driving circuit

The elements used in both stages, their respective Pspice libraries and their use is tabulated and is included in appendix. When gate pulse is provided, the MOSFET is short circuited and the input current flows through D2 and D3 (during the positive half cycle) or through D1 and D4 (during negative half cycle). The four diodes D1-D4 ensure that the current always flows in the same direction through the switch. The gate pulses have been generated by comparing a sinusoidal signal with a triangular one. The triangular wave signal and the sinusoidal signal are connected to the non-inverting and the inverting terminals of an OP-Amp (AD648A) respectively.

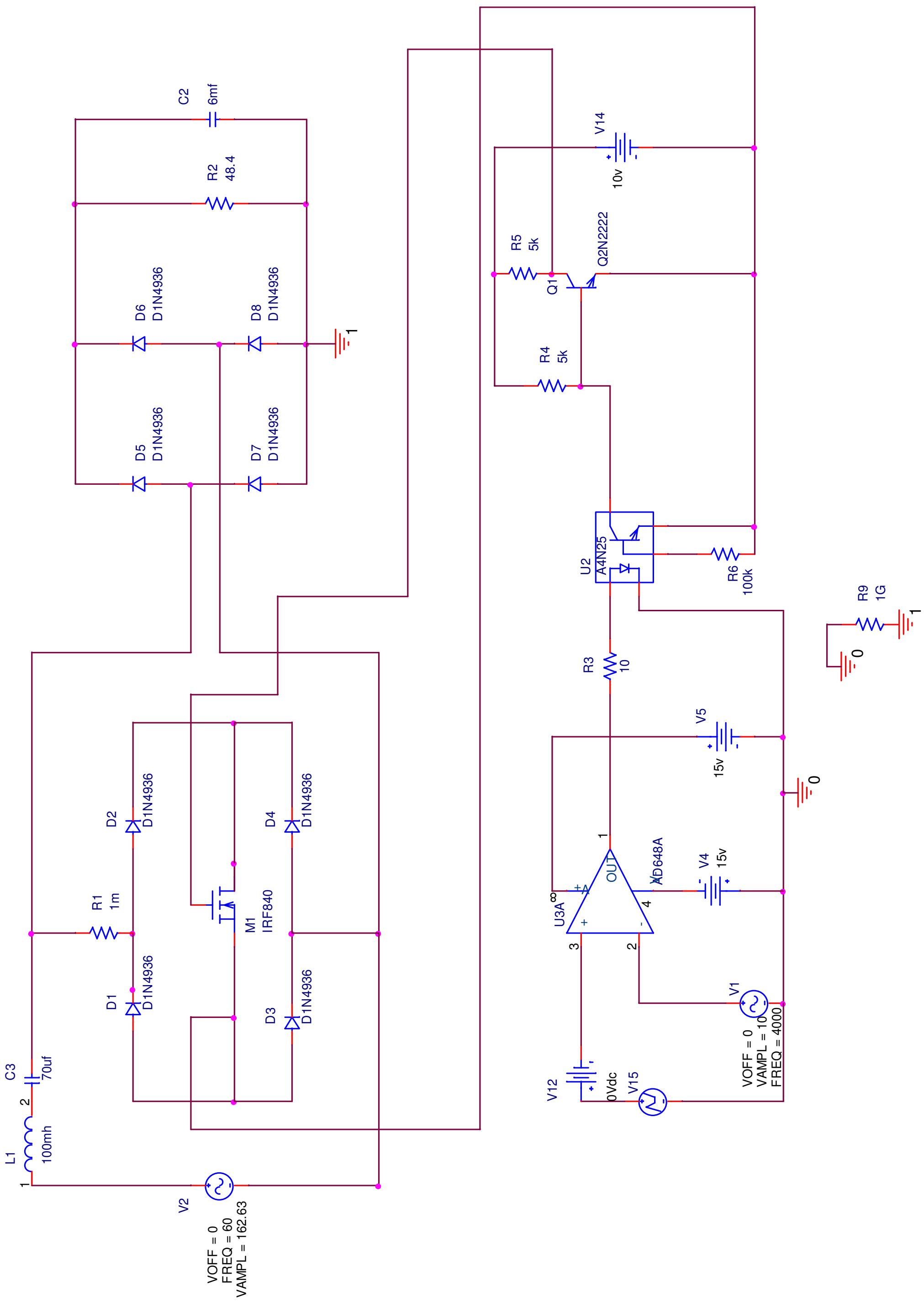

Fig 4.14 single phase diode rectifier with switching on input side

The Fourier components of transient response of I (L_L1) are tabulated in table 4.7

