INPUT CURRENT SHAPING OF A SINGLE PHASE RECTIFIER WITH A SINGLE STAGE ĆUK CONVERSION STAGE

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By

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Dedication

"To My All Well-wisher"

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Abstract

Modern power supplies connected to AC mains introduce harmonic currents in the utility. Such harmonic currents cause problems including voltage distortion, heating, radiated and conducted noises, and reduction of line capacity. International standards/ recommendations have been adopted that make the use of harmonic mitigation and power factor correction circuits in power supplies mandatory. As a result, rectifiers with input current shaping and power-factor improvement arrangement have received attention to alleviate the problems mentioned. In this thesis, an active switching of a single phase rectifier has been investigated to find out a solution to the harmonic current and poor power factor. Boost switching regulator is widely used for this purpose. Other converter topology, the Ćuk switching regulator is also being investigated due to its advantageous characteristics like, high frequency insulation, short circuit protection capability, step-up and step-down regulation, reduction of input current ripple and inductor coupling.

In this thesis, the performance of active regulator (Boost and Ćuk) based input current shaping of a single phase rectifier has been studied by simulation. The study has been done with and without passive input LC filter. Study and comparison reveals the advantages of Ćuk switching regulator over the boost regulator commonly used for this purpose. The Total Harmonic Distortion (%THD) shows a small value in case of Ćuk regulator. As a result input current is almost sinusoidal for Ćuk regulator compare to Boost regulator. The variation of power factor and voltage gain with respect to the change of duty cycle show a steady nature for Ćuk regulator. Efficiency wise, the Ćuk regulator shows almost a constant value within the range of certain duty cycle, whereas in Boost regulator the efficiency variation is high.

Chapter 1

INTRODUCTION

1.1 Introduction

Large numbers of electrical equipments are supplied by 50 or 60 Hz power and in most of them; rectifiers are required to convert ac voltage to dc voltage. Generally, a diode bridge rectifier is followed by a bulk capacitor. This causes input current to be pulsating in shape. Pulsating current drawn by the rectifier creates problem for the power distributing networks and other electrical systems in the vicinity. Some of these problems are [1,2,3] -

a) Low power factor (0.6-0.8) and high Total Harmonic Distortion (THD),
b) Low efficiency because of large input current,
c) Requires higher voltage rating of the ac source and distributing system due to the phase displacement of current and voltage fundamentals,
d) Input ac voltage gets distorted because of the saturation associated high peak current,
e) Higher passive component size of filters,
f) Additional heating due to harmonics, over voltage due to resonance, interference with communication and control signal, malfunctioning of utility relays etc.

This has drawn the attention of regulatory bodies around the world. They impose enforcement of regulation such as IEC-1000-3 and IEEE 519 [4]. To meet the specification of these regulations, there is a need for the reduction in line current harmonics, power factor correction and harmonics reduction circuits. As the unity power factor is not necessary to meet the regulation, so it allows the solutions with a variety of ways. The general approach to improve the power factor can be classified as passive and active approaches. The passive approach uses capacitive-inductive filters to achieve power factor while the active approach uses a switched mode power supply to shape the input current [8-10]. This approach varies due to power range (Low, Medium, and High), efficiency, cost and size. Although various research efforts have produced power circuit configurations for Power Factor Corrections (PFC) and reduction of Total Harmonics Distortions (THD) to alleviate the problem, they greatly increase the cost and complexity compared to conventional low quality rectifiers. Thus research is still being carried out to reduce cost and complexity and to improve the performance [5,6,7,8,9].

1.2 Previous work

In order to meet IEEE-519 and IEC-1000-3, a cost effective and economical solution to mitigate harmonics generated by power electronic equipment is currently of high interest.

In normal passive approach, a full bridge rectifier with an LC filter is used to reduce the line current harmonics. Passive Power Factor Correction (PFC) can meet the regulation with reliability and low EMI [10]. On the other hand, the filter capacitor voltage varies with the line voltage, which has a detrimental effect on the performance and efficiency of the dc/dc converter. For large hold up time for the power supply, the bulk capacitance has to be increased and becomes bulky. On the other hand, use of small value of inductance degrades the power factor. As a result, the passive approaches seem to be attractive for low power application and for narrow voltage range [7,8].

To overcome the drawbacks of passive approach, the active approach is explored. In active solutions, a converter with switching frequencies higher than the AC frequency is placed between the output of the diode rectifier and the bulk capacitor. The reactive element of this converter is small, because their size depends on the converter switching frequency rather the than AC line frequency. The frequency of this converter is to make the load behave as an ideal resistive load and thus eliminate the generation of the line current harmonics. However, adding a high frequency switching converter in series with the input circuit causes reduction in overall efficiency of the whole converter due to the losses contributed by the active PFC circuit. Moreover the active PFC circuit contributes to an increase in overall cost, increase in EMI and reduction in reliability due to an increase in the number of components. So, the target is to reduce the cost and enhance the performance of the active PFC. Many researches have been done on the enhancing the performance of active approaches. Normally two stages active PFC is widely used which consists of two converters to achieve both power factor correction and output voltage regulation in addition to the rectification circuit and the input EMI filter. These converters are possessed with separate switches and control circuit. To reduce the cost and complexity of the two-stage structure, the single stage PFC is used. But as the voltage across the storage capacitor is not regulated (because the control is to be used to regulate the output voltage), output voltage can vary greatly [10].

Power factor correction can be done by harmonic injection method, which is an involved and expensive approach [11]. Nonlinear carrier control (NLC) method is also used. But the technique is complicated due to the NLC controller [12].

Input current shaping by Buck [13,14], Boost [15,16,17], Ćuk [18,19], Buck-Boost, Fly back, ZETA, SEPIC [20,21,22] converters offer different aspects of active filtering. Normally Boost topology is used as the converter due to its advantages of input inductor and switching simplicity. But Boost PFC converter has a low bandwidth which implies a loosely regulated output voltage across the storage capacitor. Also only step-up voltage option is available here [6, 15].

1.3 Objectives of the work

The objectives of this thesis are to make the input current of a single-phase rectifier circuit near sinusoidal and at the same time in phase with the supply voltage. This will eliminate the harmonic contents in the input current and will improve the power factor of the circuit as the standard regulation emphasizes. Conventionally Boost regulated rectifier scheme is used for this purpose. Boost regulator has the disadvantage of voltage regulation above the input. In this thesis, advantages of Ćuk converter to regulate the rectifier output and maintaining near sinusoidal input current and unity power factor will be investigated.

To attain the objective, in this work, the Ćuk converter is investigated at a high frequency to shape the input current. To make current sinusoidal, an input LC filter is used. The Ćuk converter is modified to give almost exact sinusoidal input current wave shape. The simulating results of the new proposed modified Ćuk regulator are compared with that of Boost regulator. Advantages of the Ćuk PFC regulator over Boost PFC regulator have been investigated.

1.4 Thesis Outline

This thesis includes 4 chapters.

Chapter 1 gives a general introduction followed by a brief review of earlier works done and objective of the work. Chapter 2 provides the literature review related to this thesis. The description of a single-phase full bridge diode rectifier is described here with its problem. It starts from simple full-bridge diode rectifier, which follows with output LC filter and then both output and input LC filter. Full bridge diode rectifier with active filter approach is studied later. First Boost regulated rectifier is studied. Then analysis has been done with Ćuk regulator. A modified Ćuk regulator is studied to find out a better solution of the problem than the Ćuk regulator. Chapter 3 includes the study of these converters--their advantages, disadvantages and their performance comparison. Chapter 4 is the conclusive discussions and remarks. Some suggestions leading to future scope of work are also presented in Chapter 4.

Chapter 2

Single-Phase Diode Rectifier

2.1 Introduction

Power factor: Power factor is defined as the ratio of the average power to the apparent power drawn by a load from an AC source. Assuming an ideal sinusoidal input voltage source, the power factor can be expressed as the product of the distortion power factor and displacement power factor, as given in (2.1). The distortion power factor K_d is the ratio of the fundamental root-mean-square (RMS) current ((Irms(1)) to the total RMS current(Irms). The displacement power factor K_θ is the cosine of the displacement angle between the fundamental input current and input voltage.

$$PF = K_d \times K_\theta \quad \text{.........2.1}$$

The distortion factor K_d is given by the following equation

$$K_d = \frac{Irms(1)}{Irms} \quad \text{.........2.2}$$

The displacement power factor K_θ is given by the following equation

$$K_\theta = Cos\theta \quad \text{.........2.3}$$

The displacement power factor K_θ can be made unity with a capacitor or inductor but making the distortion power factor K_d unity is difficult. When a converter has less than unity power factor, it means that the converter absorbs apparent power that is higher than the active power it consumes. This implies that the power source should be rated to a higher VA rating than what the load needs. In addition, the current harmonics generated by the converter deteriorates the power quality of the source, which eventually affects other equipment.

High power factor and low harmonics do not go hand-in-hand. Though there is no direct correlation between the two, the following equations relates total harmonic distortion (THD) to power factor.

$$THD(\%) = 100 \times \sqrt{\frac{1}{K_d^2} - 1} \quad \text{.......... 2.4}$$

The distortion power factor K_d is also given by the following equation

$$K_d = \frac{1}{\sqrt{1 + \left(\frac{THD(\%)}{100}\right)^2}} \quad \text{.......... 2.5}$$

When the fundamental component of the input current is in phase with the input voltage, K_θ =1 and power factor is given by,

$$PK = K_d K_\theta = K_d \quad \text{.......... 2.6}$$

Substituting 2.5 in 2.6, we have

$$PF = \frac{1}{\sqrt{1 + \left(\frac{THD(\%)}{100}\right)^2}} \quad \text{.......... 2.7}$$

A sinusoidal current could also have a poor power factor if its phase is not in line with voltage. From equation (2.7) it is apparent that a 10% THD corresponds to a Power Factor of approximately 0.995. Thus specifying limits for each of the harmonics would help in the control of input current "pollution", both from the standpoint of minimizing the circulating currents and reducing the interference with other equipment. While the process of shaping this input current is commonly called "power factor correction," the measure of its effectiveness towards complying with international regulations is the amount of reduction in the harmonic content of the input current.

2.2 Power Factor Problem in AC-DC Rectifier

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 main instantaneous voltage is greater than the capacitor voltage.

Since the instantaneous main 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. 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. Fig. 2.1 shows the schematic of a typical single-phase diode rectifier filter circuit while Fig. 2.2 shows the typical simulated line voltage and current waveforms. The actual current wave shape and the resulting harmonics depend on the line impedance. Fig. 2.3 and Fig. 2.4 show the simulated odd line current harmonics normalized to the fundamental for different line impedance values.

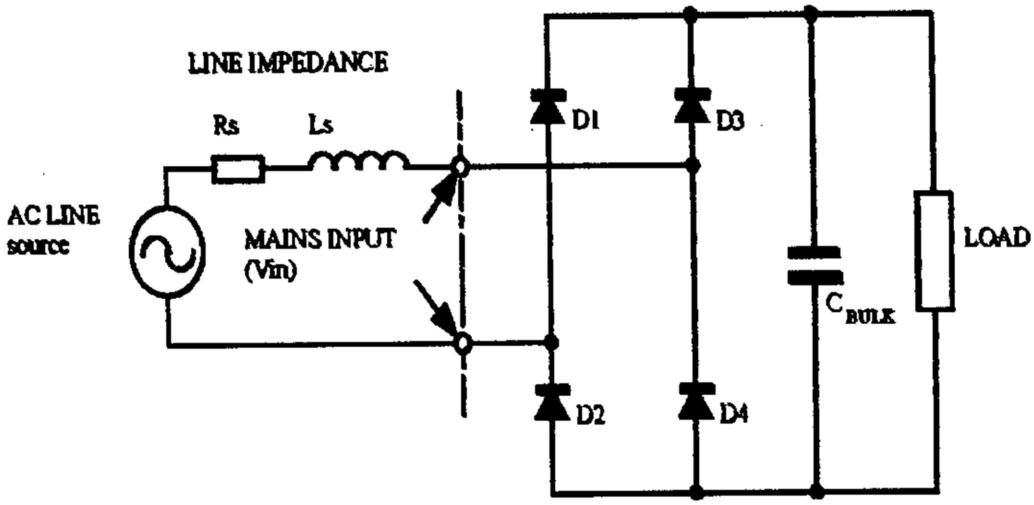

Fig. 2.1.Typical input stage schematic of an off-line switching power supply.

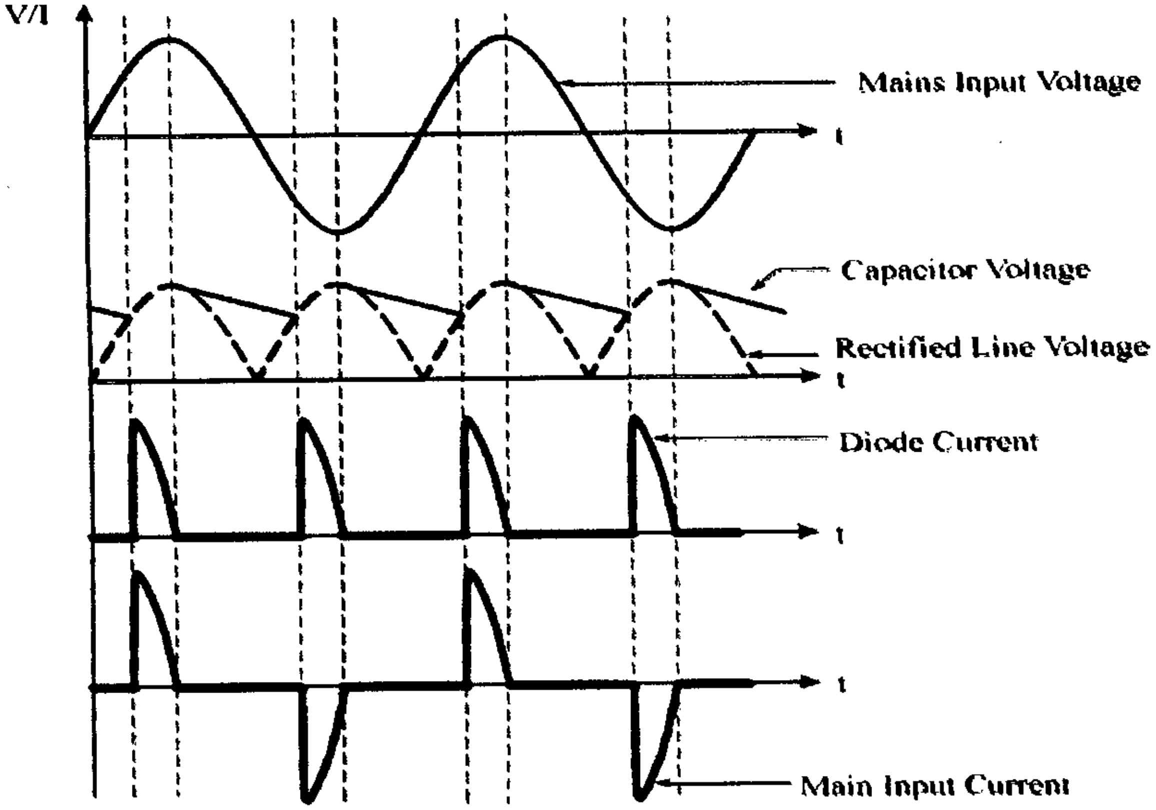

Fig: 2.2. Typical line current and voltage waveforms

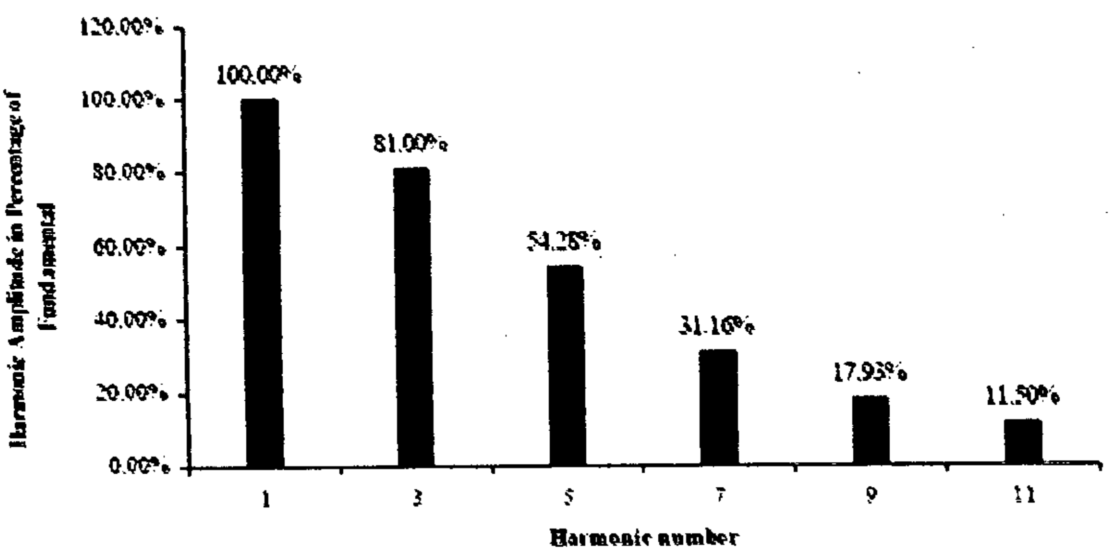

Fig.2.3. Odd line current harmonics normalized to the fundamental for the condition when the load is near the distribution transformer resulting in higher harmonic currents due to lower input line impedance.

