DESIGN OF A SINGLE PHASE UNITY POWER FACTOR SWITCH MODE POWER SUPPLY (SMPS) WITH ACTIVE POWER FACTOR CORRECTION

by

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TABLE OF CONTENTS

CHAPTER ONE : INTRODUCTION

CHAPTER TWO : LITERATURE REVIEW

CHAPTER THREE : HARMONICS AND POWER FACTOR

CHAPTER FOUR : UNITY POWER FACTOR SMPS WITH ACTIVE PFC

CHAPTER FIVE : RESULTS AND DISCUSSION

CHAPTER SIX : CONCLUSIONS AND FUTURE RESEARCH

APPENDICES

LIST OF TABLES

LIST OF FIGURES

LIST OF PLATES

LIST OF SYMBOLS

		Page
V_{in}	Sinusoidal rectifier input voltage	11
I_{in}	Rectifier input current	11
V_{out}	Rectifier output voltage	11
$\%f$	Harmonic amplitude, percent of fundamental	14
n	Harmonic order	14
L_S	AC-side inductor	18
L_D	DC-side inductor	19
L_P	Parallel-resonant inductor	20
C_P	Parallel-resonant capacitor	20
THD	Total Harmonic Distortion	31
P_O	Maximum power from outlet	32
I^2R	Conductor losses	33
P	Real power	36
S	Apparent power	36
$v(t)$	Instantaneous voltage	37
$i(t)$	Instantaneous current	37
V_m	Maximum input voltage	37
I_m	Maximum input current	37
ω	Angular frequency	37
θ_V	Voltage phase angle	37
θ_i	Current phase angle	37
$p(t)$	Instantaneous power	37
V_{rms}	Root Mean Square voltage	38
I_{rms}	Root Mean Square current	38
Q	Reactive power	38
φ	Displacement angle between voltage and current	38
K_P	Distortion power factor	39
$I_{1,rms}$	Fundamental root mean square current	39
$I_{n,rms}$	Harmonic current	40
V_{AC}	Alternating current voltage	43
V_{DC}	Rectifier DC average output voltage	44
C	Rectifier DC filter output capacitor	44

C_f	DC-DC converter filter output capacitor	44
C_{f1}	Flyback converter filter output capacitor	47
V_L	Voltage across inductor	48
I_L	Inductor current	48
L	High frequency inductor	48
D	Ultrafast diode	48
I_D	Diode current	48
I_{out}	Boost output current	48
S	Boost switch	48
V_{DS}	Voltage across switch	48
V_{cont}	PWM control signal	48
ΔI_L	Inductor current changes	49
t_1	Switching ON time	49
t_2	Switching OFF time	49
k	Switching duty cycle	49
f_s	Switching frequency	50
I_1	Flyback input current	52
I_2	Flyback output current	52
N_1	Flyback primary winding ratio	52
N_2	Flyback secondary winding ratio	52
V_1	Flyback primary voltage	52
V_2	Flyback secondary voltage	52
S_1	Flyback switch	52
T	Switching period	54
R_s	Snubber resistance	56
C_s	Snubber capacitance	56
D_s	Snubber diode	56
N_3	Flyback tertiary winding ratio	56
R_m	Sense resistor	60

LIST OF ABBREVIATION

		Page
AC	Alternating Current	2
ACM	Average Current Mode	59
APFC	Active Power Factor Correction	5
ASD	Adjustable Speed Drive	30
BSF	Band Stop Filter	20
CCM	Continuous Conduction Mode	23
CF	Crest Factor	41
DC	Direct Current	1
DCM	Discontinuous Conduction Mode	23
DPF	Displacement Power Factor	39
EMI	Electromagnetic Interference	22
HVDC	High Voltage Direct Current	30
IC	Integrated Circuit	73
IEC	International Electrotechnical Commission	34
IGBT	Insulated Gate Bipolar Transistor	71
KVA	Kilovoltamperes	36
KVAR	Kilovoltampereactive	36
KW	Kilowatts	36
MOSFET	Metal Oxide Silicon Field Effect Transistor	64
PC	Personal Computer	35
PCB	Printed Circuit Board	121
PESIM	Power Electronic Simulation	77
PF	Power Factor	3
PFC	Power Factor Correction	2
PI	Proportional Integral	60
PPFC	Passive Power Factor Correvtion	5
PWM	Pulse Width Modulation	48
RMS	Root Mean Square	15
SEPIC	Single Ended Primary Inductance Converter	26
SMPS	Switch Mode Power Supply	2
THD	Total Harmonic Distortion	15
UPF	Unity Power Factor	5

LIST OF PUBLICATIONS & SEMINARS

		Page
1	M Nazir & M Syafrudin : ‘Unity Power Factor For Single Phase Rectifier with Active Power Factor Correction (APFC)’, Proc of International Conference on Robotics, Vision, Information and Signal Processing (ROVISP 2005), USM.	126
2	M Nazir, M Syafrudin & S Taib: ‘300W Unity Power Factor Rectifier as a Pre-Regulator in Power Supply Design’, Proc of International Conference on Energy and Environment (ICEE 2006), UNITEN.	132
3	Mokhzaini Azizan, Syafrudin Masri, M Nazir: “Correlation between THD and temperature of power conductor under harmonic influence”’ Proc of International Conference on Robotics, Vision, Information and Signal Processing (ROVISP 2007), USM.	137