DC COMPONENT = -1.239093E-01

Table 4.7 Fourier components of transient response of input current of fig 4.14

Harmonic Number	Frequency (Hz)	Fourier component	Normalized component	Phase (deg)	Normalized phase (deg)
1	6.000E+01	1.254E+01	1.000E+00	0.000E+00	0.000E+00
2	1.200E+02	1.671E-01	1.332E-02	1.578E+02	4.579E+02
3	1.800E+02	1.375E-02	1.097E-03	-1.400E+02	3.101E+02
4	2.400E+02	5.221E-02	4.163E-03	1.682E+02	7.683E+02
5	3.000E+02	1.017E-01	8.110E-03	1.133E+02	8.635E+02
6	3.600E+02	3.431E-02	2.735E-03	1.627E+02	1.063E+03
7	4.200E+02	4.144E-02	3.304E-03	1.361E+02	1.186E+03
8	4.800E+02	2.956E-02	2.357E-03	1.647E+02	1.365E+03
9	5.400E+02	3.842E-02	3.063E-03	-1.756E+02	1.175E+03
10	6.000E+02	2.544E-02	2.028E-03	1.708E+02	1.671E+03

Total harmonic distortion = 1.729924E+00 percent

The power factor is unity and the efficiency of the circuit in fig 4.14 is 86.9% for a switching frequency of 4 KHz. A 120 Hz triangular wave is compared to a sine wave of 4 KHz frequency to produce gating signals. The efficiency for the present method is highly improved. The power factor is also unity which is the desired one. The total harmonic distortion is a very low value, 1.72% which is highly acceptable. The input current and the output voltage wave forms are plotted which clearly shows that the power factor is unity and input current wave shape is continuous and the distortions are very less.