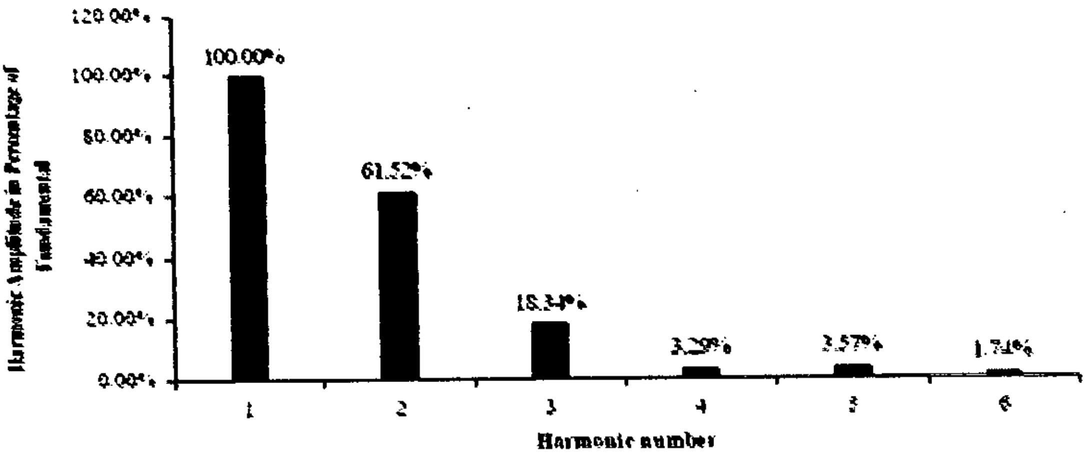

Fig.2.4 Odd line current harmonics normalized to the fundamental for the condition when the load is away from the distribution transformer resulting in lower harmonic currents due to higher input line impedance.

2.3 Power Factor Correction Methods (PFC):

Power factor depends on both harmonic content and displacement power factor. The EN 61000-3-2 standard sets limits on the harmonic content of the load current and does not specifically regulate the power factor or the total harmonic distortion of the line current. In consideration of the above, the following can be concluded.

◆ A high power factor can be achieved even with a substantial harmonic content. The power factor is not significantly degraded by harmonics, unless its amplitude is quite large.

◆ Low harmonic content does not guarantee high power factor.

Thus, PFC circuits for nonlinear loads have their primary goal to reduce the harmonic content of the line current. PFC circuit solutions can be broadly categorized as passive or active circuits.

2.3.1 Passive Power Factor Correction Method:

In passive PFC, passive elements are used in addition to the diode bridge rectifier, to improve the shape of the line current. For example, the passive LRC input filter is typically used in electronic ballast for harmonic reduction. In general, passive solution offers reliable, rugged and quick reduction of harmonic current. They are insensitive to line surges and spike. However they have many disadvantages; they are relatively bulky. They are sensitive to line frequency and may produce excessive phase shift. They lack voltage regulation and their dynamic response is poor.

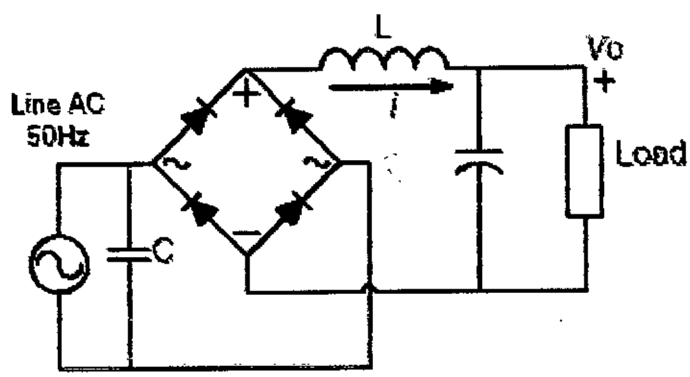

Fig 2.5 The simple Rectifier with output and input Filter

2.3.2 Active Power Factor Correction Method:

In active PFC, switches are used in conjunction with inductors to force the line current to follow the envelope of the line voltage and go in phase with it. The output voltage is usually regulated for variations. The switching frequency differentiates the active PFC solutions into two classes, the low -frequency and the high-frequency active PFC. In low-frequency active PFC circuits; the switching is synchronized to the line voltage. This scheme has the advantages that it generates less EMI, requires a smaller inductor when compared to the passive PFC and the simple low frequency circuit is more reliable and efficient when compared to the active PFC scheme. Compared to the high frequency PFC circuit, the reactive elements are larger and the regulation of the output voltage is poor.

The high frequency active PFC circuit can be realized by placing a buck or a boost or a buck-boost converter in between the bridge rectifier and the filter capacitor of a conventional rectifier filter circuit and operating it by a suitable control method that would shape the input current. For all converter topologies, the switching frequency is much higher than the line frequency, the output voltage ripple is twice the line-frequency and the output DC is usually regulated.

The PFC output voltage can be higher or lower, depending on the type of converter being used. With a buck converter the output voltage can be lower, for a boost converter the output voltage can be higher, while for a buck-boost converter the output voltage can be higher or lower than the maximum amplitude of the input voltage. The inductor current in these converters can be either continuous or discontinuous. In the continuous conduction mode (CCM) the inductor current never reaches zero during one supply cycle while in the discontinuous conduction mode (DCM), the inductor current is zero during intervals of the switching cycle.

Besides square-wave converter topologies, PFC can also be achieved using quasi-resonant and interleaved converters, which can reduce the switching loss with zero-current switching (ZCS) and zero-voltage switching (ZVS). Examples are the Ćuk-PFC and SEPIC corrector. Besides the non-isolated correctors, isolated power factor corrector can be achieved by using transformer-coupled version of the basic converter, for example, the Fly-back corrector is the isolated version of the buck-boost corrector.

2.4 Single Phase Diode Rectifier including Output LC filter with Resistive Load:

Following is a diode rectifier with resistive load and output voltage filter:

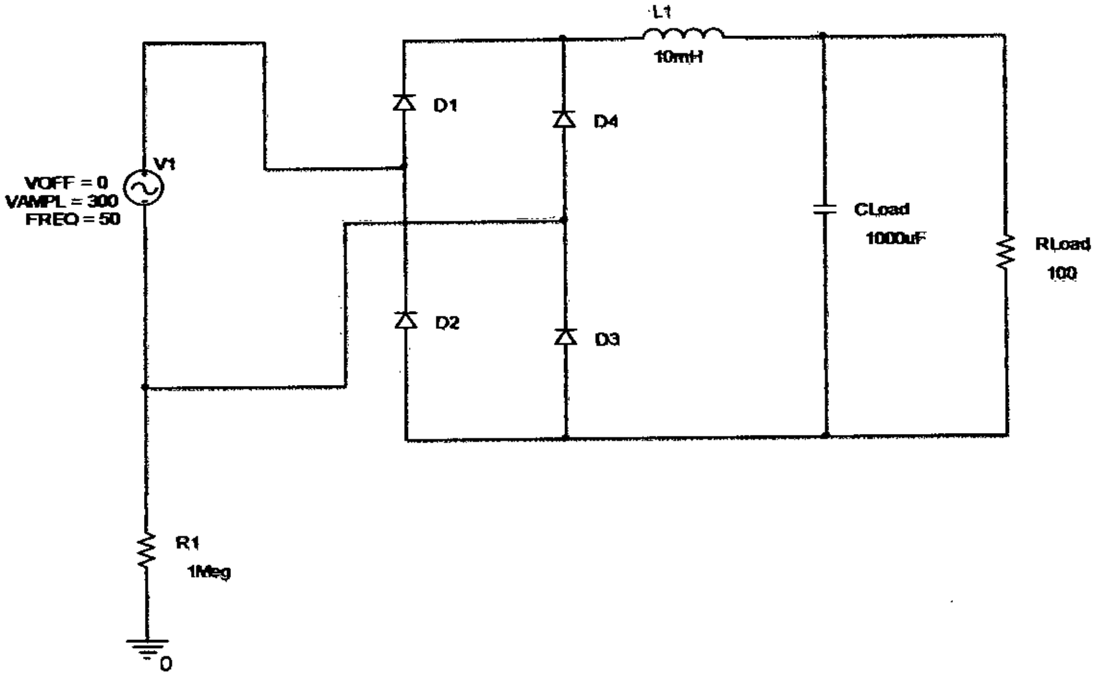

Fig 2.6: Single Phase Diode Rectifier with output LC filter and Resistive Load

It is the basic form of full-wave diode rectifier. Here the input sinusoidal voltage (V_1) has peak amplitude of 300Volts with the frequency of 50Hz.The output of the full wave rectifier contains both ac and dc components as shown in Fig. 2.7. A majority of the applications, which cannot tolerate a high value ripple, necessitates further processing of the rectified output. The undesirable ac components, i.e. the ripple, can be minimized using filters.

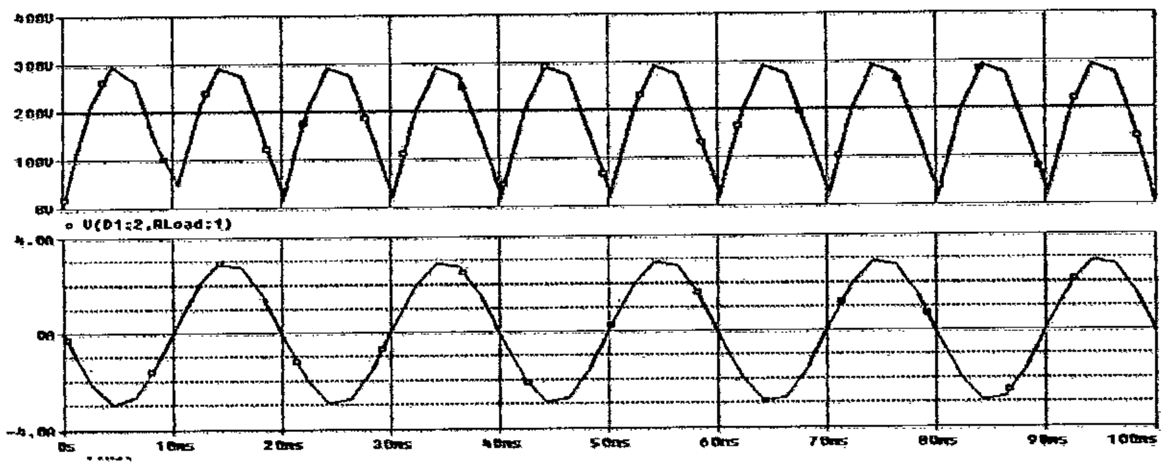

Fig 2.7. The output voltage and input current waveform of a full bridge rectifier without any filter.

In order to get low ripple output voltage, if capacitor filter is used, then the output will be like that shown in Fig. 2.8. The ripple decreases with the increase of the capacitor value. The ripple depends on output load.

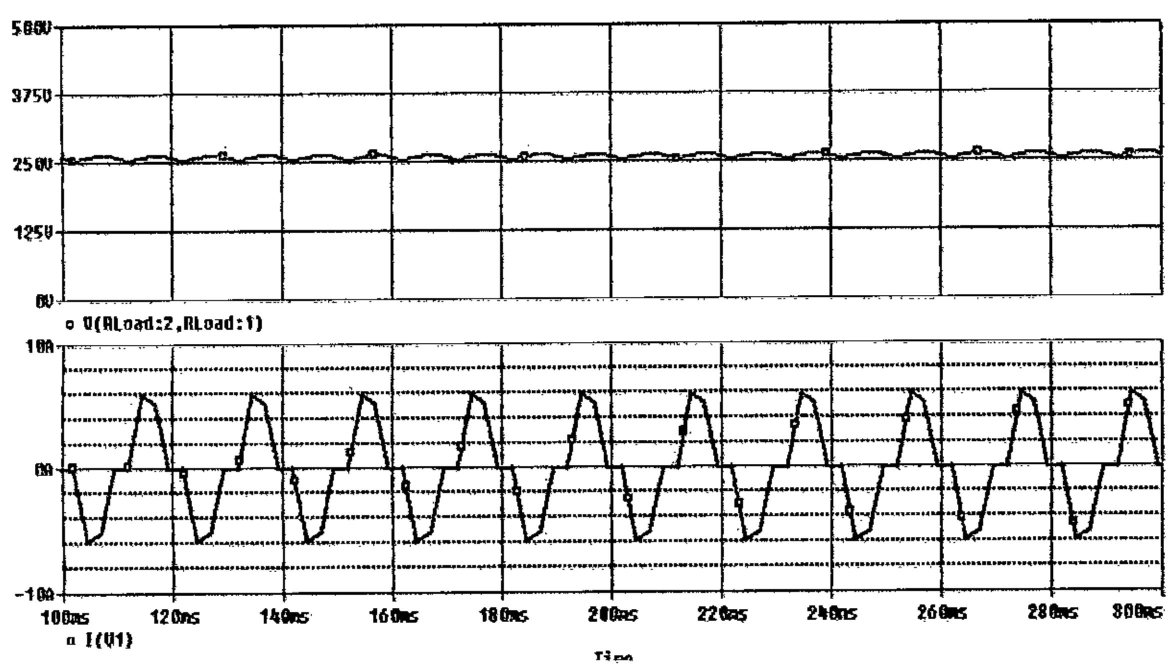

Fig 2.8. The output voltage and input current waveform of a full bridge rectifier with capacitor filter C=2000uF,Rload=100

On the other hand, for inductor filter, the ripple will decrease with the increase of the inductor value with decreasing dc value. This also has a proportional effect of the load resistance with the ripple. But it is not as effective as capacitor filter as shown in Fig. 2.9.

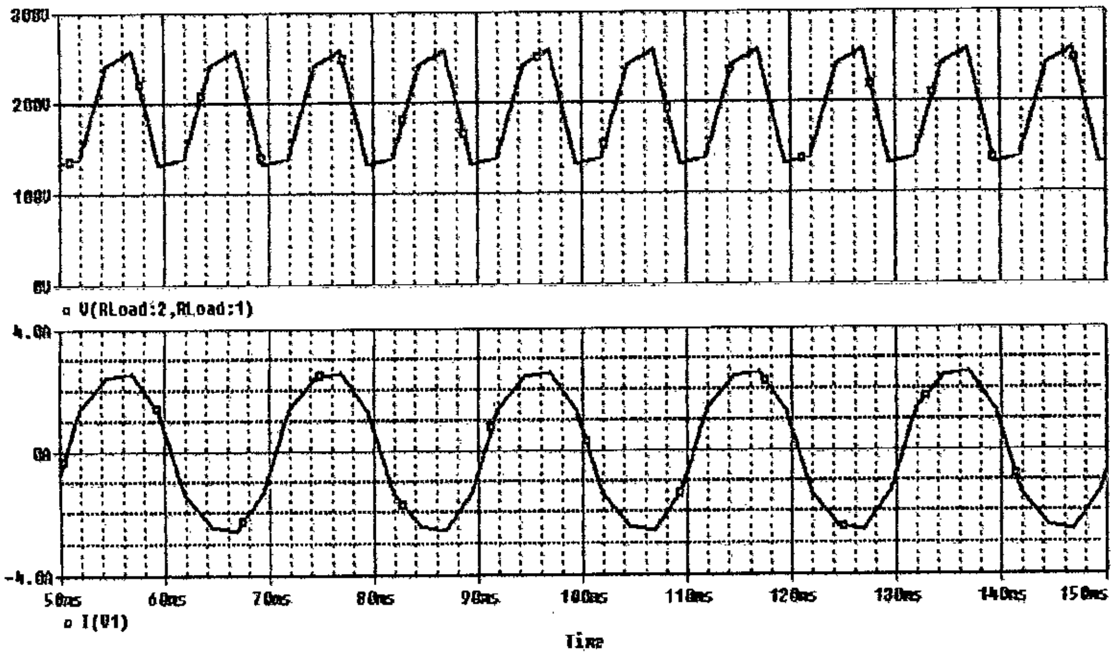

Fig 2.9. The output voltage and input current waveform of a full bridge rectifier with inductive filter, L=100mH, Rload=100.

In order to make the filter load independent, LC filter is introduced. Analysis on LC output filter is discussed in following paragraph. In order to get low ripple DC output voltage (as shown in Fig. 2.10), the filter capacitor is chosen to be 1000uF. The input current contains harmonic components.