REKABENTUK PEMBEKAL KUASA SATU FASA MOD PENSUISAN FAKTOR KUASA SATU DENGAN TEKNIK PEMBETULAN FAKTOR KUASA AKTIF

ABSTRAK

Pembekal kuasa mod pensuisan (SMPS) merupakan satu industri yang bernilai jutaan ringgit dan berkembang pesat dalam bidang elektronik kuasa. Aplikasi SMPS boleh dilihat dalam bidang komunikasi, komputer dan di dalam industri. Isu utama yang hangat diperbincangkan dalam rekabentuk penukar kuasa berfrekuensi talian ialah cara untuk menggunakan kuasa sepenuhnya daripada grid. Pembekal kuasa dengan faktor kuasa satu menjadi isu penting dalam rekabentuk selari dengan tetapan antarabangsa yang terkini. Tetapan Eropah telah menghadkan kandungan harmonik dalam pembekal kuasa. Salah satu tetapan tersebut adalah IEC61000–3–2. Kelebihan faktor kuasa satu melebihi daripada yang ditetapkan oleh tetapan antarabangsa termasuklah kecekapan yang tinggi, kadaran kuasa yang lebih besar dan kualiti kuasa yang baik memberikan kelebihan ekonomi kepada syarikat pembekal elektrik. Matlamat penulisan tesis ini adalah untuk menghasilkan sebuah litar penerus satu fasa faktor kuasa satu. Tujuan membangunkan produk litar ini adalah untuk membina sebuah litar pembekal kuasa beregulasi yang mampu membekalkan kuasa tanpa menghasilkan jumlah herotan arus yang tinggi. Projek ini melibatkan proses merekabentuk penerus faktor kuasa satu 300W. Penukar beroperasi pada voltan masukan 240VAC dan voltan keluaran beregulasi 350VDC. Ini membolehkan penukar beroperasi terus daripada soket keluaran kediaman pengguna. Untuk menghasilkan voltan keluaran pada nilai yang lebih rendah, sebuah penukar DC ke DC peringkat kedua telah dibina. Litar rekabentuk telah diuji pada parameter berbeza dan sesuai digunakan sebagai prototaip untuk pembekal kuasa. Rekabentuk boleh dikembangkan dan ditingkatkan dengan melaksanakan pensuisan resonan bagi meningkatkan kecekapan keseluruhan.

DESIGN OF A SINGLE PHASE UNITY POWER FACTOR SWITCH MODE POWER SUPPLY (SMPS) WITH ACTIVE POWER FACTOR CORRECTION

ABSTRACT

The Switch Mode Power Supplies (SMPS) are a multi-million dollar industry and continuesly growing industry within the field of power electronics. SMPS is widely been used in communication, computers and industrial. One of the leading issues in line-frequency operated power converter design is how to consume power from the grid but not to return it. The Unity Power Factor (UPF) SMPS has become an important design issue as a consequence of recent legislation. European legislation restricts the harmonic content of power supplies. One of them is international standards known as IEC61000–3–2. The advantages of UPF are more than legislative compliance. The advantages include greater efficiency, larger power density and improved power quality result in economical benefits to the electricity service provider. The goal of this thesis is to develop a unity power factor rectifier. The motivation in developing this product was to develop a regulated power supply capable of producing power with low level of harmonic current distortion. This research involves the design of a 300W Unity Power Factor Rectifier. The converter operates at an input voltage of 240VAC and regulated output at 350VDC. This allows the converter to operate directly from a residential mains outlet. To obtain the output at low level voltage, a second-stage DC to DC converter is added. The prototypes were fully tested at different parameters to test its capabilities. The future work to be completed on this project includes developing a computer power supply operated at unity power factor which can be applied for domestic and industrial use. Future designs could be enhanced by the implementation of a resonant switching stage in the second stage converter to increase the overall efficiency.

CHAPTER 1

INTRODUCTION

1.0 Background

As the use of energy is increasing, the requirements for the quality of the supplied electrical energy are more tighten. This means that power electronic converters must be used to convert the input voltage to a precisely regulated DC voltage to the load. Regulated DC power supplies are needed for most analog and digital electronic system. Most power supplies are designed to meet regulated output, isolation and multiple outputs (Mohan, et al. 2005).

Regulation means that the output voltage must be held constant within a specified tolerance for changes within a specified range in the input voltage and the output loading. Isolation is needed when the output may be required to be electrically isolated from the input. They may be multiple outputs that may differ in their voltage and current ratings. Such outputs may be isolated from each other.

Beside these requirements, common goals are to reduce power supply size and weight and improve their efficiency. Traditionally, linear power supplies have been used. However, advances in semiconductor technology have lead to switching power supplies, which are smaller and much more efficient compared to linear power supplies. But the cost comparison between linear and switching power supplies depends on the power rating (Dixon, 1988).

The number of switched mode power supplies (SMPS) and other power electronics appliances are increasing. SMPS are needed to convert electrical energy from AC to DC. SMPS are used as a replacement of the linear power supplies when higher efficiency, smaller size or lighter weight is required. Motors, electronic power supplies and fluorescent lighting consume the majority of power in the world and each of these would benefit from power factor correction. In the middle of 1990s, many of the countries of the world have adopted requirements for power factor correction for new products marketed within their borders.

As predicted by Electrical Power Research Institute in California, USA, more than 60 percent of utility power will be processed through some form of power electronics equipment by the year 2010. The added circuitry will add about 20-30 percent to the cost of power supplies, but the energy savings will much more than the initial costs (Brown, 1994). Power factor correction (PFC) is becoming a very important field in power electronic world. Adding more generating capacity to the world's electrical companies due to higher demand recently is very costly and would consume additional resources. One method of using extra power capacity is to use the AC power more efficiently through the broad use of power factor correction (Brown, 1994).

Most of researches in power factor correction are based on reduction of harmonic contents in the line current. In passive PFC, only passive elements are used to repair the shape of input line current. Obviously, the output voltage cannot be controlled. In active PFC circuit, an active semiconductor device is used together with passive elements to shape the input current and also controlling the output voltage (Ross, 1997).

1.1 Problem Statements

The term “power factor” or PF in the field of power supplies is slightly deviate from the traditional usage of the term, which applied to reactive AC loads, such as motors powered from the AC power line. Here, the current drawn by the motor would be displaced in phase with respect to the voltage. The resulting power being drawn would have a very large reactive component and little power is actually used for producing work. However, in power electronics field, some of that equipment generates pulsating currents to the utility grids with poor power quality at high harmonics contents that adversely affect other users (Mohan,et al. 2005). The situation has drawn the attention of regulatory bodies around the world. Governments are tightening the regulations and setting new specifications for low harmonic current.