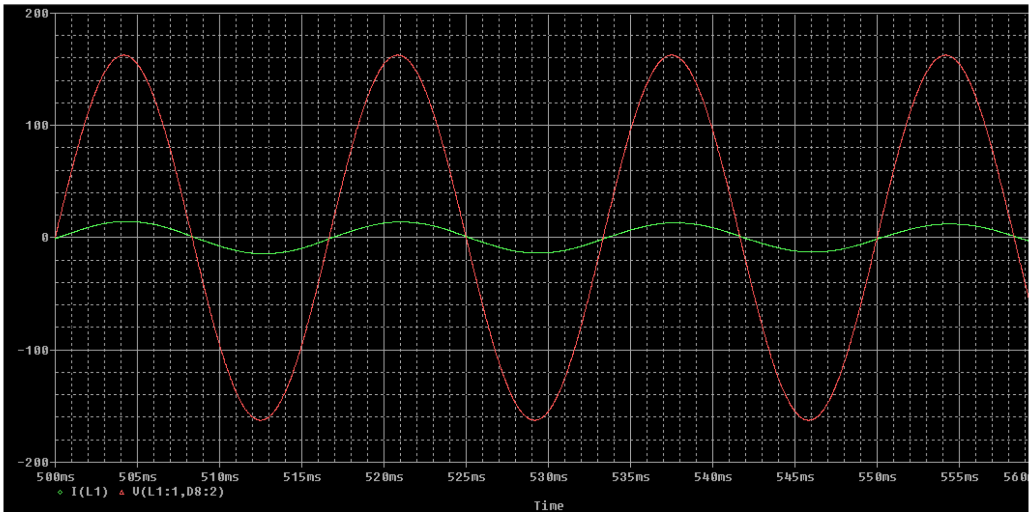

Fig 4.15: input current waveform with respect to the input voltage of fig 4.14

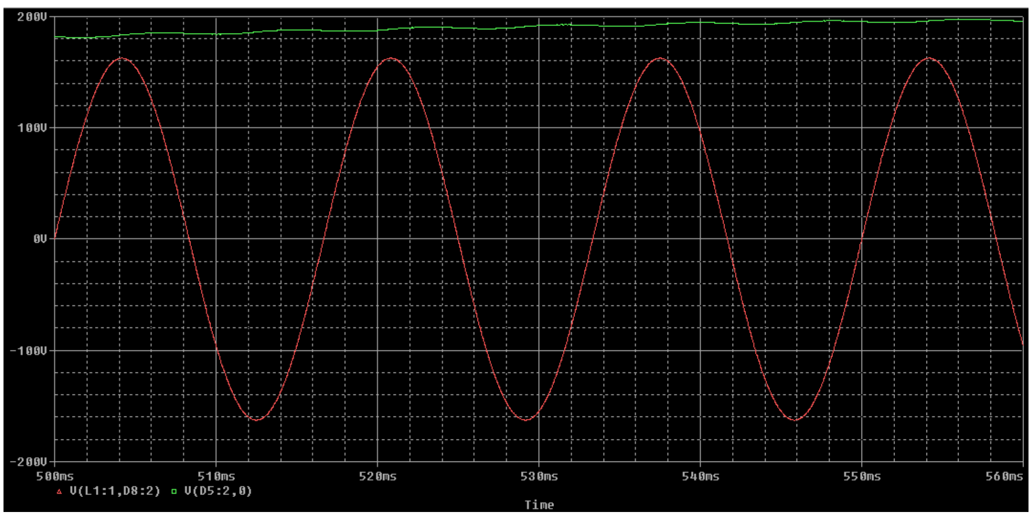

Fig 4.16: output voltage waveform with respect to the input voltage of fig 4.14

The total harmonic distortion and the efficiencies of prototype in fig 4.14 are calculated for various switching frequencies and found that the efficiency is more for a switching frequency of 4 KHz. The values are tabulated in table 4.8

Table 4.8 calculated THD and η for various values of switching frequencies

Switching frequency (Hz)	Efficiency (%)	Total Harmonic Distortion (%)
1000	82	0.8316
1500	84.1	1.067
2000	84.3	1.379
2500	85.2	1.2459
3000	85.45	1.4567
3500	85.48	1.807
4000	86.9	1.7229
4500	85.49	1.818
5000	85.73	2.041
5500	85.2	2.25

The efficiency curve is plotted for the values in the table 4.8. From the curve it is clear that the peak of the curve occurs at 4 KHz switching frequency.

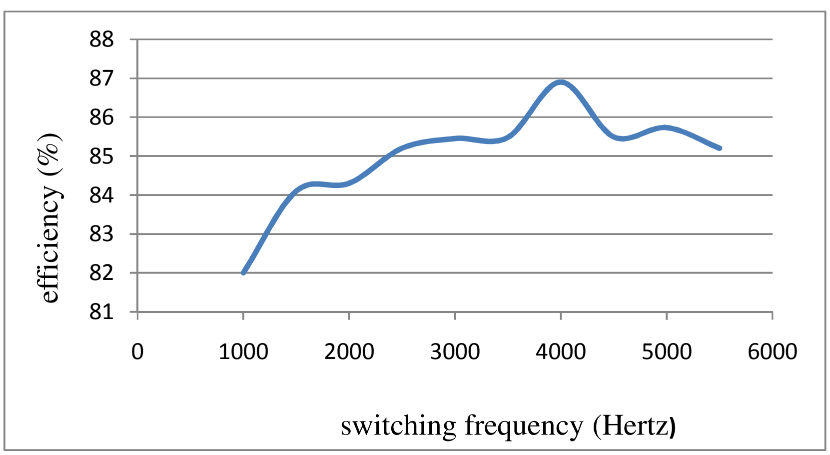

Fig 4.17 chart of values in table 4.8

CHAPTER 5: CONCLUSIONS AND FUTURE WORK

Most electronic equipment is supplied by 50 Hz or 60 Hz utility power, and in almost all of them power is processed through some kind of power converter. Usually, power converters use a diode rectifier followed by a bulk capacitor to convert AC voltage to DC voltage. Unless some correction circuit is used, the input rectifier with a capacitive filter circuit will draw pulsating currents from the utility grid resulting in poor power quality and high harmonic contents that adversely affect other users. Improvements in power factor and total harmonic distortion can be achieved by modifying the input stage of the diode rectifier filter capacitor circuit. Passive solutions can be used to achieve this objective for low power applications. With a filter inductor connected in series with the input circuit, the current conduction angle of the single-phase full-wave rectifier is increased leading to a higher power factor and lower input current distortion. With smaller values of inductance, these achievements are degraded. However, the large size and weight of these elements, in addition to their inability to achieve unity power factor or lower current distortion significantly, make passive power factor correction more suitable at lower power levels.