Table2.1: Harmonic content of Input Current of Single Bridge Diode Rectifier

Harmonics	Values(mA)	Harmonics	Values(mA)
I_1(50Hz)	5700	I_4(250Hz)	410
I_2(100Hz)	600	I_5(300Hz)	25
I_3(150Hz)	1200	I_6(350Hz)	75
I_4(200Hz)	50	I_7(400Hz)	—

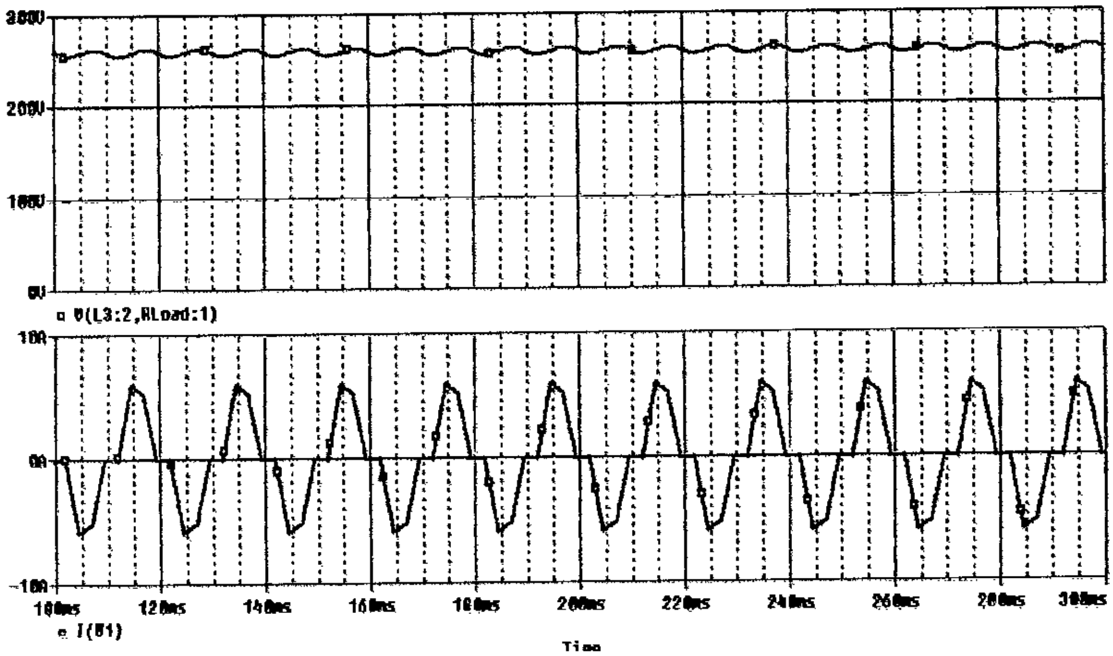

Fig 2.10 The output voltage and input current waveform of a full bridge rectifier with LC filter, L=10mH, C=1000uF, Rload=100

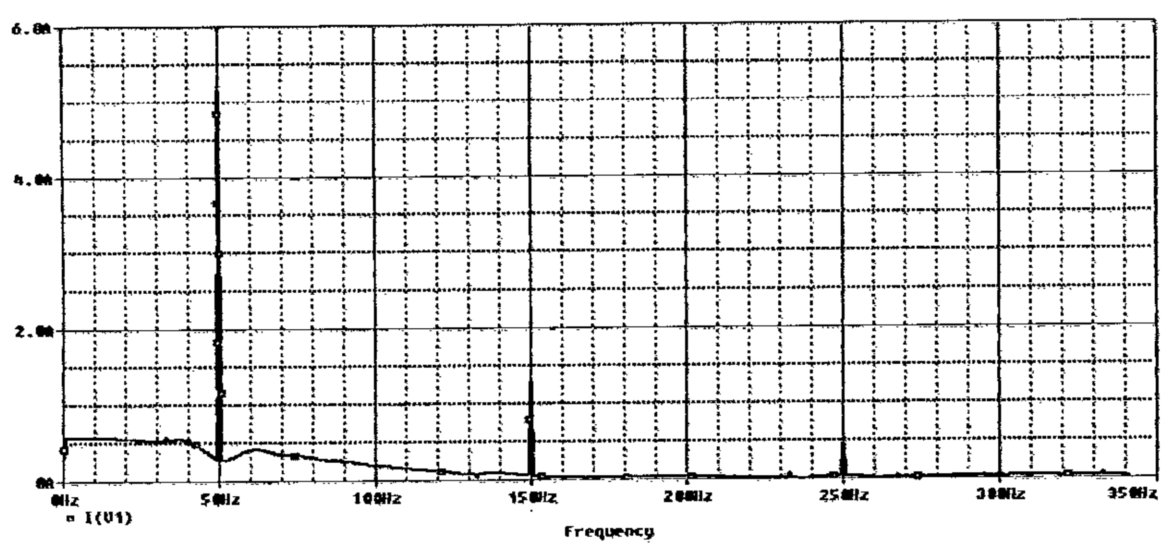

Figure 2.11 Harmonic content of Input current of a single phase diode bridge full wave Rectifier with output LC filter, L=10mH, C=1000uF, Rload=100

Total Harmonics Distortion, $THD\% = \frac{\sqrt{\sum_{h=2}^{h=\infty}(M_h)^2}}{M_1} \times 100\%$

Where, M_h is the magnitude of either voltage or current harmonic component and M_1 is the magnitude of either the fundamental voltage or current.

Putting the values in the equation we have got the THD values for a simple rectifier is 24.68%.

So, according to equation 2.7, from THD (%), the power factor of this simple diode rectifier can be calculated. Efficiency (Shown in Appendix) of the circuit is calculated in Table 2.2

Table 2.2: Efficiency of Single Phase Diode Bridge Rectifier

Output Voltage(V_{out})	259V
Output Load (R_{out})	100 Ω
Input voltage (V_{in})	300 Volts
Input current (I_{in})	6A
Power factor (pf)	0.809
Efficiency(% η)	92.13%

2.5 Single Phase Diode Bridge Rectifier with Input LC filter(Output LC filter with Resistive Load):

The following figure shows a rectifier circuit with output filter and the input filter which will shape the input current to sinusoidal shape:

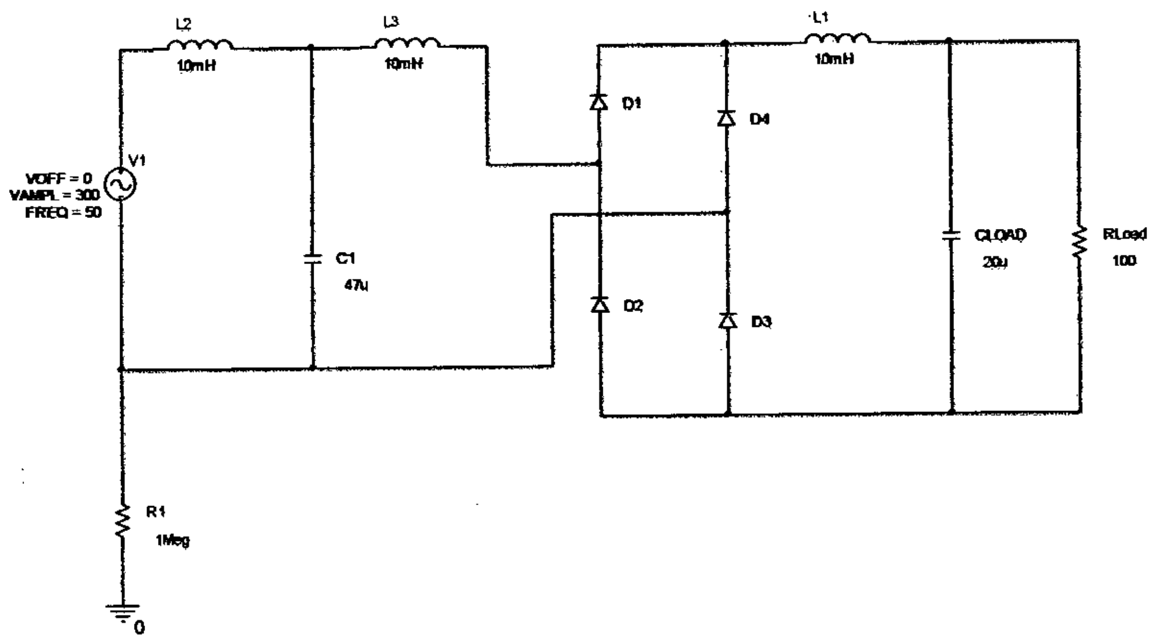

Fig 2.12: Single Phase Diode Rectifier with input and output LC filter and Resistive Load.

In order to improve the input current wave shape, the passive LC filter is introduced at the input side of the rectifier. By observing the input current wave shapes of this filter we can say about the harmonic contents of them that there is no even harmonics as the waveforms are symmetrical about the X-axis. The 7^{th} harmonic and higher is a point where the magnitude diminishes to a very low level. Thus 3^{rd} and 5^{th} orders are the dominant harmonics.

Table 2.3 Harmonic Contents of Single Phase Diode Bridge Rectifier with input LC filter

Harmonics	Per unit value	Frequency
Fundamental	1	50Hz
3^{Th}	0.21	150Hz
5^{th}	0.072	250Hz

Passive filters may be used for reducing the harmonics content of the input current. But they do not allow the regulation of the output voltage and also decreases the output voltage levels in comparison with the unfiltered rectifiers.

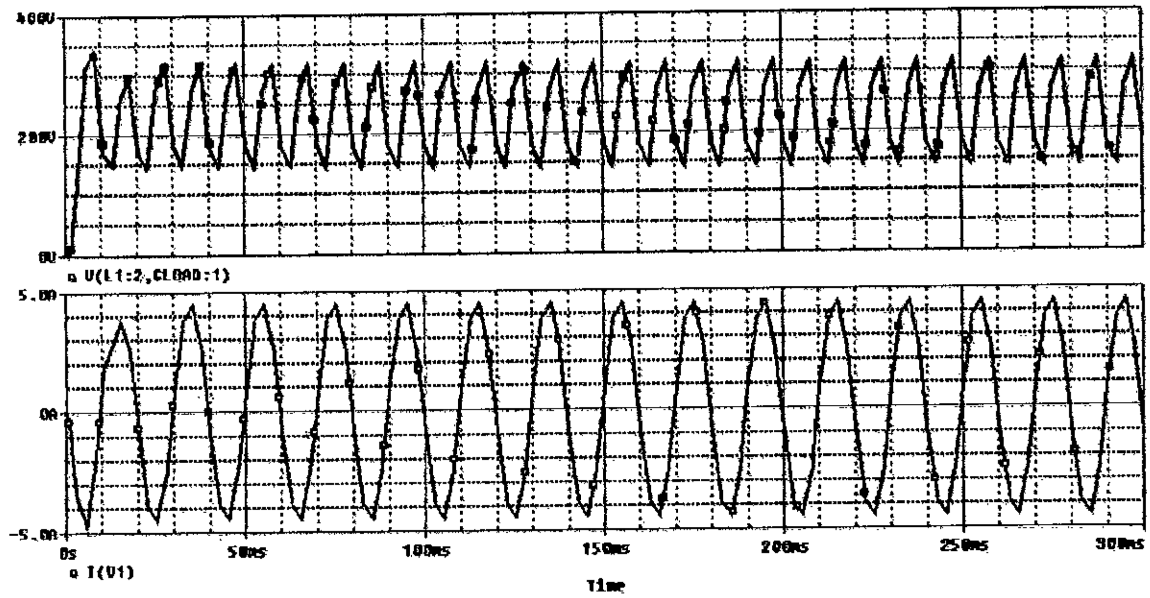

Fig. 2.13. Output voltage and input current of rectifier with passive filter, L=47mH, C= 10uF

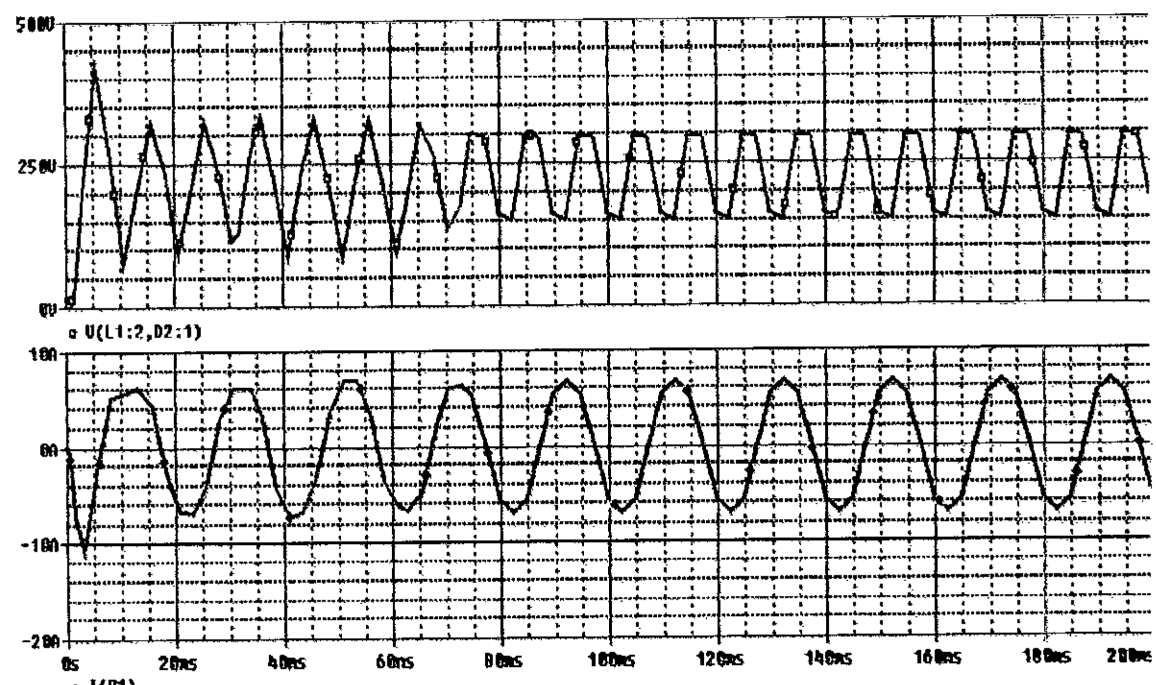

Fig.2.14 Output voltage and input current of rectifier with passive filter, L=10mH, C= 47uF

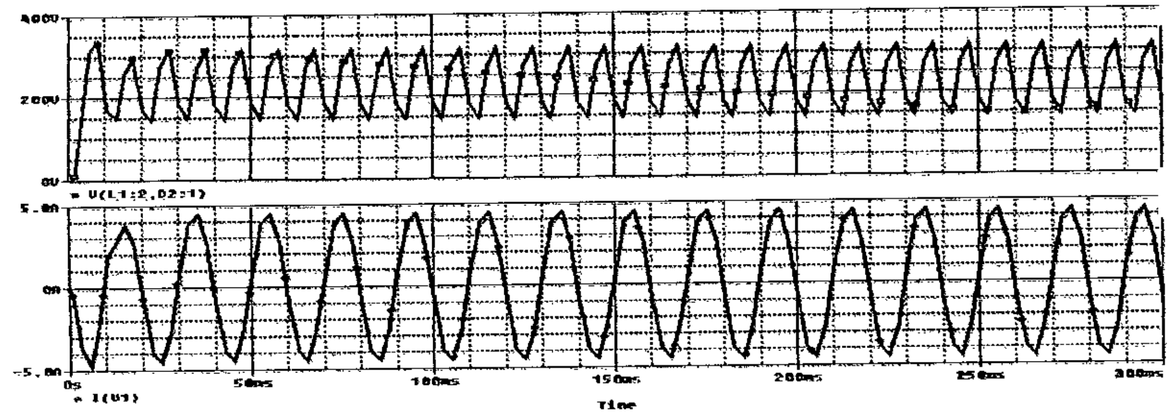

Fig 2.15. Output voltage and input current of rectifier with passive filter, L=10mH, C= 10uF.

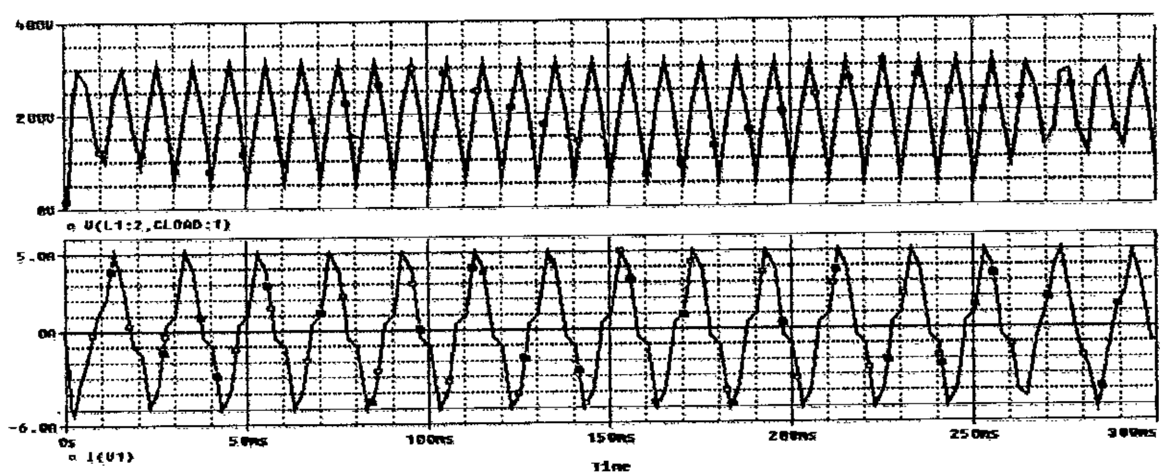

Fig. 2.16. Output voltage and input current of rectifier with passive filter, L=1mH, C=10uF.

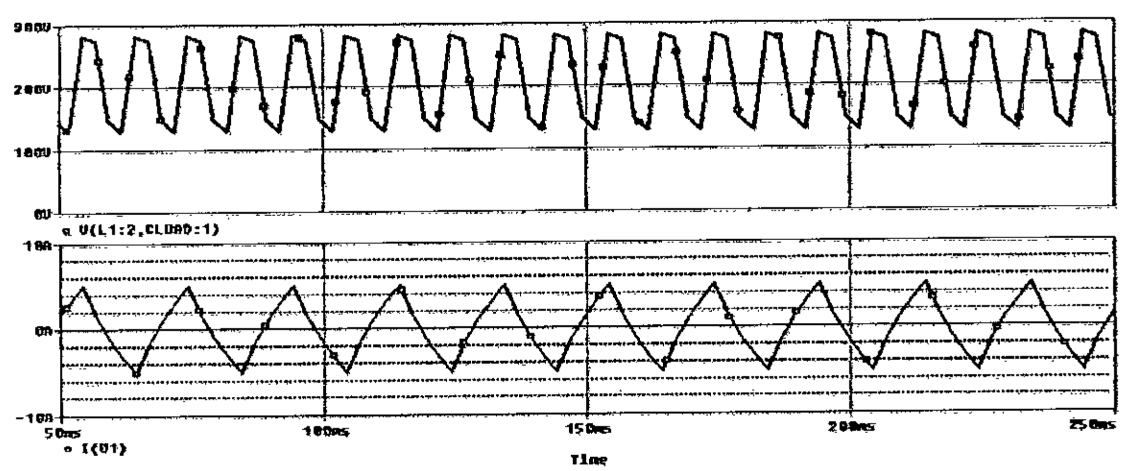

Fig. 2.17. Output voltage and input current of rectifier with passive filter, L=10uH, C=10uF

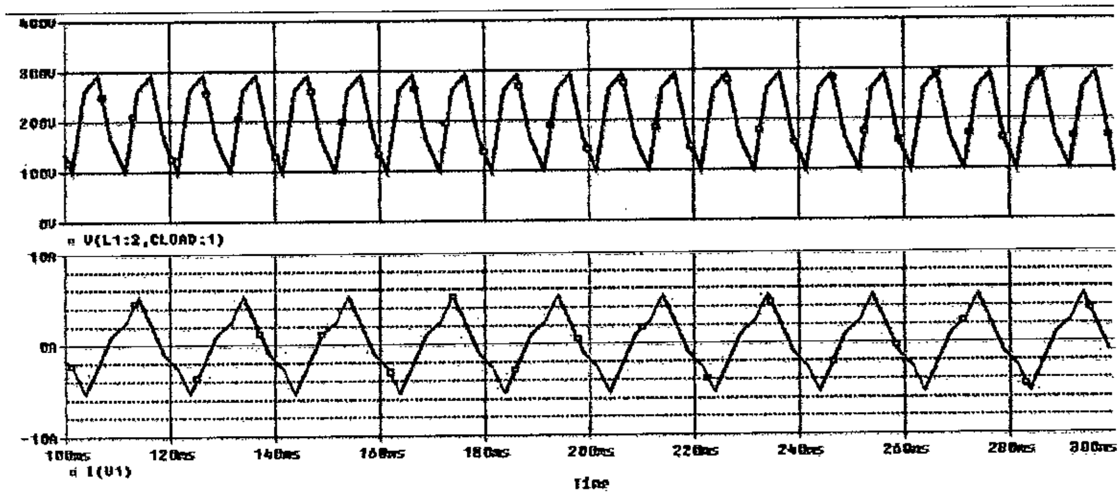

Fig. 2.18 **Output voltage and input current of rectifier with passive filter, L=0.1uH,** C= 10uF

From above figures, it is seen that decreasing the value of C decreases input current in magnitude but output voltage remains almost same. For fixed value of C, increasing L increases magnitude of output voltage and input current, the amount is very negligible especially in case of input current.