Since the number of electronic appliances is growing, an increasing amount of non-sinusoidal current is drawn from the distribution network (Mohan, et al. 2005). Consequently, due to the increasing amount of harmonic currents drawn, the distribution network becomes more and more polluted. As a direct consequence, available power from the grid becomes less. This is because unnecessary current components, which contribute to the root mean square (RMS) value of the line current is drawn from the grid which produces unnecessary power. On the other hand, the harmonic currents distort the line voltage waveform, and may cause malfunction in sensitive electrical equipment connected to the grid.

In SMPS, the problem lies in the input rectification and filter network. The equipment connected to an electricity distribution network usually needs some kind of power conditioning, typically rectification (Dalal, 2005). AC to DC rectifiers usually interfaced with the mains. These devices convert the sinusoidal line voltage to a DC voltage. However, the rectification process produces a non-sinusoidal line current due to the nonlinear input characteristic. The most significant examples of nonlinear loads are reviewed in next chapter. It is a well-known fact that the input current of an SMPS tends to have a non-sinusoidal, distorted waveform. The distorted line current of a power converter is composed of the line frequency component and higher frequency harmonic components of the current. It should be noted that only the line frequency component of the current is carrying the power when voltage is sinusoidal (Erickson, 2005).

The current drawn by simple SMPS is non-sinusoidal and out-of-phase with the supply voltage waveform so the most common rectifier and SMPS designs have a very low power factor of below than 0.60, and their use in personal computers and compact fluorescent lamps presents a growing problem for power distribution. PFC circuits can reduce this problem and are required in some European countries by regulation. PFC is not yet widely required or used in North America and Asian countries. Linear power supply units also do not have unity power factors, but they do not have current waveform like SMPS does.

1.2 Research Objectives

The Active Power Factor Correction (APFC) is a method to improve the power factor near to unity, reduces harmonics distortion noticeably and automatically corrects the distorted line current of an SMPS. It will replace the Passive Power Factor Correction (PPFC) which has become a conventional method for the past 20 years. This research aims to implement the Unity Power Factor (UPF) for single-phase rectifier which is used in designing the high-end SMPS by using APFC approach. For this purpose, a power electronic circuit is inserted between the bridge rectifier, the output filter capacitor and the load. This approach requires additional semiconductor switches and control electronics, but permits cheaper and smaller passive components

The goals of this research are:

- To simulate and analyze the typical power supplies.
- To investigate the effects of harmonics and low power factor to the power system.
- To simulate and analyze the methodology chosen for UPF.
- To determine the best control mode for UPF.
- To implement a single-phase UPF rectifier in designing the better SMPS.

In this thesis, three types of converters are considered and they were designed in two stages converter. The first stage deals with a rectification process that is AC to DC conversion together with PFC Boost topology while the second stage deals with DC to DC conversion as Flyback topology was used. The preferable type of PFC is Active Power Factor Correction (APFC) since it provides more efficient power frequency. An active PFC uses a circuit to correct power factor and able to generate a theoretical power factor near to unity. Active Power Factor Correction also markedly diminishes total harmonics, automatically corrects AC input voltage, and capable for a wide range of input voltage.

1.3 Design Methodology

The research was carried out in two stages via analysis and experimental. The analysis starts with a literature studies which are related to the thesis topic. A completed studies and investigations were carried out on the characteristic of nonlinear loads, voltage and current distortion, total harmonic distortion, power factor and active power. In the literature survey, various topologies have been evaluated which might be able to fulfill the design specifications. Based on the literature survey, two stages topology were selected for further evaluation. The first stage is the Boost converter and the second stage is the Flyback converter. After a comparison of various topologies, this Boost-Flyback topology benefits in terms of their current waveform, cost and device rating, power rating and maximum power factor achievable.

To obtain unity power factor, all the odd harmonics in the input current should be eliminated as well as not producing any displacement angle between input voltage, V_{in} and input current, I_{in} meaning that the value of distortion factor and displacement power factor is equal to unity. To generate odd current harmonics represents the characteristic of a nonlinear loads, a single-phase full-bridge rectifier containing diodes was used during the experiment. A computer power supply was also used as one of the sample for nonlinear loads.

In measuring power factor, harmonics in term of Total Harmonic Distortion (THD) and power ratings of different nonlinear loads, Fluke 43B Power Quality Analyzer was used. After collecting the data and identifying the problems associated with SMPS, an active PFC circuit has been designed in order to achieve unity power factor. A second stage converter is then designed to provide voltage regulation at the output. Finally the results were recorded and some evaluations were made.

The design and analysis of the above-mentioned circuit is based on a pre-regulator circuit required for SMPS application. Most of computer SMPS now do not have an input pre-conditioner section which makes the SMPS meet the minimum requirements of power factor and total harmonic distortion. By designing a two-stage converter, the computer SMPS would have near unity power factor and regulated DC output voltage. Figure 1.1 shows the flow chart on how the research is organized.