Active PFC solutions are a more suitable option for achieving near unity power factor and sinusoidal input current waveform with extremely low harmonic distortion. In these active solutions, a converter with switching frequencies higher than the AC line frequency is placed in between the output of the diode bridge rectifier and the bulk capacitor. The reactive elements of this converter are small, because their size depends on the converter switching frequency rather than the AC line frequency. The function of this converter is to make the load behave as an ideal resistive load and thus eliminate the generation of line current harmonics. However, adding a high frequency switching converter in series with the input circuit naturally causes a reduction in overall efficiency of the whole converter due to the losses contributed by this active PFC circuit. Moreover, the active PFC circuit contributes to an increase in overall costs, increase in EMI, and reduction in reliability due to an increase in the number of components.

Table 5.1: Simulation results of active and passive wave shaping methods

wave shaping method	Total harmonic distortion (%)	Power factor (PF)	Efficiency (η %)
Conventional method	169.44	0.4071	66.6
Novel method	43.66	0.6287	72.81
Series resonant filter method	10	0.9479	61
Improved method	2.62	0.9960	11.76
Active wave shaping method	1.729	1	86.9

As seen in the chapters 2, 3 and 4, the research activities in the area of single phase PFC falls under 2 categories.

1. Passive PFC techniques
2. Active PFC techniques with an input filter.

Passive PFC techniques result in significant improvement in power factor and harmonic performance compared to the conventional ac-dc utility interface. However these are not superior compared to the results achieved by using the active PFC techniques. Passive PFC methods does not offer cost, size and weight benefits.

The simulation results of 5 different wave shaping circuits are tabulated in table 5.1. From the table, we can observe that the active wave shaping methods are desirable to achieve unity power factor and very low input current total harmonic distortion and also high efficiency compared to the passive methods. Among the passive wave shaping methods, though novel method is considered to have high efficiency, but it is not desirable because of the high total harmonic distortion. The improved method is considered to be the extension of the novel method. A filter capacitor is introduced at the input end to reduce the total harmonic distortion. But the efficiency is getting lowered. The series resonant filter method has high efficiency compared to the improved method which means that introduction of a switch at the input end may still make the efficiency to go up. The introduction of MOSFET switch at the input end of the series resonant filter method will result in active wave shaping method. For the active wave shaping methods, the unity power factor is achieved and the total harmonic distortion is as low as 1.73% and the efficiency is 86.9%.

Passive filters may prove to be a good solution for switch mode power supplies (SMPS) operating at lower power levels (<200 W). Typical applications are TVs, VCRs, other home entertainment electronics, and perhaps some of the lower powered office automation equipment such as computers, FAX machines etc. It is to be noted that in these applications the real aim of the filter is to contain the harmonics within the agency specified limits [16] and not improvement of power factor. At such power levels the passive solution is economical and more efficient and may also result in size benefits. But for high power levels (>1000 W) and the applications where reducing harmonics is not only the main criteria, the active techniques offer desirable results. However, even for low power levels, there are a few factors that make the passive solution less attractive than the active solution in certain cases. The factors are as below.

Universal input voltage range (85 V to 280 V ac, 47to63Hz): It is desirable for both the manufacturers and the users that the equipment works in all these supply conditions without any modifications. This requirement is difficult to meet using passive PFC technique whereas it is an inherent feature in many active PFC techniques.

Optimal use of the wall outlet power: Passive PFC technique results in lower PF than active PFC technique. Therefore, passive PFC technique is less attractive when priority is given to optimizing the use of the wall plug's volt-ampere capacity rather than just meeting the agency standards. Optimizing the wall plug's VA capacity allows a user to plug more equipment to the same wall outlet. For higher power levels, however, the passive solution suffers from disadvantages such as:

(1) Large size of the reactive elements

(2) May not be able to contain the harmonics within the agency specified limits [16]

(3) Poor power factor compared with active schemes.

(4) Not cost effective.

However, the passive solutions are simple to understand and implement, besides being robust and reliable. Also, the use of passive solutions does not generate EMI which is a problem that needs to be addressed with active solutions.