The best model for the passive filter has been obtained, for example when L=100mH and C=100uF. Actually the filter can be modeled by calculating the resonating values as $X_L=X_C$. Calculation is done by considering the fundamental component as 50Hz. The product of LC should be 1×10^{-5}. In a passive input filter the component values are very large and also regulation of the output voltage is not possible.

Table2.4: Harmonic content of Input Current of Single Phase Diode Bridge Rectifier with input LC filter

Input passive filter: L=10mH,C=47uF		Input passive filter: L=10mH,C=10uF	
Harmonics	Values(mA)	Harmonics	Values(mA)
I_1(50Hz)	7254	I_1(50Hz)	4200
I_2(100Hz)	288	I_2(100Hz)	29
I_3(150Hz)	344	I_3(150Hz)	312

I_4(200Hz)	240	I_4(200Hz)	27
I_5(250Hz)	291	I_5(250Hz)	136
I_6(300Hz)	176	I_6(300Hz)	22
I7(350Hz)	67	I7(350Hz)	74
I_8(400Hz)	115	I_8(400Hz)	17
I_9(450Hz)	140	I_9(450Hz)	52
I_{10}(500Hz)	76	I_{10}(500Hz)	12
THD (%)	8.91%	THD (%)	8.5%

Table 2.5: The Efficiency Calculation of Single Phase Diode Bridge Rectifier with input filter

Parameters	Input passive filter: L=10mH,C=47uF	Input passive filter: L=10mH,C=10uF
Output Voltage(V_{out})	225V	205V
Output Load (R_{out})	100 Ω	100 Ω
Input voltage (V_{in})	300 Volts	300 Volts
Input current (I_{in})	7A	4.2A
Power factor	0.6129	0.891
Efficiency(% η)	78.66 %	75%

In case of L=10mH and C=47uF, the efficiency is 78.66% and THD = 8.91% compared to efficiency 75% and THD = 8.47% for L=10mH, C=10uF combination.

2.6 Single Phase Diode Bridge Rectifier with Boost Regulator (Output LC filter with Resistive Load):

In active PFC, active switches are used in conjunction with inductors. In low-frequency active PFC circuit, the switching is synchronized to the line voltage and in high-frequency active PFC; the switching frequency is much higher than the line frequency. Here, the Buck, Boost, Ćuk or any kind of converter may be placed between the traditional bridge rectifier and the output filter capacitor. The output DC voltage is regulated and output voltage ripple is twice the line frequency. The PFC output voltage can be higher or lower, depending on the type of converter being used. The high frequency switching current components of the AC input current can be continuous only in the case of the Boost and ĆUK converter.

To shape input current to sinusoidal wave, the single phase diode bridge includes the Boost regulator without input current shaping passive filter. Here the input current starts to conduct in discontinuous conduction mode (DCM) and the wave shape follows the input voltage but have high frequency switching components. In Fig 2.20, the output voltage and input current wave shapes are given that is obtained from simulation of the following circuit.

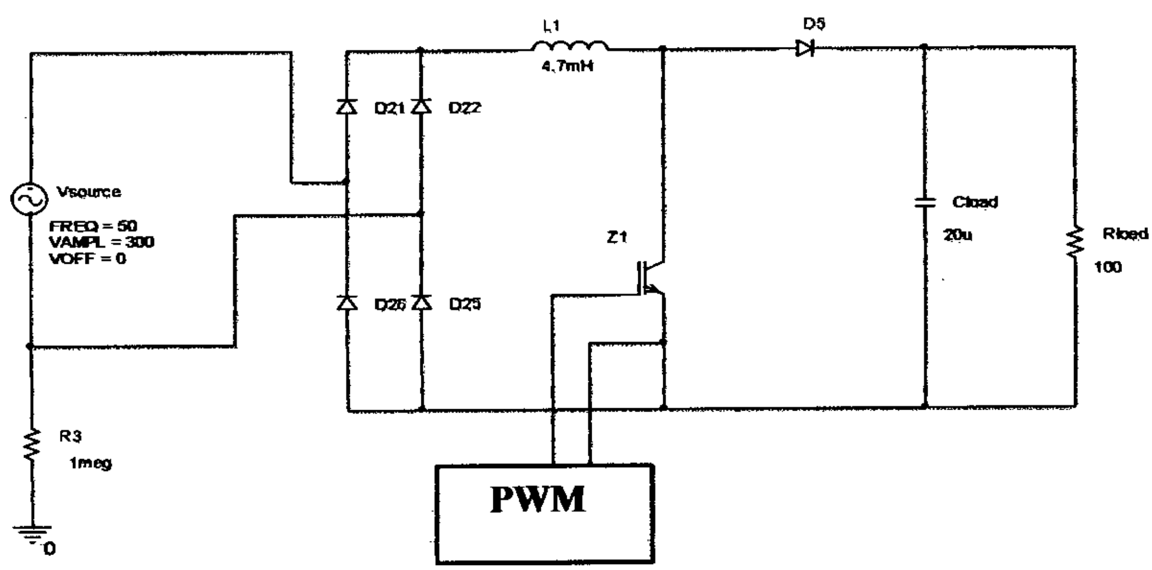

Fig. 2.19: Single phase full Bridge rectifier with Boost Regulator including output LC filter with resistive load without Input current shaping filter.

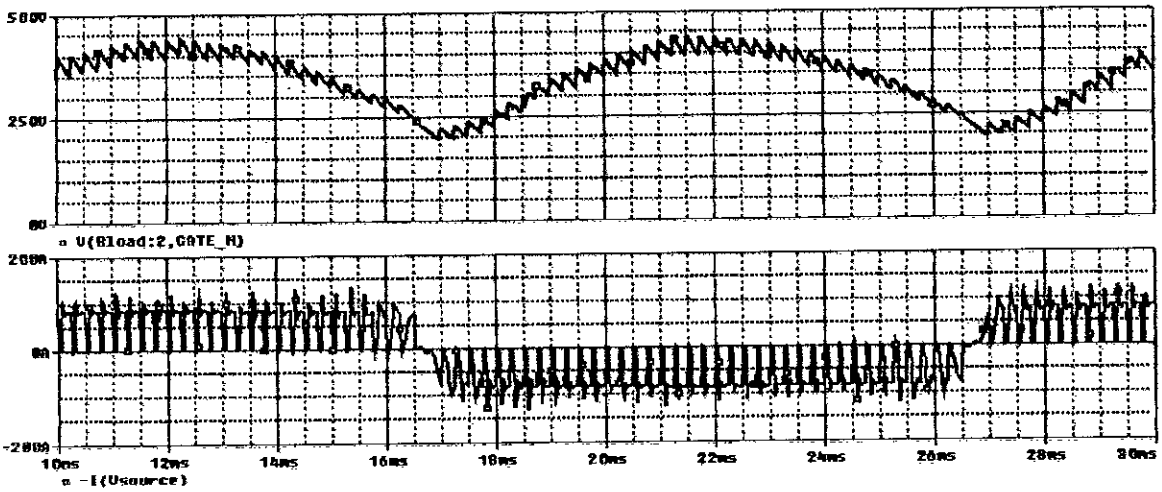

Fig. 2.20: Output voltage and Input current of a Single phase full Bridge rectifier with Boost Regulator without input filter (L1=33uH).

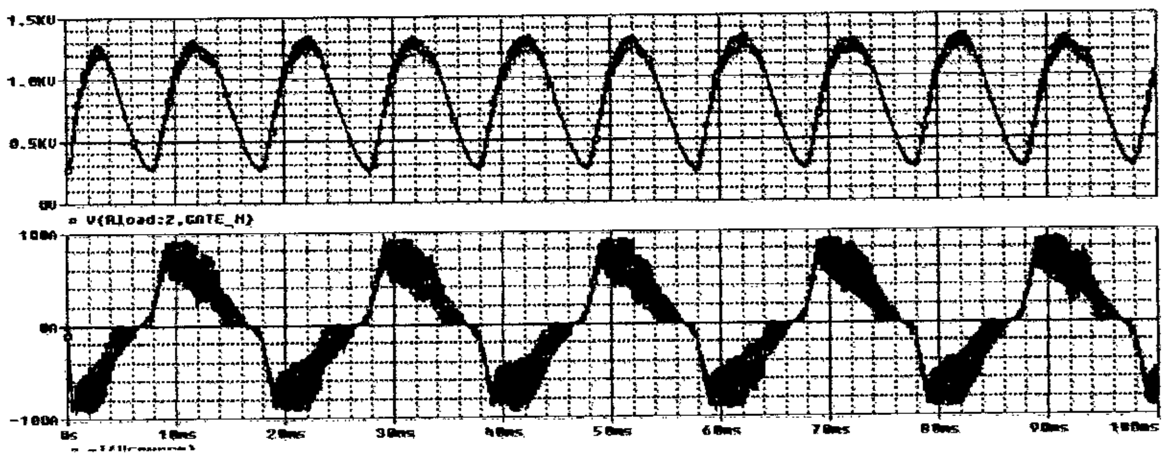

Fig. 2.21: Output voltage and Input current of a Single phase full Bridge rectifier

with Boost Regulator without input filter (L1=1mH).

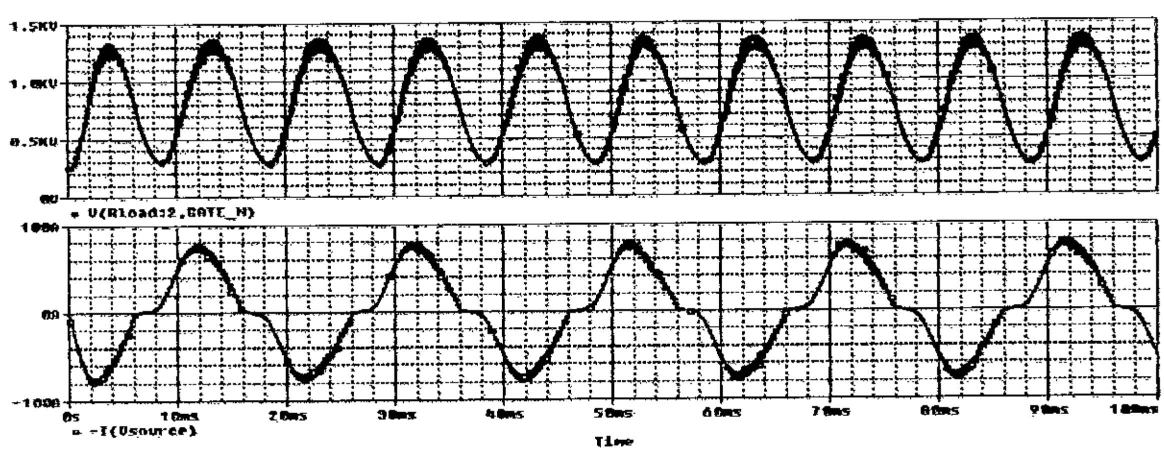

Fig 2.22: Output voltage and Input current of a Single phase full Bridge rectifier

with Boost Regulator without input filter (L1=4.7mH).

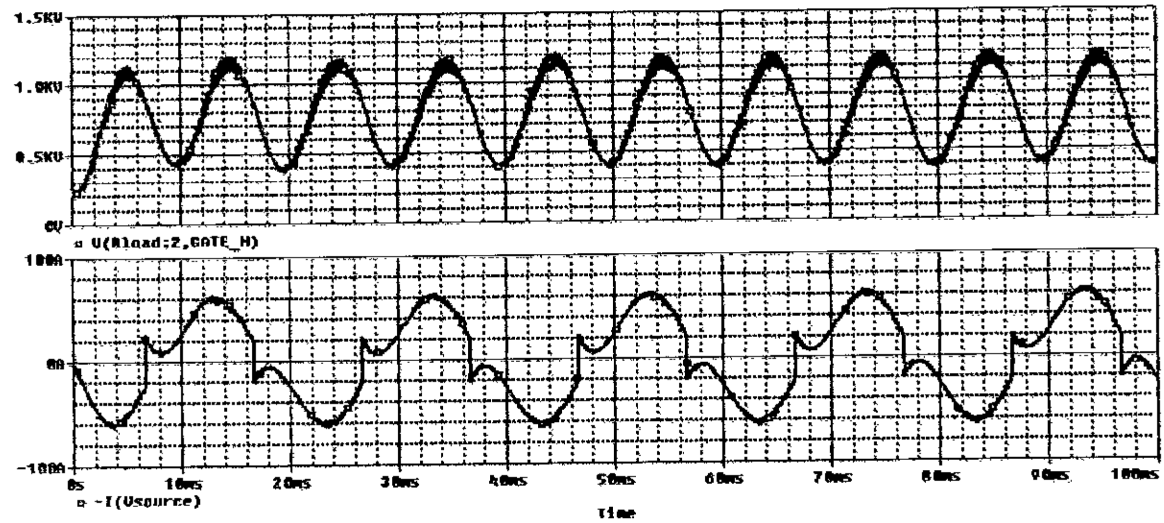

Fig. 2.23: Output voltage and Input current of a Single phase full Bridge rectifier with Boost Regulator without input filter (L1=10mH).

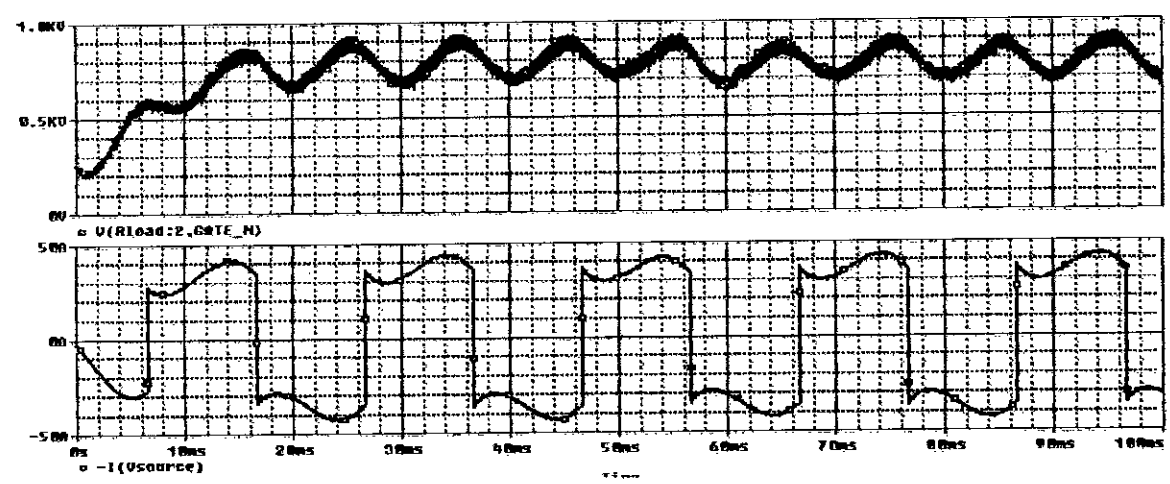

Fig. 2.24: Output voltage and Input current of a Single phase full Bridge rectifier with Boost Regulator without input filter (L1=33mH).

To have nearly sinusoidal input current L1=4.7mH is chosen. The THD and efficiency are shown in Table 2.6 and Table 2.7

Table2.6: Harmonic content of Input Current of Single Phase Boost regulator

Harmonics	Values(mA)	Harmonics	Values(mA)
I_1(50Hz)	65000	I_6(300Hz)	700
I_2(100Hz)	800	I_7(350Hz)	1750
I_3(150Hz)	13000	I_8(400Hz)	400
I_4(200Hz)	1200	I_9(450Hz)	330
I_5(250Hz)	3750	I_{10}(500Hz)	×
THD (%)		21.2%	

Table2.7: The Efficiency Calculation of Single Phase Boost regulator

Output Voltage(V_{out})	821.50V
Output Load (R_{out})	100 Ω
Input voltage (V_{in})	300 Volts
Input current (I_{in})	75A
Power Factor(p.f)	0.891
Efficiency(% η)	67.33 %

In case of Single phase diode rectifier with input passive filter of L=10mH and C=10uF, the efficiency is 75% and THD = 8.4702% compared to efficiency 67.33 % and THD =21.2% with 4.7mH inductor of Boost regulator.

2.7 Single Phase Diode Bridge Rectifier with Boost Regulator with input LC filter and Output LC filter with Resistive Load:

In order to improve the shape of the input current of the Boost regulator, input passive filter is added. Here, for different combination of input LC filter and Boost inductor, the THD is calculated and this result is compared with that of simple Boost rectifier and simple diode bridge rectifier with passive filter.