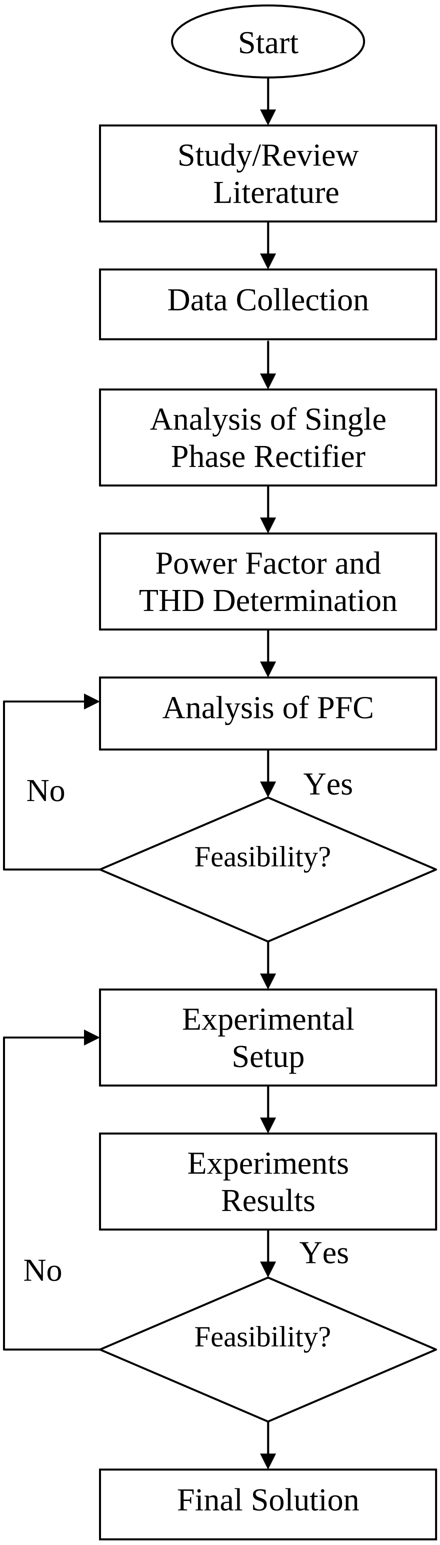


Figure 1.1: Flowchart of research work

1.4 Thesis Outline

In chapter 1, the primary focus of this research was to review, analyze and understand the problems associated with off line single-phase rectifier and SMPS. Then, the objectives and methodology were declared including a brief review on APFC approach which provides better characteristics in terms of power factor, input current and voltage regulation.

Chapter 2 covers a literature survey of this thesis. The main topics discussed here are SMPS history, a rectification process and harmonics generated by SMPS. This chapter also describes solutions taken by power designers to improve the SMPS power factor. Finally it comes out with the active PFC which is chosen to obtain unity power factor rectifier.

Chapter 3 covers the theoretical of harmonic and lists various types of non-linear loads. Afterwards, it focuses on the effect of harmonic on power system and its standard. It then lists all the classes defined by the standard. It also reviews the basic definition of power factor correction, displacement power factor, distortion power factor and the relationship between them.

Chapter 4 covers some theories of SMPS, the principle of PFC design, the APFC methodology, the double-stage design, and the control strategies to achieve unity power factor. This section also presents the power stage design as well as the controller design.

Chapter 5 presents the simulation results using PESIM, the experimental results including tables, graphs and waveforms. At the end of the chapter, details results, analysis and discussions are presented.

Chapter 6 finally closes the thesis by the conclusions. Several suggestions are also included in this chapter.

CHAPTER 2

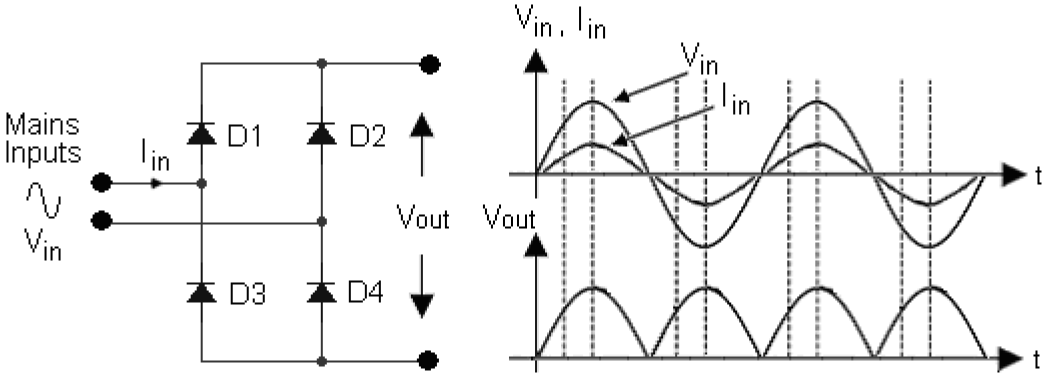
LITERATURE REVIEW

2.0 Introduction

The summary of results on previous research related to PFC techniques and input power factor corrected single-phase rectifier systems are introduced in this chapter. Numerous single-phase PFC topologies are classified and various PFC circuits for single-phase rectifiers are reviewed. The study of PFC topologies is limited to single-phase systems since most SMPS are powered by a single-phase utility source.

2.1 Typical Power Supply History

In most power electronic applications, the power input from utility is a 50Hz sine wave AC voltage. It is then converted to a DC voltage by using rectifiers. The inexpensive way to convert AC to DC in an uncontrolled manner is by using rectifier with diodes, as shown in Figure 2.1.



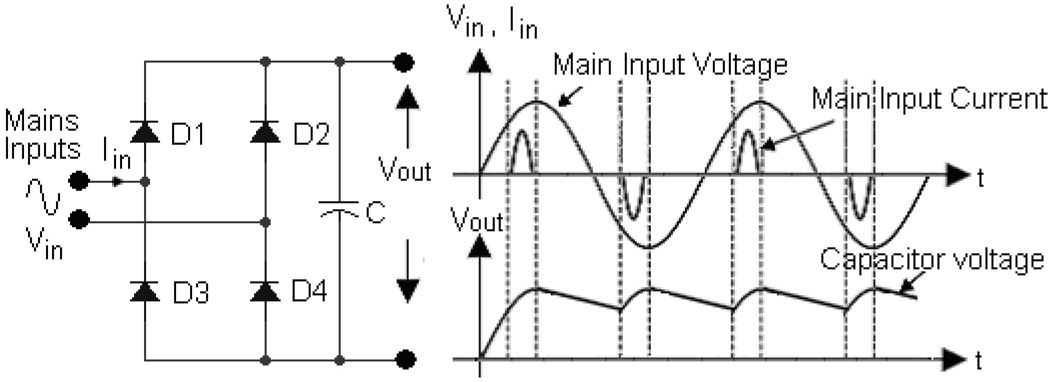
(a) Bridge rectifier (b) Inputs and Output waveforms

Figure 2.1: A diode bridge rectifier and waveforms.

The DC output contains high voltage ripple that is not suitable to supply a constant DC voltage. In most applications, the rectifiers are supplied directly from the utility source without a 50Hz transformer. The avoidance of this costly and bulky 50Hz transformer is important in most modern power electronic systems (Mohan, et al. 2005).

