DESIGN AND ANALYSIS OF AN ACTIVE FILTER BASED SINUSOIDAL INPUT CURRENT RESONANT INVERTER

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MASTER OF SCIENCE IN ELECTRICAL AND ELECTRONIC ENGINEERING

by

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The thesis entitled **"Design and Analysis of an Active Filter based Sinusoidal Input Current Resonant Inverter"** submitted by M. A. Moonem, Roll no: 040206259F, Session: April 2002 has been accepted as satisfactory in partial fulfillment of the requirement for the degree of MASTER OF SCIENCE IN ELECTRICAL AND ELECTRONIC ENGINEERING on April 26, 2008.

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DECLARATION

It is hereby declared that this thesis or any part of it has not been submitted elsewhere for the award of any degree or diploma.

Signature of the student

....

(M. A. Moonem)

DEDICATED

To all my Teachers

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Abstract

Harmonic pollution has become a serious problem in power systems due to non linear loads connected to the utility line. The injected harmonics can result in a low power factor and various other problems such as: voltage distortion, heating of transformers and reduction of system efficiency etc. In order to prevent harmonic currents from entering the utility system, corrective measures (e.g. active filtering) can be adopted within the power electronic converter that would result almost sinusoidal currents at nearly unity power factor. In this work, a single phase full bridge rectifier will supply the dc input for a high frequency resonant inverter from the utility 50 Hz ac supply. The inverter will be switched so as to produce an output with 40 kHz frequency. In between the rectifier inverter stage a Boost configuration active filtering scheme has been used to improve the power factor and to make the input ac current wave-shape nearly sinusoidal. Input current and power factor improvement using boost rectifier is common for ordinary passive loads. In this thesis, the rectifier output do not directly feed the load, rather it has another conversion stage in the form of a resonant inverter. So, the rectifier load is an inverter and passive element combination. Hence, the design and implementation of boost rectifier filtering technique is different from the reported works. In the resonant inverter, the load and rest of the series element in the circuit have to be resonating. The complete circuit has been studied by simulation in this work so as to obtain the design procedures of a boost rectifier filter for a resonant inverter load to a rectifier. The study provides an alternative for passive filters for input current shaping of rectifier – resonant inverter circuit together with improved input power factor.

Chapter 1
Introduction

বাংলাদেশ প্রকৌশল বিশ্ববিদ্যালয় লাইব্রেরী, ঢাকা

1.1 Introduction

The function of an inverter is to change a dc input voltage to a symmetrical ac output voltage of desired magnitude and frequency. Inverters are widely used in industrial and household applications (e.g. variable-speed ac motor drives, induction heating [1], standby power supplies, uninterruptible power supplies, high frequency fluorescent lighting [2] etc.).

In most cases inverters use dc power obtained from utility power system through rectification. Generally a diode-bridge rectifier is used for this purpose followed by a bulk capacitor which causes input current to be pulsating in shape. Thus rectifiers inject non-sinusoidal (harmonic) current in the power line causing distortion of waveforms, increased losses, deterioration of power factor and electromagnetic interference (EMI) [3], [4], [5]-[7].

This fact have forced to the incorporation of regulations such as IEC 1000-3-2 and IEEE 519-1992 to limit the harmonic content of the currents drawn from the AC power line.

Resonant inverters in large sizes are used in heating applications and in small sizes are used in electronic ballast [9]. Since they have rectifiers at the front and inductive loads, the line current become non-sinusoidal and power factor degrades. To meet the specifications of standard regulations we have to take steps to reduce the amount of harmonics injected to utility power line and improve the input power factor. Usually passive filters [10] are used for improving the input current shape to reduce harmonic loss. But, the power factor remains low despite passive filtering process. To obtain high power factor and sinusoidal input currents it is necessary to employ active filtering [4, 6-10] by high frequency switching of static devices. Static active filters have the advantage of smaller sizes due to high frequency switching [3], [4], and [8]. Generally both passive and active filters are employed to mitigate the problems of harmonic injections in lines by static power converters.

In recent years conversion of ac line voltages form utilities has been dominated by the use of a single-phase diode rectifier followed by a single switch (i) a buck converter or (ii) a boost converter or (iii) a buck-boost converter. Although different research and experiments are going on to improve input power factor and input current shape, most of them suffer from the disadvantages of increasing cost and complexity in comparison to conventional rectifier-inverter. In our experiment we employed a buck-boost converter for the said purpose which may be used in a low or medium power high frequency resonant inverter system.