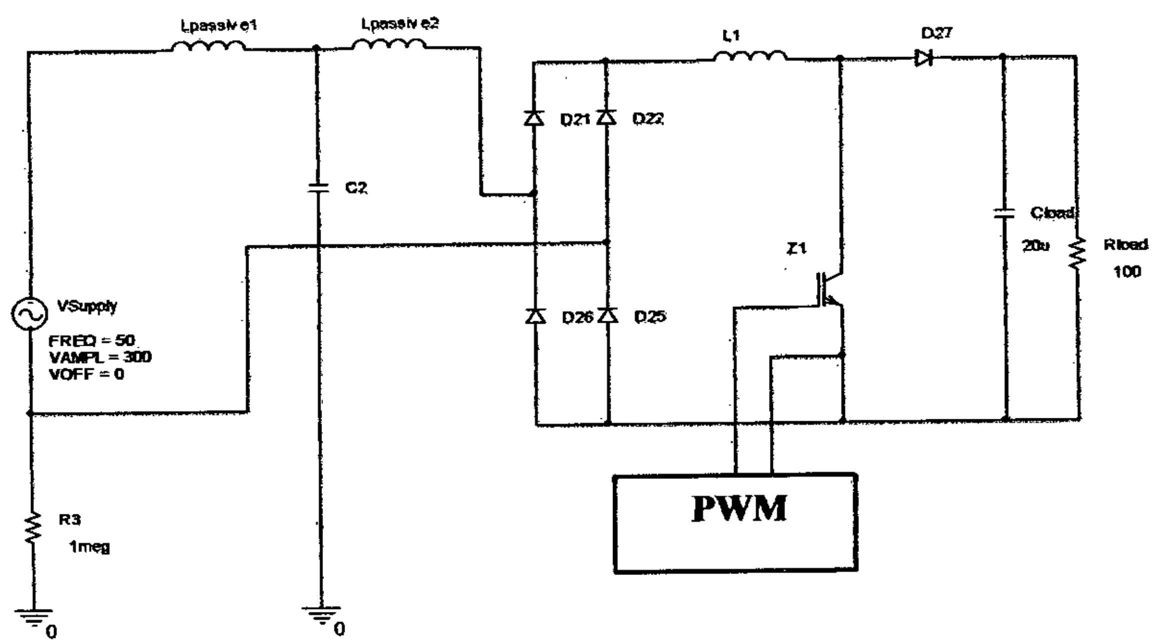

Fig. 2.25: Single phase full Bridge rectifier with Boost Regulator with input LC filter and output LC filter with resistive load

With the help of input current shaping filter, the output voltage, input current wave shape, THD and efficiency for different combination of L,C are shown in Fig 2.26, Fig 2.27, Fig 2.28

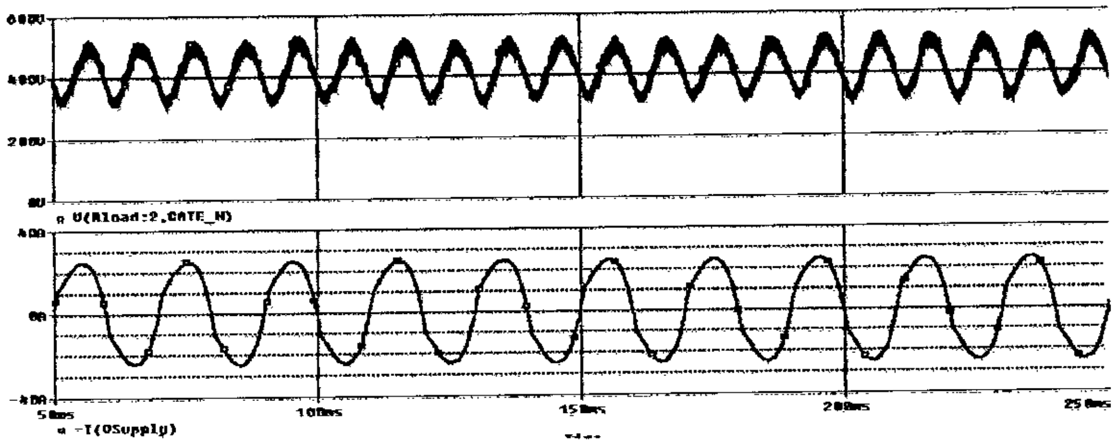

Fig. 2.26: Input current and output voltage of single phase full Bridge rectifier with Boost Regulator (input LC, L=10mH, C=0.1uF)

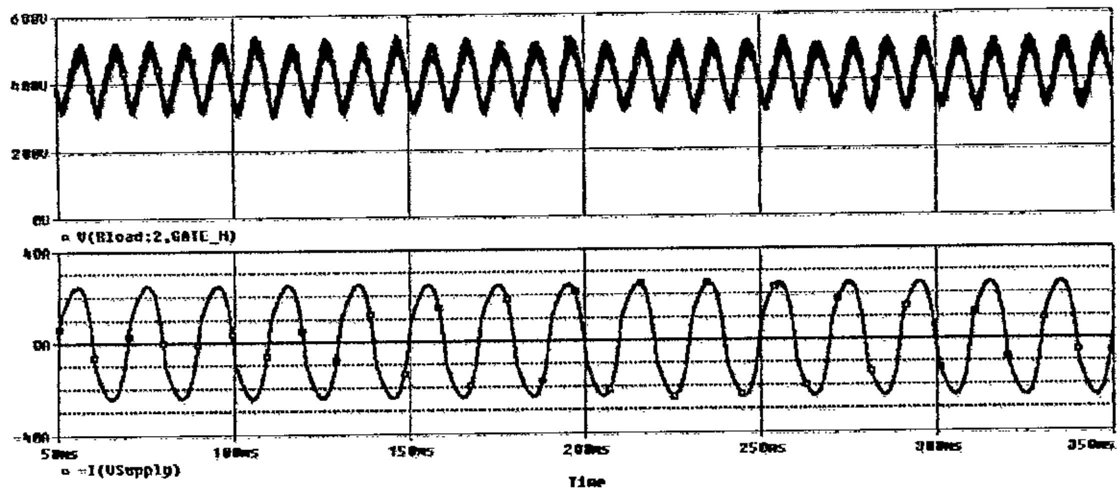

Fig. 2.27: Input current and output voltage of single phase full Bridge rectifier with Boost Regulator (input LC, L=10mH, C= 33uf)

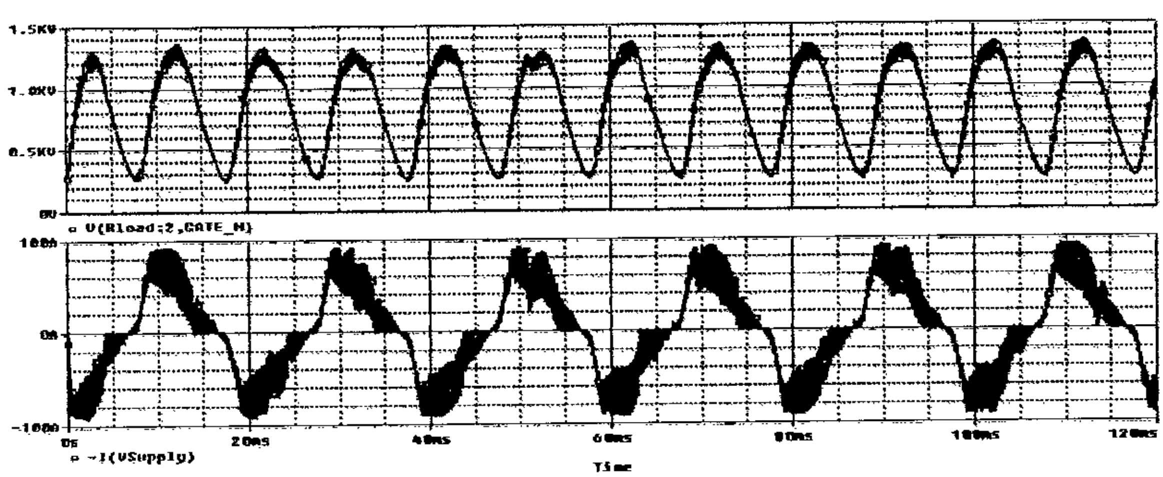

Fig. 2.28: Input current and output voltage of single phase full Bridge rectifier with Boost Regulator (input LC, L=33uH, C= 10uF)

We observe that increasing C slightly increases output voltage, but input current remains same. But lower value of L distorts the input current but output voltage is increasing. For different conditions of LC, the THD and efficiency is calculated. Here for L=10mH and C=0.1uF is comparable to other options. In this condition, for different value of Boost inductor, different THD is obtained as shown in Table 2.8

Table2.8: Relation between Boost inductor and THD (%), efficiency

Boost Inductor	THD (%)	Efficiency
10uH	5.61	28.94%
1mH	5.0	20.755%
4.7mH	4.82	21.0 %
10mH	3.78	21.10%
33mH	10.61	22.14%

Table2.9: Harmonic content of Input Current of the Boost regulator with input and output LC filter

	Input LC (L=10mH, C=10uF) Boost Inductor= 1mH	Input LC (L=10mH, C=1uF) Boost Inductor= 1mH	Input LC (L=5mH, C=1uF) Boost Inductor= 1mH	Input LC (L=10mH, C=0.1uF) Boost Inductor= 1mH	Input LC (L=10mH, C=0.1uF) Boost Inductor= 10uH
Harmonics	Values(mA)	Values(mA)	Values(mA)	Values(mA)	Values(mA)
I_1(50Hz)	40000	40000	57000	40150	41000
I_2(100Hz)	100	60	500	115	130
I_3(150Hz)	2000	1900	5500	1800	2080
I_4(200Hz)	90	50	100	35	30
I_5(250Hz)	800	700	2000	750	820

I_6(300Hz)	50	20	70	20	40
I_7(350Hz)	400	1370	1000	370	420
I_8(400Hz)	20	10	20	5	40
I_9(450Hz)	220	220	500	230	250
I_{10}(500Hz)	10	0	30	20	30
I_{11}(550Hz)	120	0	0	170	175
I_{12}(600Hz)	10	0	0	20	20
THD (%)	5.52%	6.14%	10.50%	5.00%	5.61%

Table2.10: The Efficiency of Input Current of the Boost regulator with input and output LC filter

Parameters	Input LC (L=10mH, C=10uF) Boost Inductor= 1mH	Input LC (L=10mH, C=1uF) Boost Inductor= 1mH	Input LC (L=5mH, C=1uF) Boost Inductor= 1mH	Input LC (L=10mH, C=0.1uF) Boost Inductor= 1mH	Input LC (L=10mH, C=0.1uF) Boost Inductor= 10uH
Output Voltage(V_{out})	524V	524.50V	705V	500V	550V
Output Load (R_{out})	100 Ω	100 Ω	100 Ω	100 Ω	100 Ω
Input voltage (V_{in})	300 Volts	300 Volts	300 Volts	300 Volts	300 Volts
Input current (I_{in})	40.50A	41.0A	62.0A	40.15A	43.7A
Power factor	0.68455	0.68455	0.9114	0.68455	0.68455
Efficiency (% η)	66.025%	65.345%	58.665%	60.64%	67.414%

With the input passive filter in the circuit, THD of the Boost regulator reduces from 21.2% to 5.00%. In case of simple diode bridge rectifier with input passive filter, THD is 8.47%. The value of input L, C of passive filter has reduced from L=10mH, C=10uF (for Single phase diode bridge rectifier) to L=10mH, C=0.1uF (for Boost rectifier).

2.8 Single Phase Diode Bridge Rectifier with Ćuk Regulator (Output LC filter with Resistive Load, without Input Filter):

Ćuk converter has the benefit of having continuous ripple current both at input and output, i.e., there is no time gap where the ripple current falls to zero. In the boost regulators, input current is continuous but the output current through the rectifier diode is discontinuous. This is a very essential parameter to have ripple currents at input and output ramp up and down without going back to zero for having low input and output noise. Thus this feature is examined for improving input current shape.

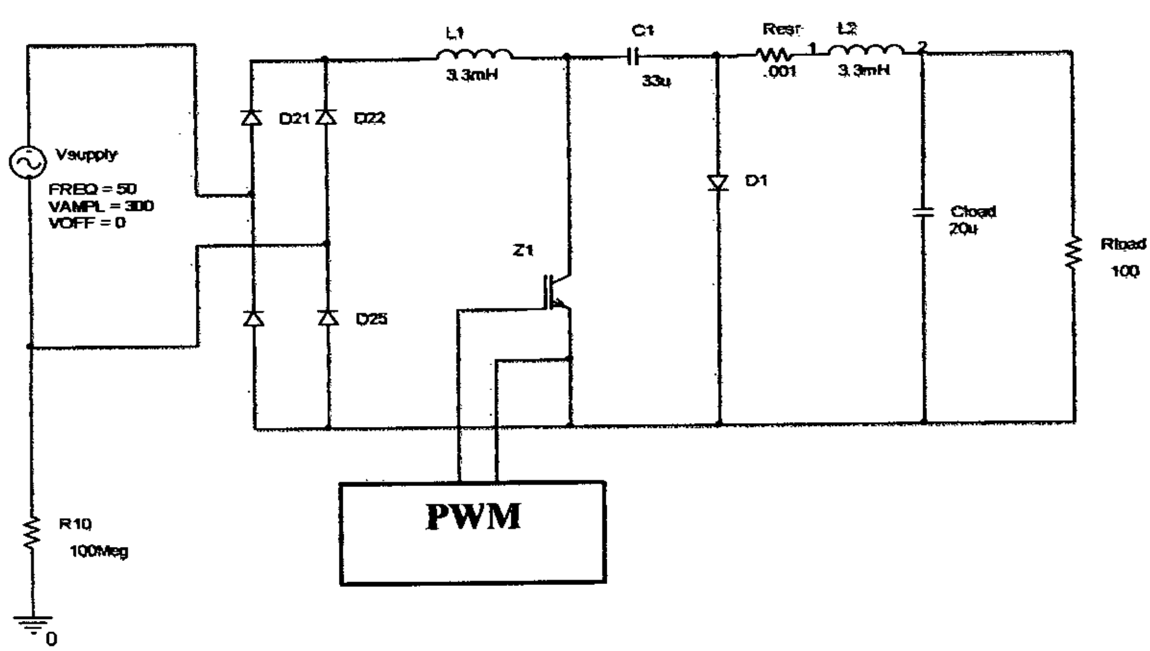

Fig. 2.29: Single phase full Bridge rectifier with Ćuk Regulator (output LC filter with resistive load, without Input Filter).

The output voltage and input current for this circuit for L1=L2=3.3mH, C1=33uF is shown in Fig 2.30 and for L1=L2=1mH, C1=10uF is shown in Fig 2.31.

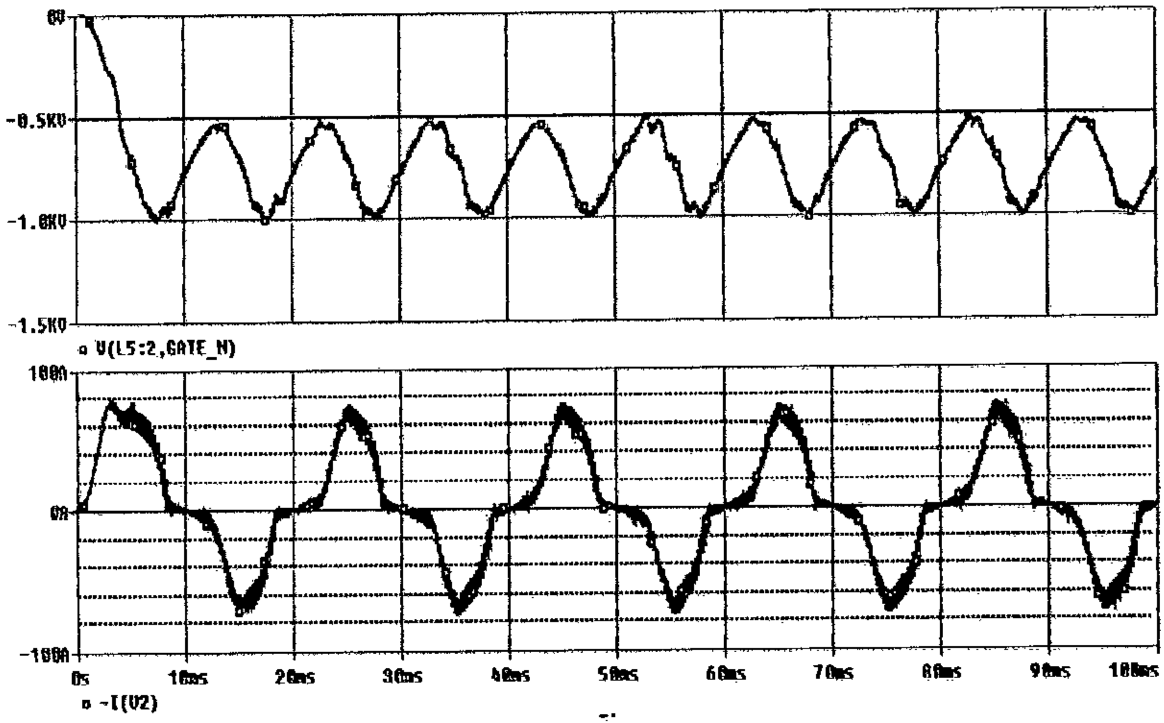

Fig. 2.30 **Output voltage and input current a of single phase full Bridge rectifier with Ćuk Regulator (output LC filter with resistive load without input filter)**