It should be noted in the circuit of Figure 2.1(a) that if a pure resistive is connected as load, the input current follows the waveform of input voltage. The voltage and current waveforms are shown in Figure 2.1(b). The circuit will have power factor equals to unity but a large output voltage ripple. This circuit models power factor corrected rectifier and will be discussed later.

The conventional input stage of an off-line rectifier design associated with its waveforms is shown in Figure 2.2.



(a) Off-line rectifier (b) Inputs and Output waveforms

Figure 2.2: A typical power supply with filter capacitor and waveforms.

It is comprised of a full-bridge rectifier followed by a large-input-filter capacitor. This input-filter capacitor reduces the ripple on the voltage waveforms into the DC converter stage. The problem with this input circuit is that it produces excessive peak input currents and high harmonic distortion on the line. The high distortion in the input current occurs due to the fact that the diode rectifiers only conduct during a short interval. This interval corresponds to the time when the mains instantaneous voltage is greater than the capacitor voltage. Since the capacitor must meet hold-up time requirements, its time constant is much greater than the frequency of the mains (Dalal, 2005).

The DC output voltage of rectifier should be as ripple free as possible. Therefore, a large capacitor is connected as a filter on the DC side. The capacitor will be charged during the peak of the AC input voltage and this will result in high peak input current. This rectifier draws highly distorted current from the utility. Because of harmonic standards set by USA and European countries, guidelines will limit the amount of current distortion allowed into the utility. Therefore the simple diode bridge rectifiers may not be allowed (Tse, 1998).

The mains instantaneous voltage is greater than the capacitor voltage only for very short periods of time, during which, the capacitor must be charged fully. Therefore, large pulses of current are drawn from the line over a very short period of time, as shown in Figure 2.2 (b). This is true for all rectified AC sinusoidal signals with capacitive filtering. Twice per cycle every single-phase rectifier draws a pulse of current to recharge its capacitor to the peak value of the supply voltage. Between voltage peaks the capacitor discharges to support the load and the rectifier does not draw current from the utility. Therefore, the generation of harmonic currents due to the behavior of single-phase rectifiers, distorted currents are normally drawn from the input line resulting in low power factor, low distortion factor and high total harmonic distortion.

They draw high amplitude current pulses, the fundamental current of the line current is essentially in phase with the voltage, and the displacement factor is close to the unity. However, the low-order current harmonics are quite large, close to that of the fundamental. From the line current spectrum we can see that the waveform contains a lowered fundamental frequency component plus 3rd, 5th, 7th, 9th and higher of current harmonics (Lopez, et al. 2001). A typical power supply current spectrums are shown in Figure 2.3.

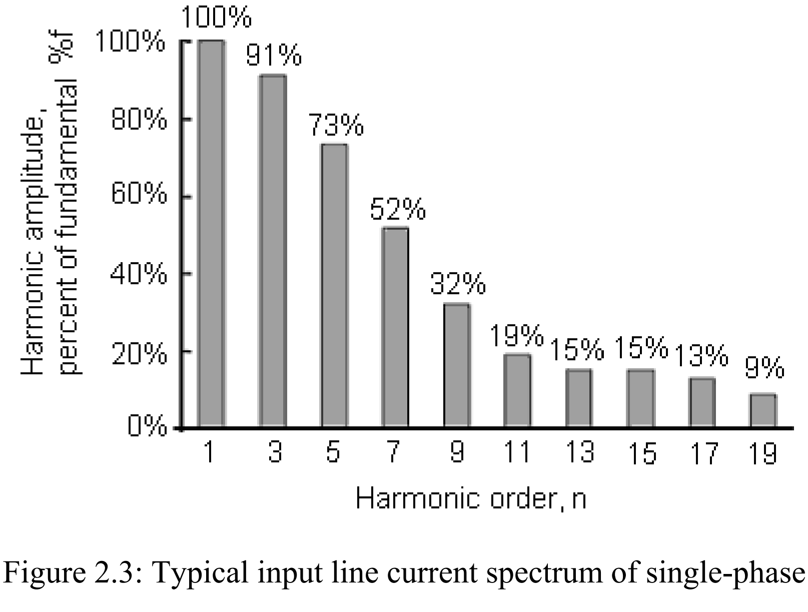


Figure 2.3: Typical input line current spectrum of single-phase power supply (Lopez, et al. 2001)

The addition of harmonic currents to the fundamental component increases the total RMS current. Because they affect the RMS value of the current, harmonics will affect the power factor of the circuit. A diode bridge rectifier with filtering capacitor is considered here as a non-linear load. The power factor for this circuit varies from 0.40 to 0.60 depending on the capacitance value (Wei, 2000). For a typical single-phase power supply shown above, it has 136% total current harmonic distortion, 59% distortion factor, unity displacement power factor and 0.59 true power factor.

2.2 Power Factor Correction (PFC)

Due to the large harmonic content as indicated in Table 2.1, typical single-phase bridge rectifiers used for interfacing power electronic equipment with utility system may exceed the limits on the individual current harmonics and THD (Total Harmonic Distortion) specified by international standards. In view of low power factor drawbacks, some of alternatives for improving the input current waveforms are discussed along with their advantages and disadvantages. The technique used to improve the value of power factor is called Power Factor Correction (PFC) (Lopez, 2001). The classification of single-phase PFC topologies for diode bridge rectifier is shown in Figure 2.4.