1.2 Previous Work

The expected imposition of the line-current harmonic limits for power supplies intended for the European markets are described in the IEC 1000-3-2. These regulations prompted many manufacturers to intensify their efforts toward finding cost-effective solutions for complying with these specifications. Majority of these efforts are related to improving the performance and reducing the cost of the existing active power-factor-correction (PFC) circuits based on continuous or discontinuous conduction mode boost converter, and on finding practical single-stage PFC topologies which would integrate the PFC function and dc/dc conversion step in one circuit. Besides these mainstream efforts, a number of manufacturers are still exploring the merits and limitations of passive solutions [16].

Experiments have been done mostly on input current quality improvement for single phase or three phase diode rectifiers [11]. Resonant inverter characteristics have been studied with pure dc source [1, 22] and dc input obtained from diode rectifier stage [6, 9]. A number of passive wave shaping circuits have been introduced and analyzed in literature [8, 16]. The line current wave-shaping method using a series connection of a parallel LC circuit on the ac side and the rectifier is introduced and analyzed in [11, 14].

It is a common practice to use a passive LC filter on input side to limit line current harmonics. Passive approach for power factor correction can meet the regulation with reliability and low EMI [5]. The filter capacitor voltage of the rectifier varies with line voltage, which affects the performance and efficiency of the converter. To get large hold-up time and dc output with less ripple, the bulk capacitance has to be increased making it bulkier. Small valued inductance degrades the power factor. Harmonic series and/or parallel resonances between the passive filter and the power system impedance may occur at a lower frequency than each tuned frequency [4]. Moreover, a passive filter may sink specific harmonic currents from other non-linear loads on the same feeder and/or from the power system upstream of the passive filter. This may make the passive filter overloaded and ineffective. Thus, passive power conditioning approaches seem to be attractive for narrow voltage range and low power applications.

Active filters or power conditioners have overcome much of the limitations faced in passive filtering scheme. Unlike traditional passive harmonic filters, modern active filtering, damping, isolation and termination, reactive-power control for power factor correction and voltage regulation, load balancing, voltage-flicker reduction and/or their combinations. Modern active harmonic filters are superior in filtering performance, smaller in physical size and more flexible in application compared to traditional passive harmonic filters. In active solutions, a converter with switching frequencies higher than the power line frequency is placed before rectifier. Reactive elements of this converter are small due to higher switching 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, addition of a high frequency switching converter in series with the input circuit causes reduction in overall efficiency of the whole converter due to 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 research have been done on 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 proposed with separate switches and control circuits. 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.

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

Input current wave shaping by Buck, Boost, Cûk, Buck-boost etc. converters offer different aspects of active filtering. Normally boost topology is used [11] 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 storage capacitor. Only the step-up (boost) voltage option is available here. Boost configuration has another problem of achieving stable, symmetrical ac input current with simple circuit configuration. Buck-boost and Cûk converters offer good performance to some extent.

1.3 Objectives of the Work

The objective of this work is to make the input current of a Rectifier - Resonant inverter combination circuit near sinusoidal and at the same time in phase with the supply voltage.

In order to prevent harmonic currents from entering the utility system, corrective measures (e.g. active filtering) will be taken within the power electronic converter that would result almost sinusoidal currents at nearly unity power factor.

In this thesis, the rectifier output will not directly feed the load, rather it will have another conversion stage in the form of a resonant inverter. So, the rectifier load will be an inverter – passive element combination. In the resonant inverter, the load and rest of the series element in the circuit have to be resonating.

In this study, the complete circuit will be studied by simulation to obtain the design procedures of a boost rectifier filter for a resonant inverter load to a rectifier. The study will provide an alternative for passive filters for input current shaping of rectifier – resonant inverter circuit together with improved input power factor which is not possible by normal passive filters.

1.4 Thesis Outline

This thesis includes four chapters.

Chapter-1 provides a general introduction followed brief overview of earlier works done and objective of the thesis.