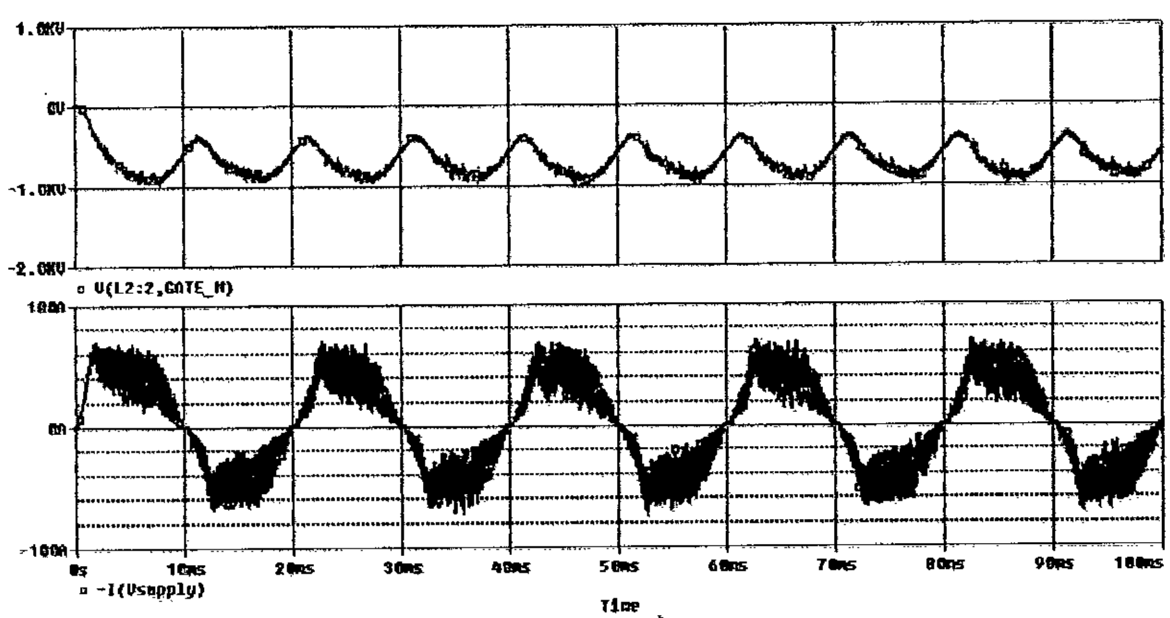

Fig. 2.31: Output voltage and input current of single phase full Bridge rectifier with Ćuk Regulator (output LC filter with resistive load without input filter)

Table2.11: Harmonic content of Input Current of Ćuk regulator without input filter

	L1=L2=3.3mH,C1=33uF	L1=L2=10mH,C1=10uF	L1=L2=5mH,C1=10uF
Harmonics	Values(mA)	Values(mA)	Values(mA)
I_1(50Hz)	49430	41750	47000
I_2(100Hz)	687	1000	1000
I_3(150Hz)	18930	9300	15000
I_4(200Hz)	436	210	700
I_5(250Hz)	312	2500	1750
I_6(300Hz)	497	200	50
I_7(350Hz)	2859	1100	1000
I_8(400Hz)	458	100	100
I_9(450Hz)	1507	600	700
I_{10}(500Hz)	85	80	50
I_{11}(550Hz)	678	475	450
I_{12}(600Hz)	268	20	100
THD (%)	38.94%	23.44%	32.36%

Table 2.12 The Efficiency of Ćuk regulator without input filter

Parameters	L1=L2=3.3mH, C1=33uF	L1=L2=10mH, C1=10uF	L1=L2=5mH, C1=10uF
Output Voltage(V_{out})	764 Volts	675 Volts	725 Volts
Output Load (R_{out})	100 Ω	100 Ω	100 Ω
Input voltage (V_{in})	300 Volts	300 Volts	300 Volts
Input current (I_{in})	67.5A	47A	60.5A
Power Factor	0.9298	0.87	0.8
Efficiency(% η)	62.0%	74.28%	72.40%

2.9 Single Phase Diode Bridge Rectifier with Ćuk Regulator with input LC filter including Output LC filter with Resistive Load

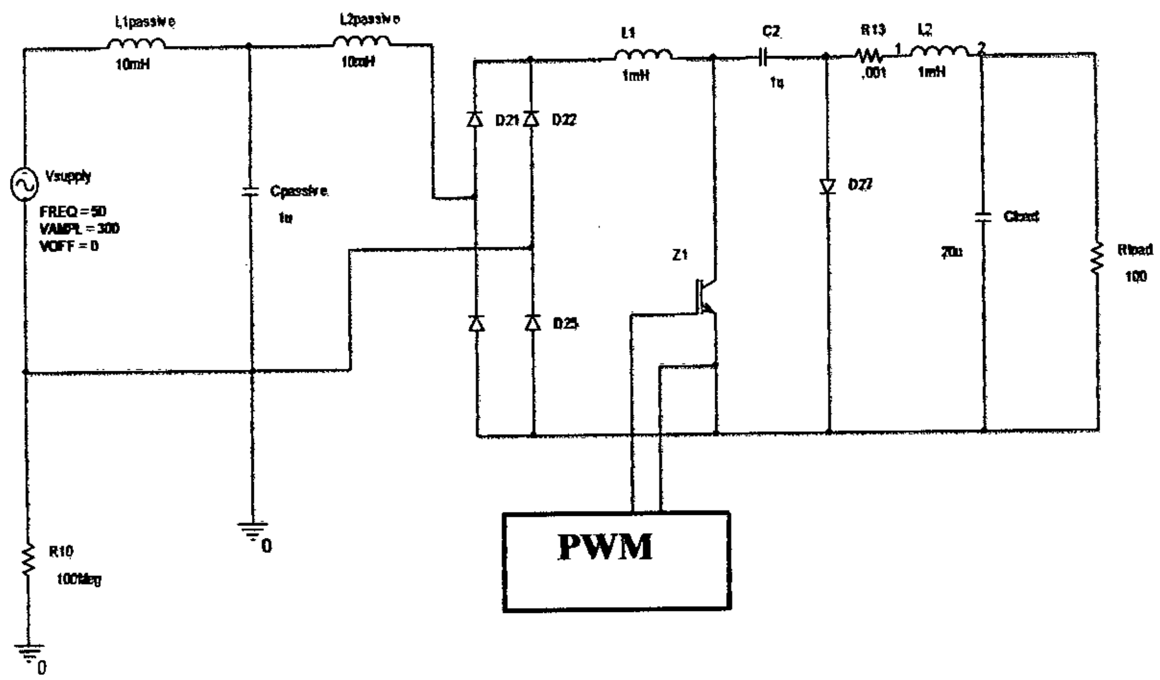

Fig. 2.32: Single phase full Bridge rectifier with Ćuk Regulator with input LC filter including output LC filter with resistive load Ćuk

For sinusoidal input current, input passive filter is attached with the Ćuk regulator. For different values of input passive filter (L, C) THD (%) is measured. Also values of inductor (L), capacitor (C) of Ćuk rectifier are varied for obtaining the sinusoidal wave shape. Output voltage and input current of this circuit having passive filter (L=10mH, C=10uF) and Ćuk inductor- capacitor (L=1mH, C=5uF) are shown in Fig 2.33. With passive filter (L=10mH, C=1uF) and Ćuk inductor- capacitor (L=10mH, C=10uF), the results are shown in Fig 2.34. Fig 2.35 shows the output voltage and input current for the combination of passive filter (L=10mH, C=1uF) and Ćuk inductor- capacitor (L=1mH, C=1uF).

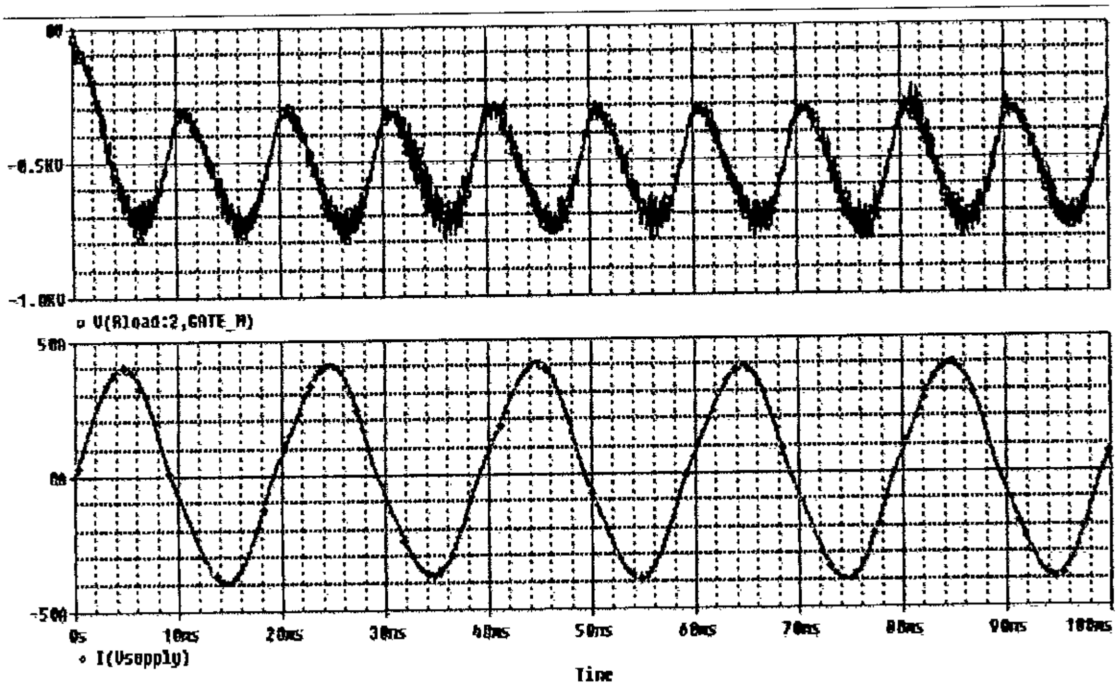

Fig. 2.33: Output voltage and input current of Ćuk regulator with input passive LC filter.

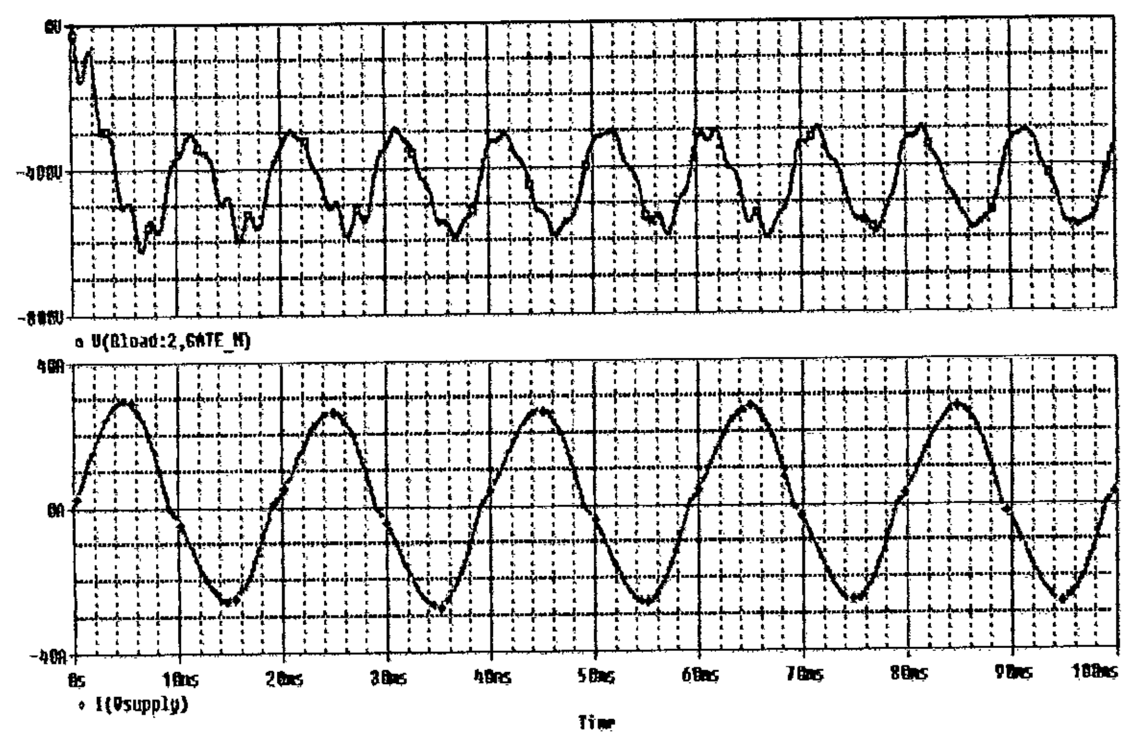

Fig. 2.34: Output voltage and input current of Ćuk regulator with input passive LC filter.

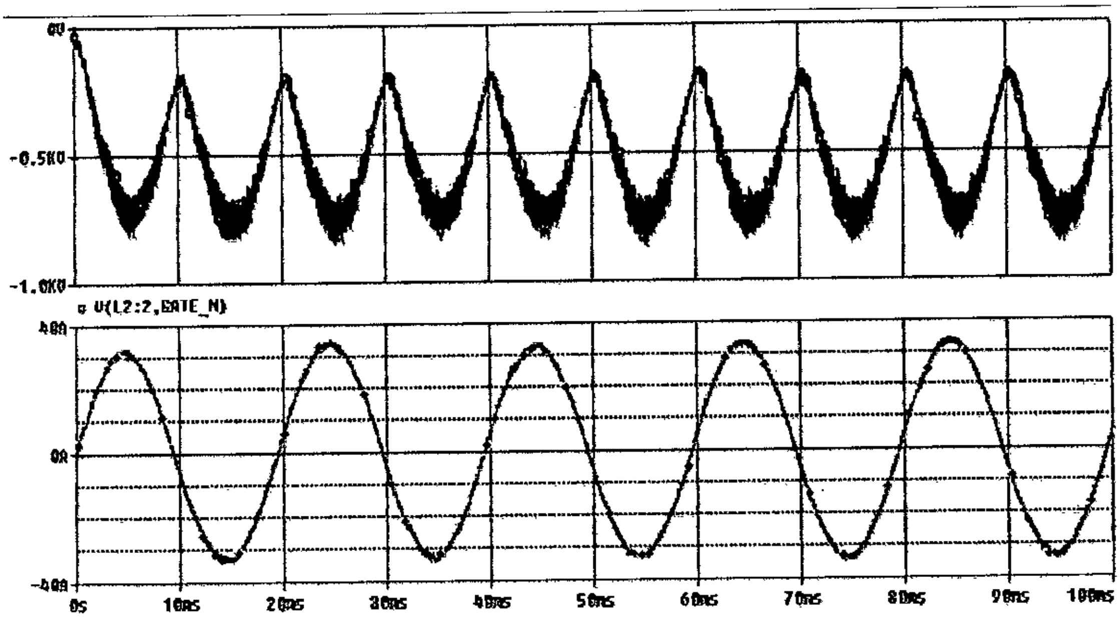

Fig. 2.35: Output voltage and input current of Ćuk regulator with input passive LC filter.

Table2.13: Harmonic content of Input Current of Ćuk regulator with input filter

	Input passive filter:L1=L2=10mH, C=10uF Ćuk inductor: L1=L2=1mH, C1=5uF	Input passive filter:L1=L2=10mH, C=1uF Ćuk inductor: L1=L2=10mH, C1=10uF	Input passive filter:L1=L2=10mH, C=1uF Ćuk inductor: L1=L2=1mH, C1=1uF
Harmonics	Values(mA)	Values(mA)	Values(mA)
I_1(50Hz)	32000	25800	33370
I_2(100Hz)	450	200	277
I_3(150Hz)	850	2000	233
I_4(200Hz)	250	80	10
I_5(250Hz)	500	800	310
I_6(300Hz)	140	70	56
I_7(350Hz)	375	400	22
I_8(400Hz)	150	20	24
I_9(450Hz)	55	250	71
I_{10}(500Hz)	90	55	10
I_{11}(550Hz)	0	150	26
I_{12}(600Hz)	0	15	60
THD (%)	3.74%	8.62%	1.47%

The THD (%) for Ćuk rectifier with input passive filter gives a lower value (1.47%) than that of Boost rectifier with input passive filter (5.00%).

Table 2.14: The Efficiency Calculation of Ćuk regulator with input filter

	Input passive filter:L1=L2=10mH C=10uF Ćuk inductor: L1=L2=1mH, C1=5uF	Input passive filter:L1=L2=10mH C=1uF Ćuk inductor: L1=L2=10mH, C1=10uF	Input passive filter:L1=L2=10mH C=1uF Ćuk inductor: L1=L2=1mH, C1=1uF
Output Voltage (V_{out})	536.50V	450V	460V
Output Load (R_{out})	100 Ω	100 Ω	100 Ω
Input voltage (V_{in})	300 V	300 V	300 V
Input current (I_{in})	41A	26.6A	33A
Power factor	0.729	0.707	0.637
Efficiency(% η)	64.20%	71.785%	67.10%

2.10 Single Phase Diode Bridge Rectifier with modified Ćuk Regulator with input LC filter including Output LC filter with Resistive Load:

With a slight modification, a new approach of Ćuk regulator has been proposed here.

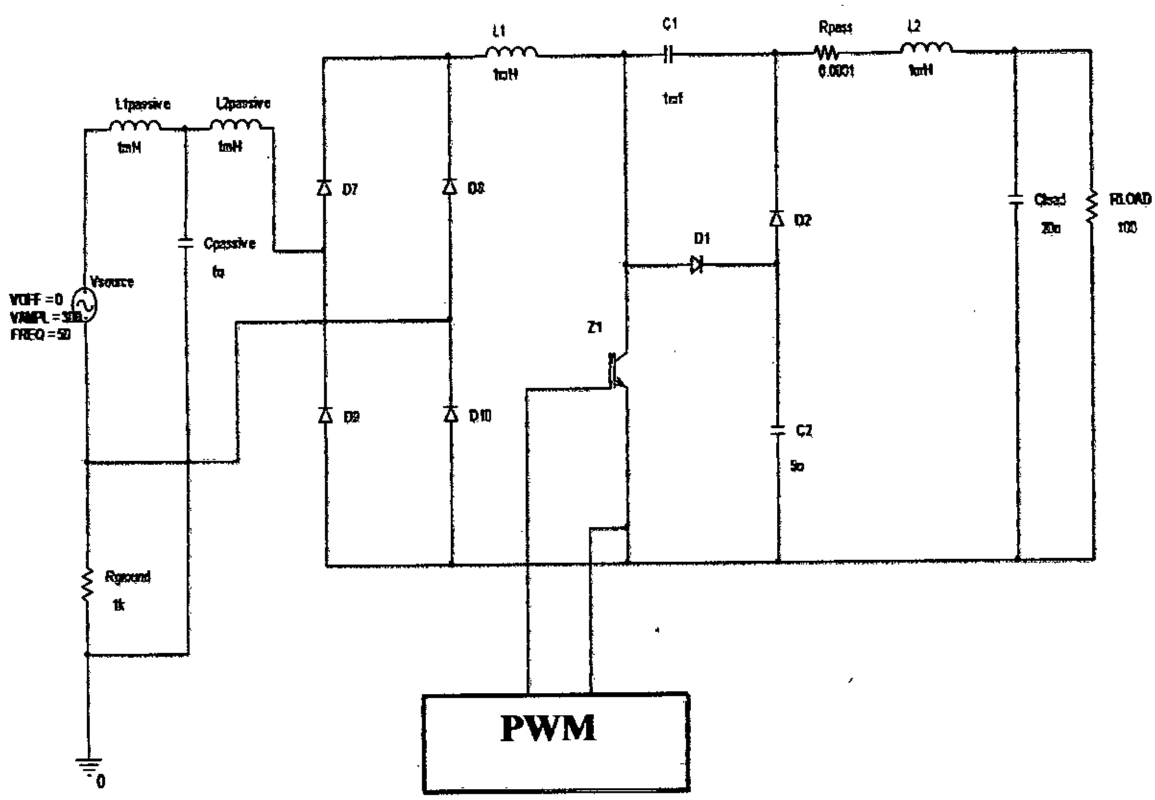

Fig. 2.36: Single phase full Bridge rectifier with modified Ćuk Regulator with input LC filter (with output LC filter with resistive load)

The output voltage and input current with passive filter (L=10mH, C=1uF) with Ćuk Regulator with (L=1mH, C1=1uF, C2=1uF) is shown in Fig 2.37. With slight modification of Ćuk regulator (L=1mH, C1=4.7uF, C2=1uF), the output voltage and input current is shown in Fig 2.38.