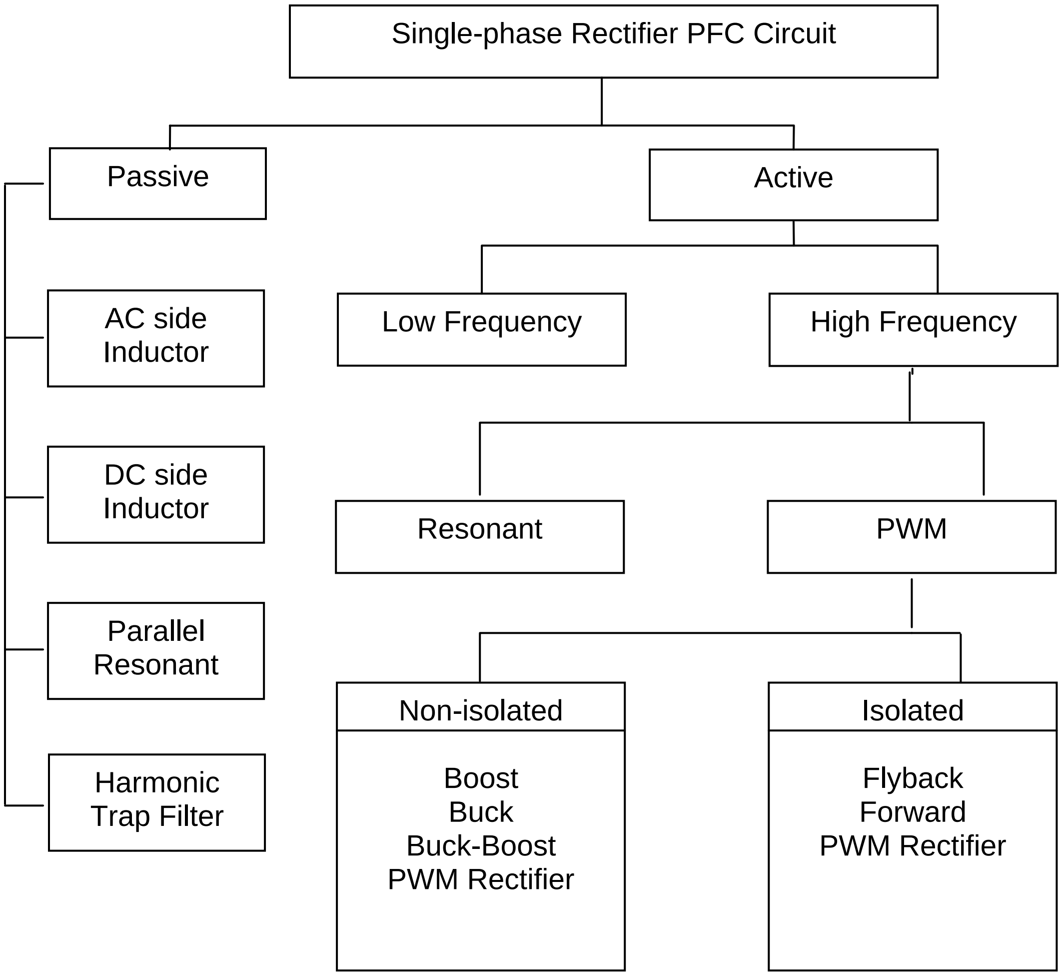


Figure 2.4: Classification of single-phase input PFC topologies for diode bridge rectifier (Lee, 1999).

PFC shaped the distorted input current waveform to approximate a sinusoidal current that is in phase with the input voltage. There are several effective techniques for getting a sinusoidal input current waveform with low distortion. The objective of PFC is to make the input to a power supply looks like a simple resistor (Wei, 2000). Two typical techniques for PFC can be divided into Passive Power Factor Correction (PPFC) and Active Power Factor Correction (APFC). In this thesis, both the correction techniques are discussed for a single-phase circuitry.

Regardless of the particular converter topology that is used, the output voltage carries a ripple at twice the line-frequency (Eissa, 1996). This is because in a single-phase system the available instantaneous power varies from zero to a maximum, due to the sinusoidal variation of the line voltage. On the other hand, the load power is assumed to be constant. Every single-phase PFC converter requires energy-storage (bulk) capacitor to handle difference between instantaneous input power and average output power.

There are several approaches that have been taken by power designers to improve the value of power factor when they are designing SMPS. Most of them make used of PPFC as a solution to improve the waveform of line current in order to reduce the harmonic contents generated by SMPS. These approaches can be described as follows.

2.2.1 Passive PFC

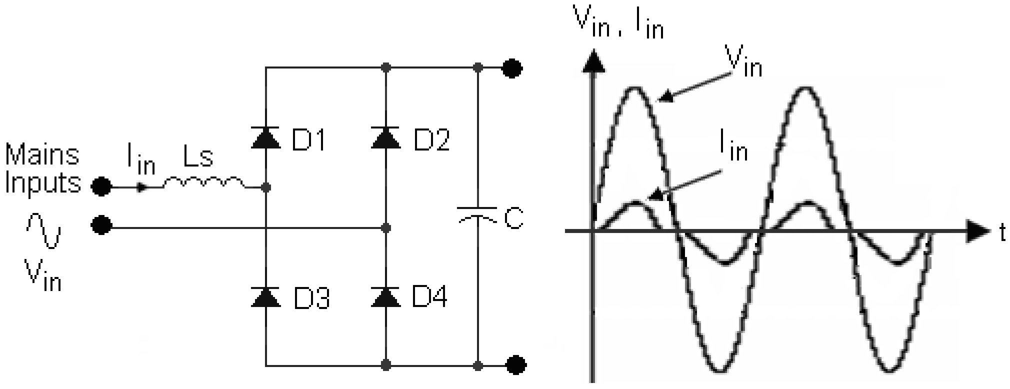
The most common type of PFC is passive PFC. PPFC methods use additional passive components (capacitor or inductor) in conjunction with the diode bridge rectifier to correct poor power factor. A PPFC is more reliable than an APFC because no active devices are utilized. Because it operates at line frequency of 50Hz, PPFC requires relatively large fixed value inductors and capacitors to reduce the low frequency harmonic currents (Shimizu, 1997).

PPFC includes passive filters which can broadly be classified into series filters, shunt filters and a hybrid combination of the two. Series filters introduce impedances in series with the utility to reduce harmonic currents. Shunt filters provide a low impedance path for the harmonic currents generated by the rectifiers so that they are not reflected in the current drawn from the utility.

These filters use resonant pass or resonant trap circuits sensitive to both frequency and load. It is difficult to achieve unity power factor with PPFC. Also, very large currents may circulate in the filter. However, the passive is an effective PFC solution in cases where the line frequency, line voltage and load are relatively constant. The various types of PPFC and the waveforms of input voltage and input current are discussed below and their associated waveforms are taken from the simulation results.