Chapter-2: In this work, a single phase full bridge rectifier will supply the dc input for the inverter from the utility 50 Hz ac supply. So, a single phase full-bridge diode rectifier will be studied at various conditions. It starts from simple full-bridge rectifier, which follows with input and output filters. Then, the single phase rectifier with active filtering approach is studied. First, a boost regulated rectifier is studied and then the study has been done with Buck-boost regulator. A boost scheme is used to raise the output voltage level of the rectifier stage. A modified buck-boost regulator is studied to find out a better solution of the problem than the reported works.

Chapter-3: In this chapter a resonant inverter is formed using pure dc source and then with the rectified dc output obtained from ac main (as discussed in chapter-2), will feed the inverter. It includes the study of the converters, individual and overall efficiency of these power conversion stages. The overall work will be carried out by simulation.

Chapter-4 is the conclusive discussions and remarks. Some suggestions leading to future scope of work is also presented in this chapter.

Chapter 2

Single Phase Diode Rectifier

2.1 Performance Parameters

A rectifier is a power converter that gives a dc output voltage preferably with minimum amount of harmonic contents. At the same time, it should maintain the input current as sinusoidal as possible and in phase with the input voltage so that the power factor is near unity. The power processing quality of a rectifier requires the determination of harmonic contents of the input current, output voltage, output current and input power factor.

Power and Power Factor:

The output power of a rectifier can be defined as,

$$P_{dc} = V_{dc} I_{dc} \tag{2.1}$$

Where, V_{dc} is the average output (load) voltage of the rectifier and I_{dc} is the average output (load) current of the rectifier.

From the definition of average (ac) power for input side of the rectifier, we get –

$$P_{in} = \frac{1}{T}\int_0^T p(t)dt = \frac{1}{T}\int_0^T v_s(t)i_s(t)dt \tag{2.2}$$

Where, v_s is the utility input voltage at fundamental frequency,

$$v_s = \sqrt{2}\ V_s \sin \omega_1 t \tag{2.3}$$

and i_s is the utility input current in steady state as the sum of its Fourier (harmonic) components,

$$i_s(t) = i_{s1}(t) + \sum_{h\neq 1} i_{sh}(t) \tag{2.4}$$

$$i_s(t) = \sqrt{2}\, I_{s1} \sin(\omega_1 t - \phi) + \sum_{h\neq 1} \sqrt{2} I_{sh} \sin(\omega_h t - \phi_h) \qquad 2.5$$

here, I_{s1} is the fundamental (line-frequency f_1) component and I_{sh} is the component at the h harmonic frequency $f_h(=hf_1)$. I_s denotes the rms value of i_s.

Power factor is a measure of how effectively the load draws the real power. For sinusoidal quantities,

Power factor (PF) = $\frac{P}{S}$; here $S = VI$ which denotes Apparent Power

$$or, \quad PF = \frac{VsIs1 \cos\phi 1}{VsIs} = \frac{Is1}{Is} \cos\phi_1 \qquad 2.6$$

Here cos ϕ_1 is the displacement factor (DPF), which is same as the power factor (PF) in linear circuits with sinusoidal voltages and currents.

$$DPF = \cos\phi_1 \qquad 2.7$$

Therefore, the power factor with a non-sinusoidal current is,

$$PF = \frac{Is1}{Is} . DPF \qquad 2.8$$

Harmonic Distortion:

The amount of distortion in the voltage or current waveform is quantified by means of an index called the *total harmonic distortion (THD).* The distortion component of current from equation 2.4 is,

$$i_{dis}(t) = i_s(t) - i_{s1}(t) \qquad 2.9$$

In terms of the rms values,

$$I_{dis} = [I_s^2 - I_{s1}^2]^{1/2} \qquad 2.10$$

The THD in the current is defined as,

$$\%THD_i = 100 \times \frac{Idis}{Is1} = 100 \times \frac{\sqrt{Is^2 - Is1^2}}{Is1} \qquad 2.11$$

Relating equation 2.8 with equation 2.11 we get,

$$PF = \frac{1}{\sqrt{1 + THDi^2}} \cdot DPF \qquad 2.12$$

Where, the subscript *i* indicates the THD in *current*. This equation shows a relation of total harmonic distortion to power factor.