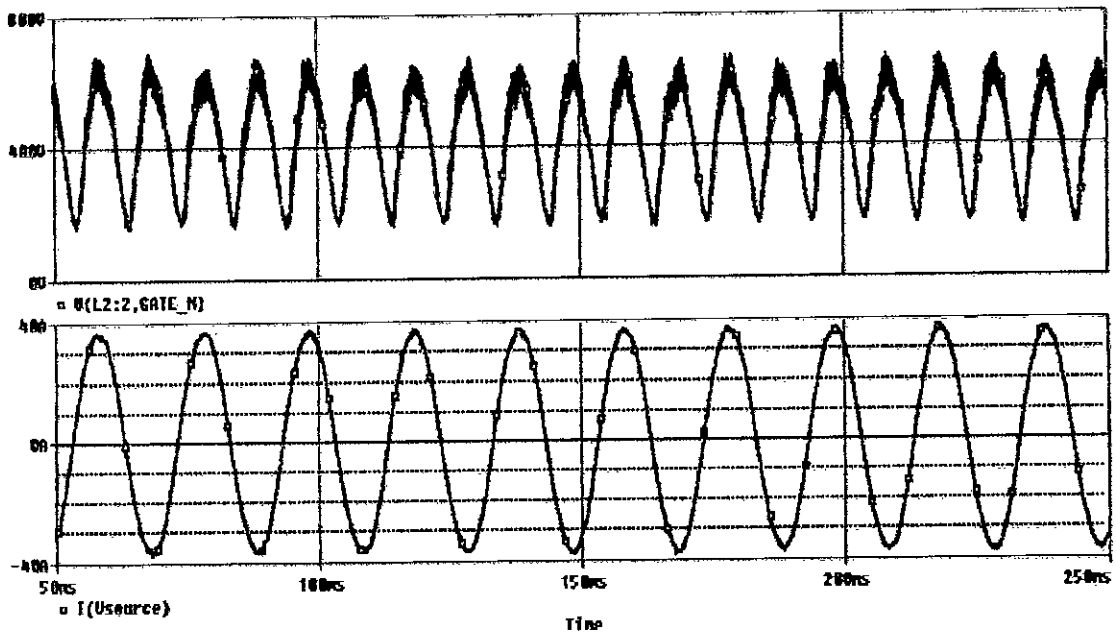

Fig. 2.37: Output voltage and input current of modified Ćuk regulator with passive LC and output LC filter.

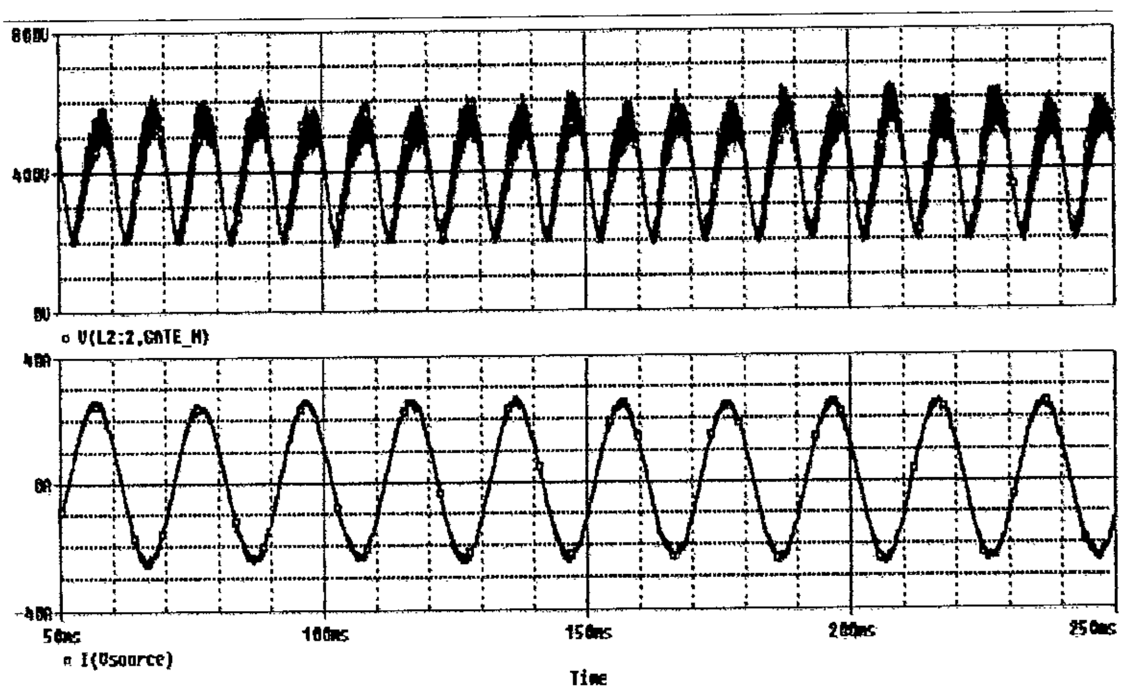

Fig. 2.38: Output voltage and input current of modified Ćuk regulator with passive LC and output LC filter.

Table2.15: Harmonic content of Input Current of modified Ćuk regulator

	Passive filter L1=L2=10mH,C=1uF Ćuk Rectifier L1=L2=1mH C1=1uF,C2=1uF	Passive filter L1=L2=10mH,C=1uF Ćuk Rectifier L1=L2=1mH, C1=4.7uF,C2=1uF
Harmonics	Values(mA)	Values(mA)
I_1(50Hz)	37000	24500
I_2(100Hz)	330	140
I_3(150Hz)	470	170
I_4(200Hz)	205	85
I_5(250Hz)	215	70
I_6(300Hz)	130	80
I_7(350Hz)	65	70
I_8(400Hz)	90	30
I_9(450Hz)	100	50
I_{10}(500Hz)	45	50
I_{11}(550Hz)	75	40
I_{12}(600Hz)	55	20
THD (%)	1.85%	1.15%

Table2.16: The Efficiency Calculation of modified Ćuk regulator

	Passive filter L1=L2=10mH C=1uF Ćuk Rectifier L1=L2=1mH C1=1uF,C2=1uF	Passive filter L1=L2=10mH C=1uF Ćuk Rectifier L1=L2=10mH, C1=4.7uF,C2=1uF
Output Voltage (V_{out})	380V	310V
Output Load (R_{out})	100 Ω	100 Ω
Input voltage (V_{in})	300 V	300 V
Input current (I_{in})	37A	26A
Power factor	0.5358	0.5358
Efficiency(% η)	48.56%	45.60%

With input passive filter (L=10mH, C=1uF) and modified Ćuk regulated rectifier (L=1mH, C1=4.7uF, C2=1uF) gives the THD 1.15% where as in Boost rectifier with input passive filter (L=10mH, C=0.1uF), THD is 5%. In the same case of Ćuk rectifier with input passive filter (L=10mH, C=1uF), THD is 1.47%.

CHAPTER 3

RESULTS & DISCUSSION

3.1 INTRODUCTION

The design simulation related work of the thesis has been presented in chapter 2. In this chapter, data obtained from the simulations are presented in graphical forms to highlight the performances of Boost, Ćuk and modified Ćuk SMPS regulator in terms of THD, power factor, voltage gain and efficiency.

3.2 RESULTS AND DISCUSSIONS

Performance study of the Boost, Ćuk and modified Ćuk SMPS regulators are considered. The regulators are operated at different duty cycles (from 30% up to 90%) and their performances with variation of duty cycles are observed. The results are presented in the following sections.

3.2.1 Performance in terms of Total Harmonic Distortion (THD %)

The performances of Boost and Ćuk and modified Ćuk regulator based rectifier (with input filter) in terms of Total Harmonic distortion are shown in graphical form in Fig. 3.1.

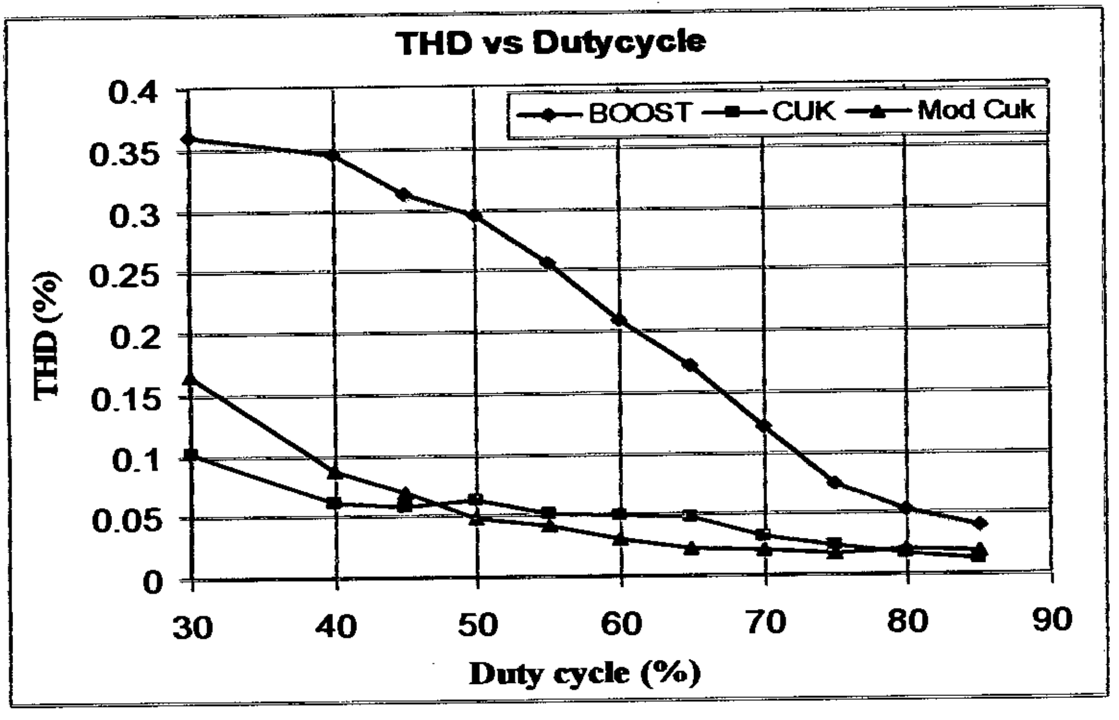

Fig 3.1: Regulators' performance in terms of THD

Performance wise Boost regulator always has high THD, which means the input current has large amount of harmonics components. Ćuk and modified Ćuk have almost same trend of THD. But around duty cycle 45% to 90%, the modified Ćuk has lower value of THD than Ćuk regulator, which may be considered as improvement. As the high rate of switching makes the input current to follow input voltage, the THD (%) decreases with the increasing rate of duty cycle. Due to continuous current at input and output, Ćuk and modified Ćuk regulator both have low THD (%) compared to Boost regulator.

3.2.2 Performance in terms of Power Factor

The main purpose of switched regulator is to have a good Power factor. The performance of these switching regulators studied in this thesis is shown in Fig 3.2 in graphical form.

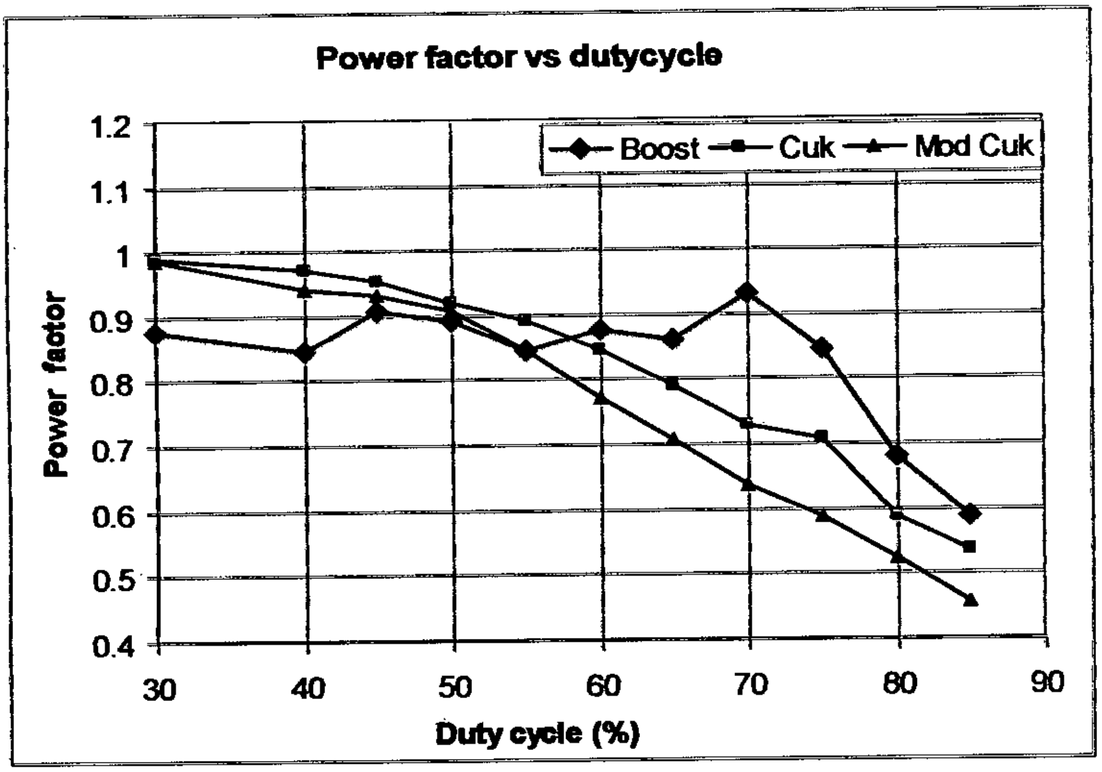

Fig 3.2: Regulators' performance in terms of Power factor

Boost, Ćuk and modified Ćuk show almost same trend for power factor up to duty cycle 45%. After 45% duty cycle Ćuk and modified Ćuk regulator show less power factor than Boost regulator. The power factor can be improved if a compact control loop is introduced. In this control block, a portion of output voltage is feedback to input block which will force the input current to follow the shape of output voltage.

3.2.3 Performance in terms of Voltage Gain

Normally Boost and Ćuk regulator are used to have more output voltage than input. The performances on the basis of voltage gain is shown in Fig. 3.3

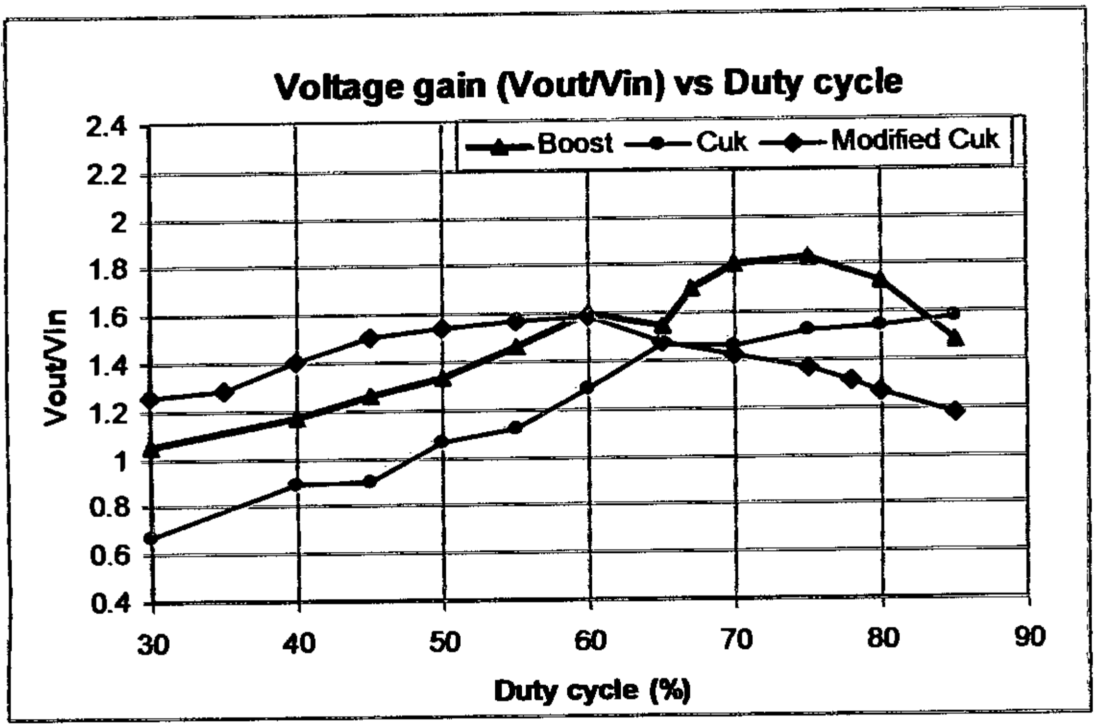

Fig 3.3: Regulators' performance on the basis of Voltage Gain

From Appendix iii, we get

$$\frac{V_o}{V_{IN}} = \frac{1}{(1+\frac{V_D}{I_O R})(1-D)+\frac{Rl}{(1-D)}+\frac{V_{sw}D}{RI_O}}.$$

The equation does not provide any linear relationship between input and output voltage. The experimental results also show this trend. It is observed in the graphs that modified Ćuk has almost same value of voltage gain (around 1.3-1.6) irrespective of duty cycle. Up to 60% duty cycle modified Ćuk has high value of voltage gain than Boost and Ćuk regulator. After 60% duty cycle, Boost regulator has high value of voltage gain.