2.2.1.1 Rectifier with AC-side Inductor

The simplest methods is by adding an inductor at the AC-side of the diode bridge, in series with the line voltage as shown in Figure 2.5, thus to create circuit conditions such that the line current is zero during the zero-crossings of the line voltage (Skvarenina, 2001).



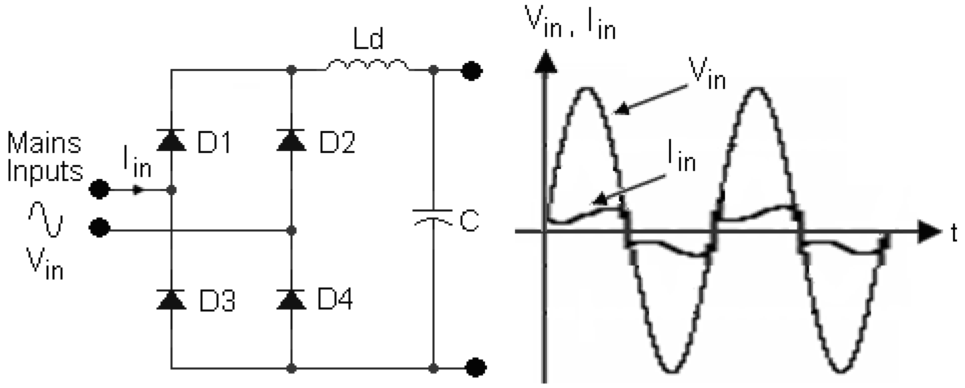
(a) AC-side inductor rectifier (b) Inputs waveforms

Figure 2.5: Rectifier with AC-side inductor and waveforms.

The advantages of this circuit are simplicity, low cost and improved shape of line current. However, the maximum power factor that can be obtained is □0.76 as recorded during simulation. It can only improve harmonic current distortion to 30% to 40% at best. The output voltage cannot be controlled and it only slightly reduces small phase displacement of fundamental component.

2.2.1.2 Rectifier with DC-side Inductor

The inductor can be also placed at the DC-side, as shown in Figure 2.6. The inductor current is continuous for a large enough inductance *Ld*. In the theoretical case of near infinite inductance, the inductor current is constant, so the input current of the rectifier has a square shape (Dewan, 1981).



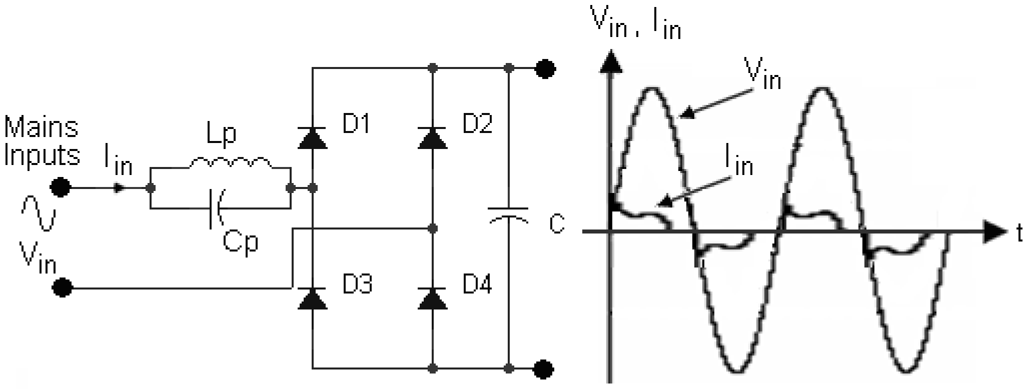
(a) DC-side inductor rectifier (b) Inputs waveforms

Figure 2.6: Rectifier with DC-side inductor and waveforms.

The advantage of this circuit is the shape of line current is improved. However, the maximum power factor that can be obtained is □0.85. Operation close to this condition would require a very large and impractical inductor. For lower inductance *Ld*, the inductor current becomes discontinuous.

2.2.1.3 Rectifier with Parallel-resonant Band-stop Filter (BSF)

The shape of the line current can be further improved by using a combination of low-pass input and output filters (Mohan, et al. 2005). There are also several solutions based on resonant networks which are used to attenuate harmonics. For example, a band-stop filter of the parallel resonant type as shown in Figure 2.7, tuned at the line-frequency, is introduced in-between the AC source and the load.



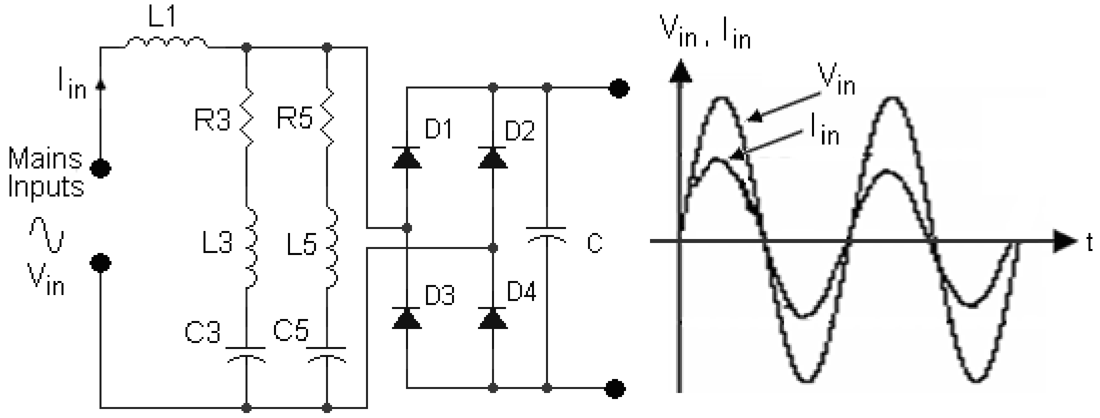
(a) Parallel BSF rectifier (b) Inputs waveforms

Figure 2.7: Rectifier with parallel-resonant BSF and waveforms.