A sinusoidal input current could also have a poor power factor if it is not in phase with the input voltage. From equation 2.12 it is apparent that a 10% THD_i 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. While the process of shaping this input current is commonly called Power Factor Correction (PFC), the measure of its effectiveness towards complying with international regulations is the amount of reduction in the harmonic content of the input current.

Efficiency:

The efficiency of a rectifier is defined as,

$$\%Efficiency, \eta = \frac{Pdc}{Pin} \times 100 \qquad 2.13$$

2.2 Power Factor in Single Phase Full-bridge 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 input current harmonic distortion. This 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 period of time, when the capacitor is fully charged, large current pulses are drawn from the line during this short period of time. Typical input current harmonic distortion for this kind of rectification is usually around 60% and power factor is about 0.6. Figure-2.1 shows the schematic of a typical single phase diode rectifier filter circuit and Fig.-2.1a,b,c shows the simulated line voltage, output voltage and input current waveforms. Actual input current wave-shape and resulting harmonics depend on line impedance.

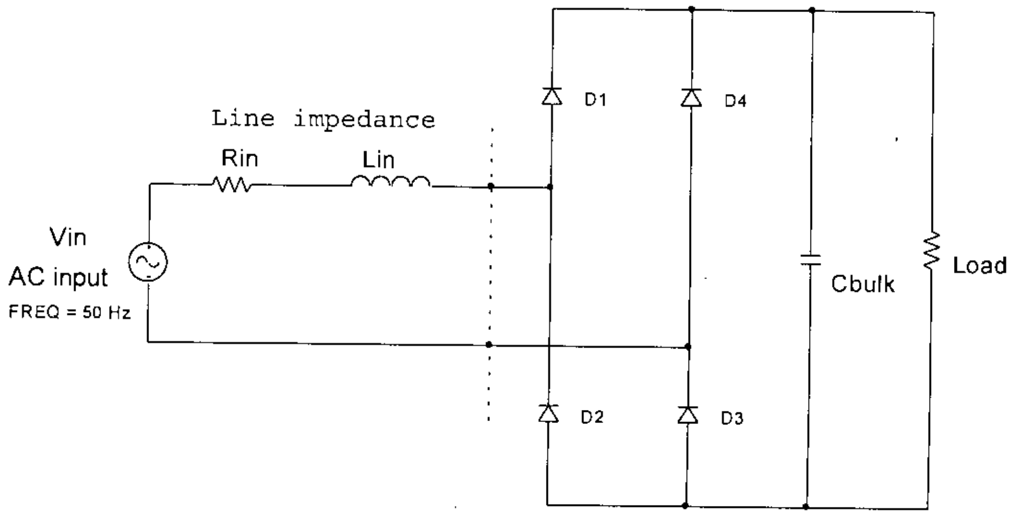


Figure-2.1: Schematic of a Single-phase Full-bridge Rectifier with a bulk capacitor