The use of active PFC techniques results in one or more of the following advantages.

- Lower harmonic content in the input current compared to the passive techniques.
- Reduced r.m.s current rating of the output filter capacitor.
- Unity power factor is possible to achieve with the Total Harmonic Distortion (THD) as low as 3-5% [14].
- For higher power levels active PFC techniques will result in size, weight and cost benefits over passive PFC techniques.

Future work:

Introducing a MOSFET switch on the DC end of the improved method with a freewheeling diode may result in better efficiency. Because among passive methods, the power factor is high and the total harmonic distortion is less for improved method. But the efficiency is very less which needs to be improved a lot. This method involves both active power switch and the passive elements. This method comes under the category of active passive wave shaping methods. Also the use of IGBTs instead of MOSFET may have significant effect in reducing the THD and the efficiency may still go up. The input and the output filter circuits should be designed accordingly.

APPENDIX A

Calculation of power factor and efficiency:

As discussed in section 1.4.2 equation (3) the expression for calculating the power factor

$$PF = \frac{I_{1rms}}{I_{rms}} \cos\varphi \qquad \text{A.1}$$

where φ is the phase angle between the 1st harmonic of the current and the voltage.

The ratio between apparent power associated with higher order harmonics and apparent power associated with fundamental harmonic is called Total Harmonic Distortion (THD)

$$THD = \frac{\sqrt{I^2{}_{2rms} + I^2{}_{3rms} \ldots + I^2{}_{nrms} + \ldots}}{I_{1rms}} \qquad \text{A.2}$$

Where $\mathbf{I_{nrms}}$ is the rms value of the **nth** harmonic of the current.

$$I_{rms} = \sqrt{I^2{}_{o} + I^2{}_{1rms} + I^2{}_{2rms} + \ldots + I^2{}_{nrms} + \ldots} \qquad \text{A.3}$$

where **Io** is the dc component of the current.

In AC lines Io=0. Then from (A.2) and (A.3) THD can be expressed as

$$THD = \frac{\sqrt{I_{rms}{}^2 - I_{1rms}{}^2}}{I_{1rms}} \qquad \text{A.4}$$

From (1) and (4) we can also derive the relationship between PF and THD:

$$PF = \frac{\cos\varphi}{\sqrt{1 + THD^2}} \tag{A.5}$$

In the present work, the power factor and efficiency are calculated using the above expressions.

Sample calculation:

In section 4.2, for the conventional single phase diode rectifier with filter capacitor the simulation result reveals that the total harmonic distortion is 169% and the Fourier components of the transient response of input current are tabulated in table 4.1. From table 4.1 the phase angle between the 1st harmonic of the current and the voltage is 36.66.

From equation A.5

PF = Cos (36.66) / $[1+ 1.69^{2}]^{2}$ = 0.407

Efficiency is calculated from the simulation result waveforms

$$\text{Efficiency} = \frac{\text{output voltage} * \text{output current}}{\text{input voltage} * \text{input current}} * 100\ \%$$

= (153.5 * 3) / (117.74 * 5.864) = 66.66 %

APPENDIX B

The elements used in the simulation prototypes and their part numbers are tabulated. Table B.1 shows the elements used for passive wave shaping methods and the tables B.2 and B.3 contain the elements used for the active wave shaping method. The purpose of the pspice elements are also included in the table for some of the major elements for the convenience of the readers.

Table B.1: Components used in passive wave shaping method

Part name	Part number	Library in Pspice
Sinusoidal Voltage source	VSIN	Source library
Diode	DIN4936	Diode.olb
Resistance, capacitance, inductance	R,L,C	Analog library

Table B.2: Major components for the power stage in active wave shaping method

Part name	Part #	Library in Pspice
Sinusoidal Voltage source	VSIN	Source library
Diode	DIN4936	Diode.olb
N channel Power MOSFET	IRF840	Pwrmos.olb
Resistance, capacitance, inductance	R,L,C	Analog library

Table B.3: Major components of PWM control and driving circuit

Part Name	Part #	Library
Piecewise linear repeated forever	VPWL_RE_FOREVER	Source library
Sinusoidal Voltage source	VSIN	Source library
Dual precision BiFET OpAmp	AD648A	Op-amp.olb
Opto Coupler	A4N25	OPTP library
Bipolar transistor	Q2N2222	Bipolar.olb

Elements used in the control stage in active wave shaping method:

The elements used to drive a MOSFET in the control circuit; ratings and their purpose are demonstrated in this section. VPWL_RE_FOREVER is used to generate a triangular wave of 120 HZ frequency. VSIN is used to generate a sine wave of amplitude 10V and frequency 120 Hz. AD648A is used to convert a sine wave signal to a rectified sine pulses and compares with a triangular wave to generate a PWM waveform. A4N25 provides electrical isolation to protect a device from overvoltage damage. Q2N2222 is used in a variety of analog amplification and switching applications.