The advantages of this circuit are lower value of capacitance element used and improve better the shape of line current. However, the maximum power factor that can be obtained is □0.90. This circuit requires a heavy and bulky inductor and must handle the rated full load current. This circuit can only supply nonlinear loads.

2.2.1.4 Rectifier with Harmonic Trap Filter

Another possibility is to use a harmonic trap filter. The harmonic trap consists of a series resonant network, connected in parallel to the AC source and tuned at a harmonic that must be attenuated (Erickson, 2005). For example, the filter shown in Figure 2.8 has two harmonic traps, which are tuned at the 3rd and 5th harmonic respectively.



(a) Harmonic trap filter rectifier (b) Inputs waveforms

Figure 2.8: Rectifier with harmonic trap filter and waveforms

Some of the advantages of this circuit are no high frequency losses, provides low impedance to tuned frequency and greatly improves the shape of line current. However, the maximum power factor that can be obtained is □0.95. It only filters a single (tuned) harmonic frequency. Therefore, multiple filters are required to satisfy typical desired harmonic limits. This resonant circuit is very sensitive to line frequency and it can import harmonics from other nonlinear loads. The voltage regulation is also low.

From the survey result as well as simulation results over various types of PPFC circuits, it was found that PPFC have certain advantages, such as simplicity, reliability and ruggedness, insensitive to noise and surges, no generation of high-frequency Electromagnetic Interference (EMI) and no high frequency switching losses. On the other hand, they also have several drawbacks. Solutions based on filters are heavy and bulky, because line-frequency reactive components are used.

They also have poor dynamic response, lack voltage regulation and the shape of their input current depends on the load. Even though line current harmonics are reduced, the fundamental component may show an excessive phase shift that reduces the power factor. Moreover, circuits based on resonant networks are sensitive to the line-frequency. In harmonic trap filters, series-resonance is used to attenuate a specific harmonic. However, parallel-resonance at different frequencies occurs too, which can amplify other harmonics (Erickson, 2005). Better characteristics are obtained with APFC circuits, which are reviewed in the following section.

2.2.2 Active PFC

An active power factor correction (APFC) performs much better and is significantly smaller and lighter than the PPFC circuits. An APFC refers to the use of a power electronic converter, switching at higher frequency than line frequency, to shape the input current to be sinusoidal and in-phase with the input utility voltage (Tse, 1998). Using APFC techniques, it is possible to achieve a power factor near unity and current *THD* less than 5%.

Despite of active wave shaping, APFC includes feedback sensing of the source current for waveform control and feedback control to regulate the output voltage even when the input voltage varies over a wide range (Dixon, 1988). Compared with passive solutions, they are less bulky and can easily meet the standards of harmonic distortion. Figure 2.9 shows the block diagram of an APFC circuit.

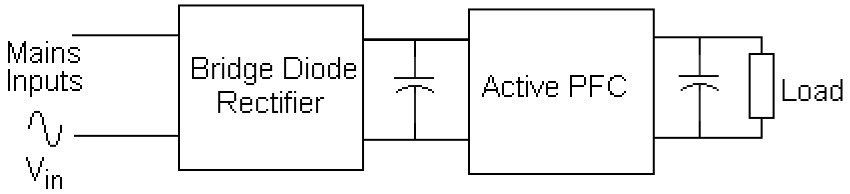


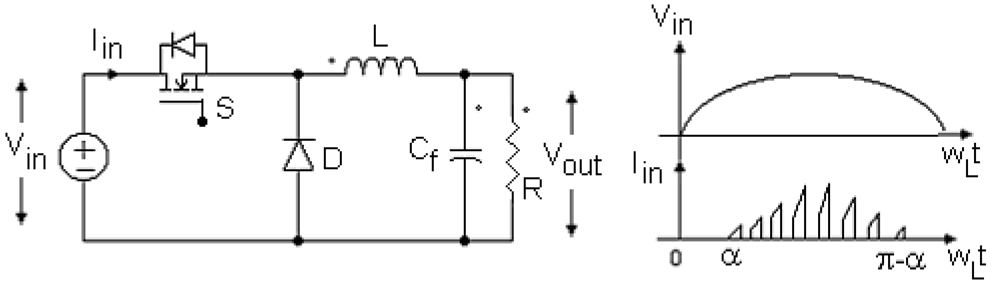
Figure 2.9: Block diagram of a rectifier with APFC.

For single phase PFC, a DC-DC converter is placed in between the input voltage and the load. In principle, any DC-DC converter can be used for this purpose, if a suitable control method is used to shape its input current or if it has inherent PFC properties. For this reason, the basic Buck, Boost and Buck-Boost converters were considered and analyzed. These converters may operate in Continuous Conduction Mode (CCM), where the inductor current never reaches zero during one switching cycle or Discontinuous Conduction Mode (DCM), where the inductor current is zero during intervals of the switching cycle.

The result is a large current ripple in DCM and a smaller current ripple in CCM. The choice of CCM or DCM depends on which SMPS is used and the necessary current and power rating required. DCM is often implemented in low power design where the current ripple is lower. CCM is often preferred at high power levels. However, the thesis will not discuss in detail about the current conduction mode, it focuses more on the specific topology to be used in PFC design. The DC to DC converters topologies with their input waveforms are shown in the following figures.

2.2.2.1 Buck Converter

The Buck converter has a lower output voltage than input voltage, and it has pulsating input current generating high harmonics into the power line. This circuit is not practical for low-line input because it does not draw the input current when input voltage is lower than the output voltage. The line current of a PFC based on a Buck converter has distortions and the input current of the converter is discontinuous as in Figure 2.10. Therefore, it has relatively low power factor.



(a) Buck converter (b) Inputs waveforms

Figure 2.10: Buck converter and waveforms.

2.2.2.2 Boost Converter

The Boost converter is shown in Figure 2.11, it has step-up conversion ratio. Therefore the output voltage is always higher than the input voltage. The converter will operate throughout the entire line cycle, so the input current does not have distortions and continuous as shown above. It has a smooth input current because an inductor is connected in series with the power source (Erickson, 2005). In addition, the switch is source-grounded, therefore it is easy to drive. This topology is a universal solution for off-line power supplies and SMPS applications.