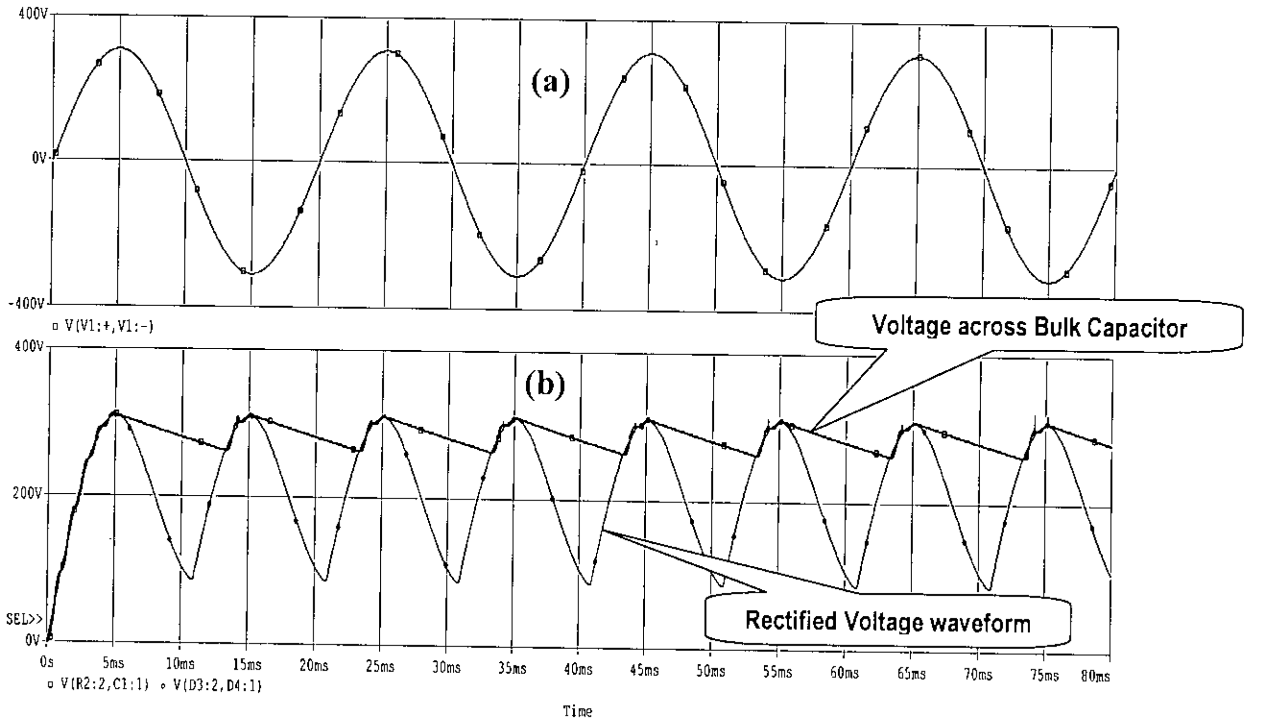


Figure-2.1(a) Wave-shape of input line voltage V_{in} (V_{rms} = 220v, freq=50Hz);
(b) Capacitor voltage and Rectified line voltage waveforms