3.2.4 Performance in terms of Efficiency

The performance in terms of Efficiency as duty cycle is changing in Boost, Ćuk and modified Ćuk are shown in Fig. 3.4

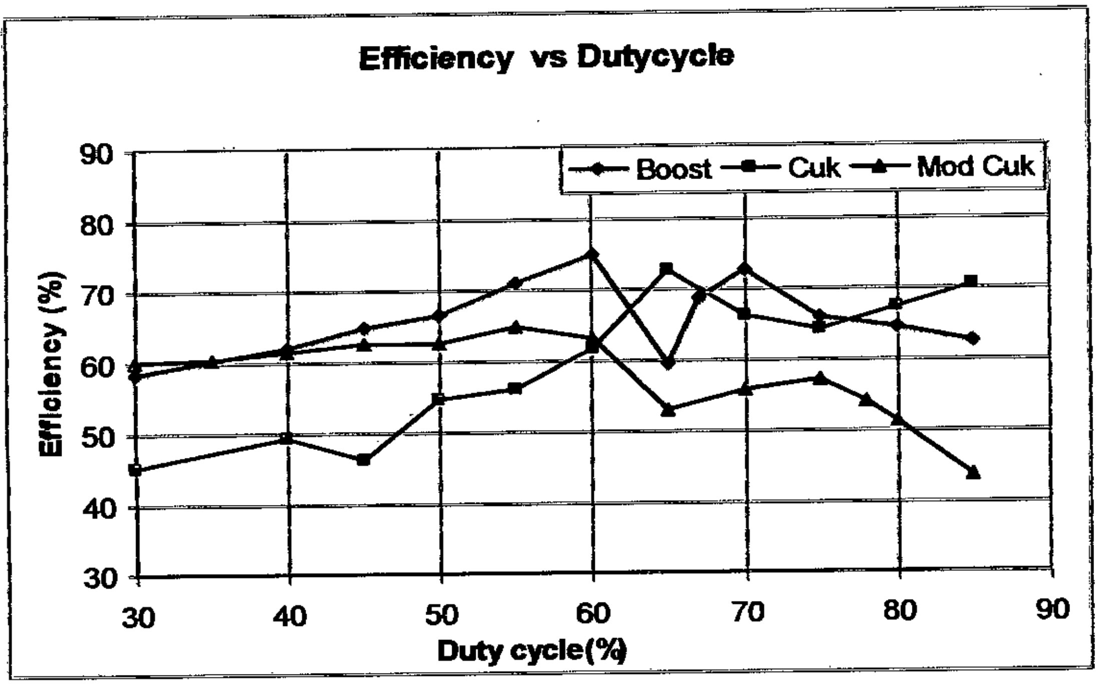

Fig 3.4: Regulators' performance in terms of Efficiency

For a fixed load the efficiency of a regulator can be expressed as (Appendix ii)

$$\eta = \frac{1}{1 + A/(1-D)^2 + B/(1-D) + C}$$

Where A, B and C are constant for a fixed load and D means duty cycle. It depicts that the efficiency has no straight relationship with duty cycle; rather it will have an optimum value for a particular range of duty cycle. Performance wise modified Ćuk shows a steady condition up to 60% duty cycle. But it has low efficiency at higher rate of duty cycle. Above 60% Ćuk has high value of efficiency but it has lower efficiency below 60% duty cycle than that of modified Ćuk. Boost regulator shows a fluctuation of efficiency around 60% - 70% of duty cycle.

3.3 CONCLUSION

Form above, it is evident that modified Ćuk regulator has better performance in terms of THD (%), Power factor, voltage gain and efficiency. Modified Ćuk regulator has small value of THD (%), which reveals that the input current follows the shape of input voltage. Also Ćuk and modified Ćuk regulator have almost steady efficiency within a fixed range of duty cycle. Though Boost regulator has high rate of efficiency, it has low value of THD %) which is a prime concern.

CHAPTER 4

CONCLUSION AND SUGGESTIONS

4.1 Conclusions

This thesis has been done with a view to have low harmonic content in input current of a single phase diode bridge rectifier. The investigation starts from a single phase full wave diode rectifier with passive input filter. With the help of input LC filter, THD (%) of the input current of a full wave rectifier (with output filter) has decreased to 8.5% from 24.68% of that without any passive filter. This kind of passive solution is bulky and has no control over voltage regulation. A solution of the problem has evolved with the help of active switching i.e. SMPS (Switch Mode Power Supply).

The Boost regulator with input passive filter gives low THD (5.0%) than the passive solution. In order to utilize the advantages of Ćuk conversion stage, Ćuk regulator is being proposed in this thesis and studied subsequently. The Ćuk regulator with passive input filter shows THD (1.47%) less than that of a Boost regulator. With a slight modification of this Ćuk regulator, it gives THD (1.15%). According to efficiency, modified Ćuk contains an overall same efficiency for a wide range of duty cycle which is a unique feature.

It is observed in this work that the SMPS regulated single phase rectifier has variable efficiency and power factor with duty cycle change. This observation is anticipated because in practical SMPS the efficiency deviates from the ideal ones because of lossy elements and non-ideal switches used in the circuits. The non ideal elements in the circuit cause a deviation of voltage gain relationship of the SMPS circuits. It results the voltage gain to increase with the increase of duty cycle of the control signal up to certain level. Then the voltage gain relationship of SMPS shows a decreasing tendency above 0.8 to 0.9 of duty cycle. So, the efficiency also shows abrupt decrease after attaining a maximum value. As the voltage gain and efficiency deviate from a high value in the DC-DC conversion stage, the overall voltage gain and efficiency of the SMPS regulated rectifier decrease. Because of the low value of voltage gain at low and high value of duty cycle, the power factor of such regulated rectifier decreases. However, the input current wave shape remains near sinusoidal. This implies that if voltage regulation from these regulated rectifiers is required, the regulation can be maintained at high efficiency for limited range of duty cycle and this limited range is high for modified Ćuk regulated rectifier. However, regulation for wide voltage variation is possible in all three types of regulated rectifier circuits. Ćuk and Modified Ćuk regulated single phase rectifier has added advantage of voltage regulation in step down and step up mode over the Boost regulated single phase regulator which has regulation in step up mode only.

4.2 SUGGESTION FOR FUTURE WORK

In this thesis, study has been done by simulation only. Practical implementation is not done. A practical implementation of Ćuk and modified Ćuk regulator base rectifier can be a future work. The practical circuit would require implementing the following items.

(1) The capacitor and inductor selection for output filter.
(2) The power transistor design for maximum current stress and gate delay.
(3) The control logic of the total regulator system.
(4) Base drive with proper isolation
(5) The switching logic with zero delay.

Favorable outcomes from the above points can lead towards a successful single phase Ćuk regulated full wave rectifier with near sinusoidal input current having high efficiency and good power factor.

APPENDIX i

We know, efficiency is (%) $\eta = \frac{P_{out}}{P_{in}} = \frac{V_0 I_o}{V_{in} I_{in}} = \frac{V_0 I_o}{V_{rms} I_m Cos\theta}$

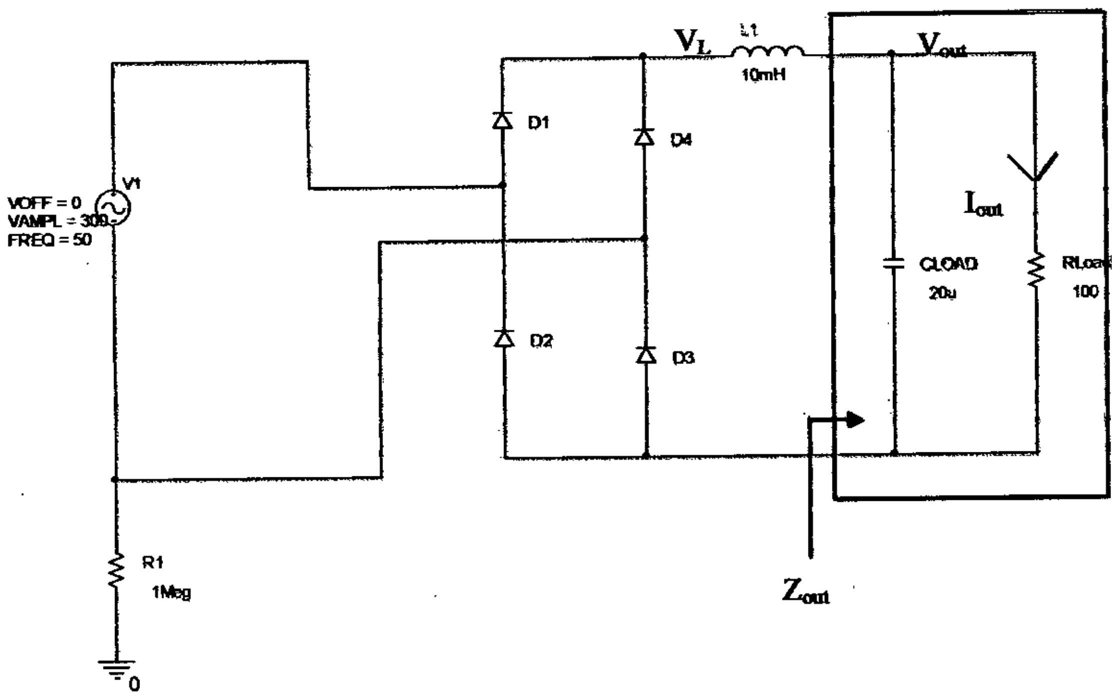

Fig i: Single Phase Diode Rectifier including Output LC filter with Resistive Load

$$P_{in} = V_{in,rms} \times I_{in,rms} \times Cos\theta = \frac{V_m}{\sqrt{2}} \times \frac{I_m}{\sqrt{2}} \times Cos\theta = \frac{V_m \times I_m}{2} \times Cos\theta$$

$$P_{out} = V_{out} \times I_{out} = \frac{V_{out}^2}{R_{Load}}$$

APPENDIX ii

For ideal case the relation between voltage gain and duty cycle is

$$\frac{V_o}{V_i} = \frac{1}{1-D} \quad \text{...} (1)$$

But for ideal and practical case we have to consider the relation between current gain with duty cycle (D), which is

$$\frac{I_o}{I_i} = (1-D) \quad \text{...} (2)$$

Now we can define efficiency as the ratio of output power to input power. So

$$\eta = \frac{I_o^2 R}{I_o^2 R + losses} \quad \text{...} (3)$$

The loss term includes total resistive loss (R_t) I_{in}^2 , switching loss $V_{sw} DI_{in}$ and diode loss $V_D(1\text{-}D)I_{in}$ etc.

Here, $I_{in} = D^* i_{in}$ ....(4)

So the equation (3) becomes:

$$\eta = \frac{I_o^2 R}{I_o^2 R + I_{in}^2 (Rt) + V_{sw} DI_{in} + V_D (1-D) I_{in}}$$

$$\eta = \frac{1}{1 + (I_{in}/I_o)^2 (Rt) + V_{sw} DI_{in}/I_o^2 R + V_D (1-D) Iin/I_o^2 R}$$

$$\eta = \frac{1}{1 + 1/(1-D)^2 (R_l + R_i) + V_{sw} D/R(1-D) I_o + V_D/I_o R} \quad \text{.............} (5)$$

So for a particular load this equation can be written as

$$\eta = \frac{1}{1 + A/(1-D)^2 + B/(1-D) + C} \quad \text{.......................................} (6)$$

Where A, B and C are constant for a fixed load.

APPENDIX iii

We know,

$$\eta = \frac{outputpower}{inputpower}$$

$$= \frac{V_O I_O}{V_{IN} I_{IN}}$$

$$= \frac{V_O}{V_{IN}} * \frac{I_O}{I_{IN}}$$

$$= \frac{V_O}{V_{IN}} * (1-D)$$

So,

$$\frac{V_O}{V_{IN}} = \frac{\eta}{(1-D)}$$

Putting the value of efficiency (in equation no (5)) we get,

$$\frac{V_O}{V_{IN}} = \frac{1}{1 + \frac{(Rt)}{(1-D)^2} + \frac{V_{sw} D}{R(1-D) I_O} + \frac{V_D}{I_O R}} * \frac{1}{(1-D)}$$

$$= \frac{1}{(1 + \frac{V_D}{I_O R})(1-D) + \frac{Rt}{(1-D)} + \frac{V_{sw} D}{R I_O}} \quad \text{..............................} (7)$$

REFERENCES

[1] R. Redl, P. Tenti and J.D Van WYK, "Power Electronics' Polluting Effects," IEEE Spectrum, May 1997, pp.32-39.

[2] Rashid M. H., "Power Electronics: Circuits, Devices and Applications", Prentice Hall of India, 2004, 3rd Edition.

[3] Mohan. Ned, Undeland. M. Tore; Robbins. William, "Power Electronics: Converters, Applications, and Design"; John Wiley & Sons, 2nd edition.

[4] "IEEE 519 Recommended Practices and Requirements for Harmonic Control in Electrical Power Systems," IEEE Industry Applications Society/ Power Engineering Society, 1993.

[5] Rustom Khalid and Batarseh Issa, "Recent Advances in Single-Stage Power Factor Correction", Invited Presentation at International Conference on Industrial Technology (ICIT'03), Slovenia, Dec13, 2003.

[6] Garcia, O; Cobos, J.A; Prieto, R; Alou, P; Uceda, J; "Single Phase Power Factor Correction: A Survey," IEEE Transactions on Power Electronics, Volume 18 Issue: 3, May 2003, pp.: 749-755.

[7] Supratim Basu, "Single Phase Active Power Factor Correction Converters-Methods for Optimizing EMI, Performance and Cost", PhD thesis, Chalmers University of Technology, Göteborg, Sweden, June 2006.

[8] Milan M. Jovanović, Yungtaek Jang "Sate of the Art, Single- Phase, Active Power Factor Correction Techniques for High Power Applications- An Overview", IEEE Trans. On Industrial Electronics, Vol.52, No.3, June 2005.

[9] Bhim Singh, Brij N. Singh, Ambrish Chandra, Kamal Al-Haddad, Amish Pandey, Dwrka P. Kothan "A Review of Single- Phase Improved Power Quality AC-DC Converters", IEEE Transactions on Industrial Electronics, Vol. 50, No. 5, October, 2003.

[10] Pressman. I. Abraham "Switching Power Supply Design", McGraw-Hill, 2nd edition.

[11] I.Ashida, J.Itoh "A Novel Three-Phase PFC Rectifier Using a harmonic Current Injection Method", IEEE PESC 92, Vol. 1,pp.:162-167(1992).

[12] Zane Regan and Maksimović, "Nonlinear- Carrier Control for High-Power-Factor Rectifiers Based On Flyback, Cûk or Sepic converters", in Proc. IEEE Appl. Power Conf. Expo., San Jose, CA, Mar.1996,pp. 814-820.

[13] Hong-Ying Wu, Xiao-Ming Yuan, Jin-Fa Zhang, Wei-Xun Lin "Single-phase Unity Power Factor Current-Source Rectification with Buck-Type Input" Power Electronics Specialists Conference, 1996 PESC apos;96, 27th Annual IEEE vol. 2, Issue,23-27 June 1996 Page(s):1149-1154 vol.2.

[14] Katsuya Hirachi and Mutsuo Nakaoka , "Improved control strategy on single Phase buck-type power factor correction converter", Int. J Electronics, 1999 Vol.86, No.10, pp. 1281-1293.

[15] J. C. Salmon, "Techiques for Minimizing the Input Current Distortion of Current Controlled Single Phase Boost Rectifiers, " IEEE Trans. On Power Electronics, vol.8, no.4, October 1993, pp. 509 - 520.

[16] A Pandey, Prof. B Singh, Prof D P Kothari "Comparative Evaluation of Single-phase Unity Power factor ac-dc Boost Converter Topologies" IEEE Transactions on Industrial Electronics, Vol: 52, Number: 3, June 2005.

[17] Ismail Daut, Rosnazri Ali, Soib Taib "Design of a Single-Phase Rectifier with Improved Power Factor and Low THD using Boost Converter Technique" American Journal of Applied Sciences 3(7):1902-1904,2006.

[18] M. Brkovic, S.Ćuk, "Input current shaper using Ćuk converter", International telecommunications and energy conference (INTELEDC), 1992, pp.532 -539.

[19] Bhim Singh, Mahima Agarwal "Analysis and design of the single-phase power factor corrected AC-DC Ćuk converter with high-frequency isolation" Int. J. Energy technology and Policy, Vol:4,Nos:1/2,2006.

[20] Qiang Li "A Single-Phase Dual-Output AC-DC Converter with high quality input waveforms", Thesis Paper, The Graduate School, University of Kentucky, 2003.

[21 Ashish Pandey, Bhim Singh, Dwarka P. Korthari "A Simple Fast Voltage controller for Single-Phase PFC Converters", IECON 02, IEEE 2002, 28th Annual Conference, Vol:2, Issue:5-8, November,2002, page(s):1235-1237.

[22] O.Sago, K.Matsui, H.Mori, L.Yamamoto, M.Matsuo, L.Fujimatsu, Y.Watanabe, K.Ando "An Optimum Single Phase PFC Circuit using CSC Converter" Industrial Electronics Society, 2004, IECON 2004, 30th Annual Conference of IEEE, Volume:3, page(s):2684-2689.