Dual Precision, Low Power BiFET Op Amp AD648

The AD648 is a matched pair of low power, precision monolithic operational amplifiers. It offers both low bias current (10pA max, warmed up) and low quiescent current (400mA max). Input bias current is guaranteed over the AD648's entire common-mode voltage range. The AD648 is recommended for any dual supply op amp application requiring low power and excellent dc and ac performance.

FEATURES

DC Performance

400 mA max Quiescent Current

10 pA max Bias Current, Warmed up (AD648C)

300 mV max Offset Voltage (AD648C)

3 mV/8C max Drift (AD648C)

2 mV p-p Noise, 0.1 Hz to 10 Hz

AC Performance

1.8 V/ms Slew Rate

1 MHz Unity Gain Bandwidth

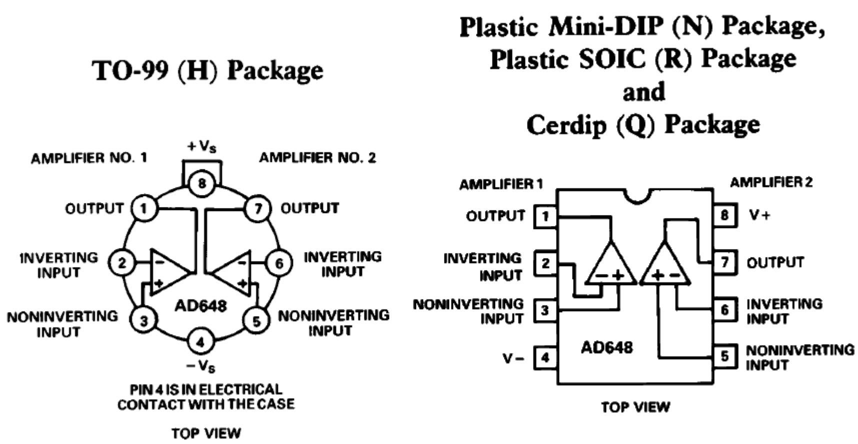

Fig B.1: Connection diagram of AD648

Opto-coupler (A4N25)

In electronics, an opto-isolator (or optical isolator, optocoupler, photocoupler, or photoMOS) is a device that uses a short optical transmission path to transfer a signal between elements of a circuit, typically a transmitter and a receiver, while keeping them electrically isolated — since the signal goes from an electrical signal to an optical signal back to an electrical signal, electrical contact along the path is broken

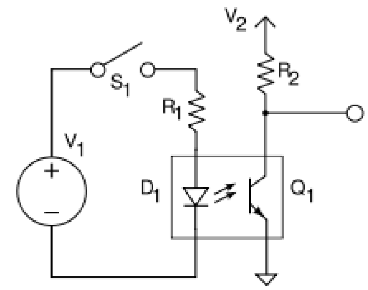

Fig B.2: Schematic diagram of optocoupler with an LED and phototransistor

Optocouplers typically come in a small 6-pin or 8-pin IC package, but are essentially a combination of two distinct devices: an optical transmitter, typically a gallium arsenide

LED (light-emitting diode) and an optical receiver such as a phototransistor or light-triggered diac. The two are separated by a transparent barrier which blocks any electrical current flow between the two, but does allow the passage of light. The basic idea is shown in Fig B.2, along with the usual circuit symbol for an optocoupler.

Bipolar transistor (Q2N2222)

The Q2N2222 is a small, common NPN BJT transistor used for general purpose low-power amplifying or switching applications. It is designed for low to medium current, low power, medium voltage, and can operate at moderately high speeds. It is a 1 amp, 50 volt, 300 milliwatt transistor capable of operating up to 100 MHz, with a beta of at least 100. It's used in a variety of analog amplification and switching applications.

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