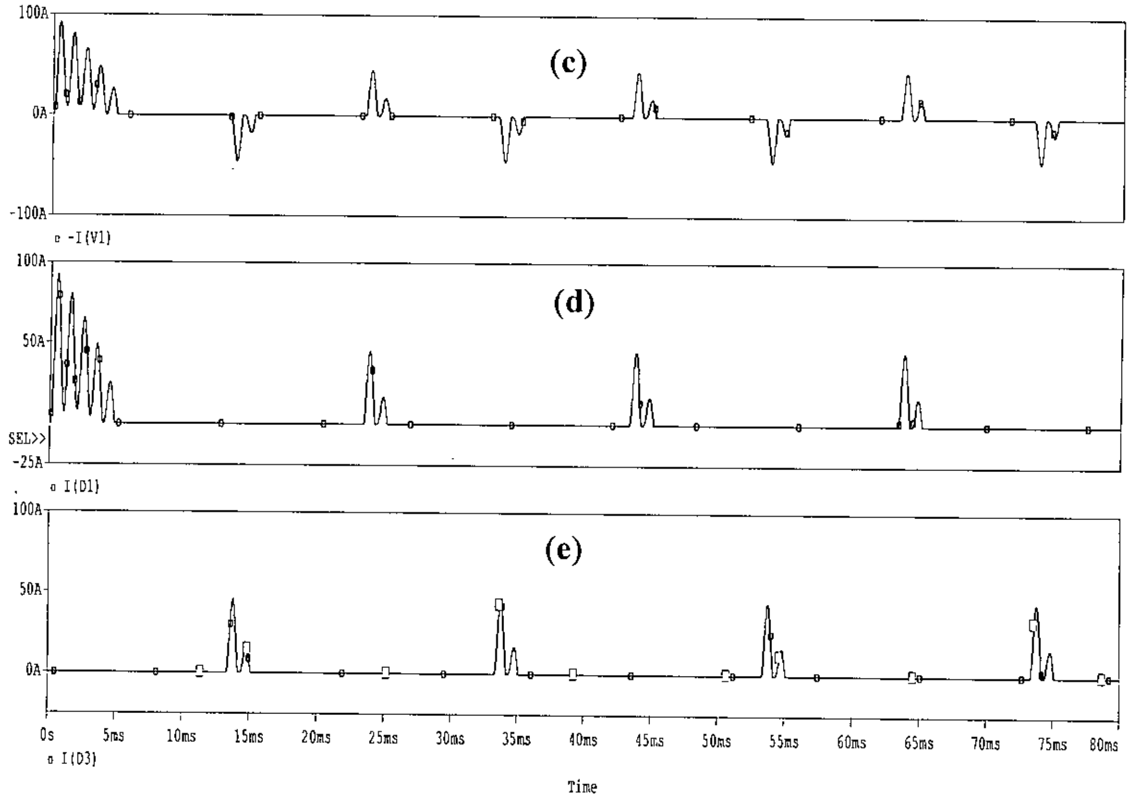


Figure-2.1(c) Wave-shape of input line Current I_{in};
(d) Diode current waveform passing (+ve) half-cycle of V_{in};
(e) Diode current waveform passing (-ve) half-cycle of V_{in}.

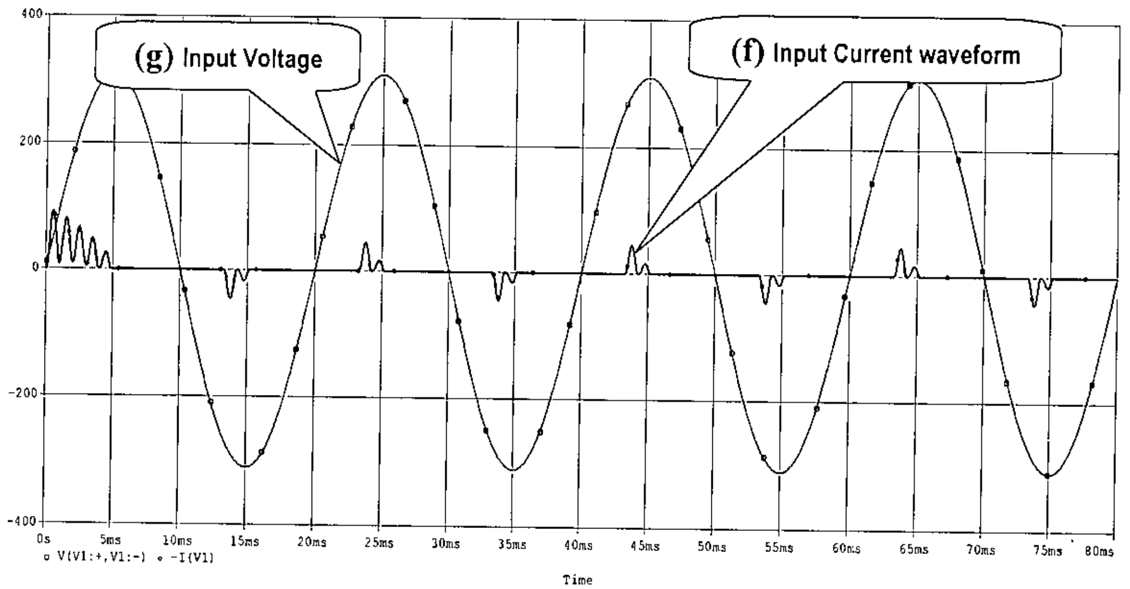


Figure-2.1(f) Wave-shape of input line Current I_{in};
(g) Input voltage waveform V_{in}.

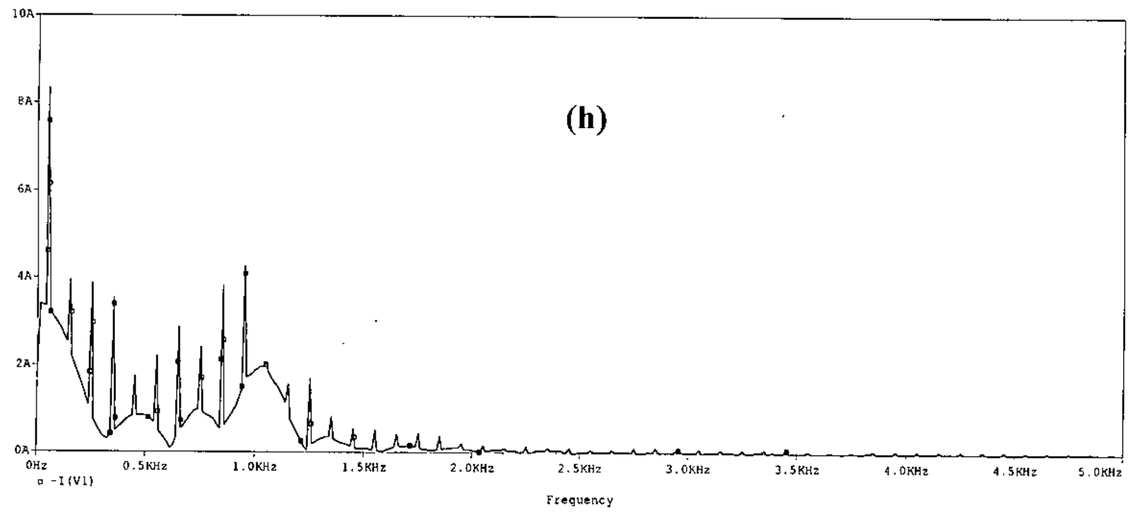


Figure-2.1(h) Input line Current harmonic contents at different frequencies.

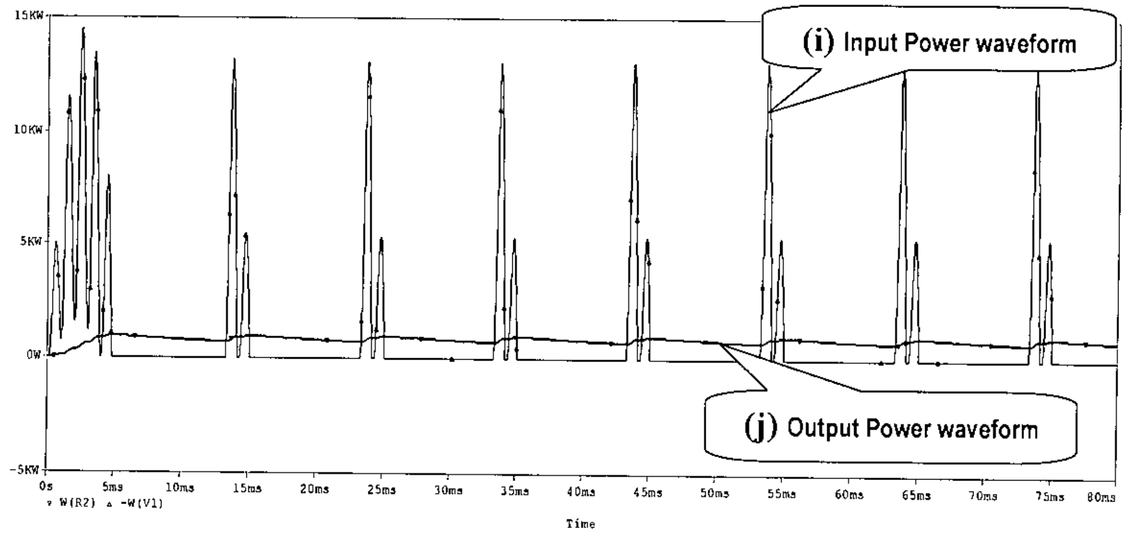


Figure-2.1(i) Wave-shape of input Power P_{ac};
(j) Wave-shape of output Power P_{dc}.

The above figures reveal some important input, output and performance parameters graphically. Fig.-2.1(c) shows that how severely input current is getting distorted and consequently Fig.-2.1(h) shows the harmonic content of input line current.

2.3 Power Factor Correction (PFC):

From the above observation it is obvious to apply some methods to improve input power factor and reduce harmonics. Power factor depends both on harmonic content and displacement power factor as was shown in equation 2.8. The harmonic limit standards given by regulatory organizations set limit on the harmonic content of the load current and does not specifically regulate the power factor of the line current. A high power factor can be achieved even with a substantial harmonic content, since the power factor is not significantly degraded by harmonics unless their amplitude is quite large. Similarly low harmonic content also does not guarantee high power factor.

PFC circuits for non-linear loads have their primary goal to reduce the harmonic content of the line current. PFC circuit solutions can be broadly categorized as passive and active circuits.

2.3.1 Passive Power Factor Correction (PFC) Method :

L, C or LC filters can be used to smooth out the dc output voltage of the rectifier and these are known as *dc filters*. *Ac filter* is used to filter out the harmonics from the supply system. The ac filter is normally of LC type as shown in Fig.-2.2.

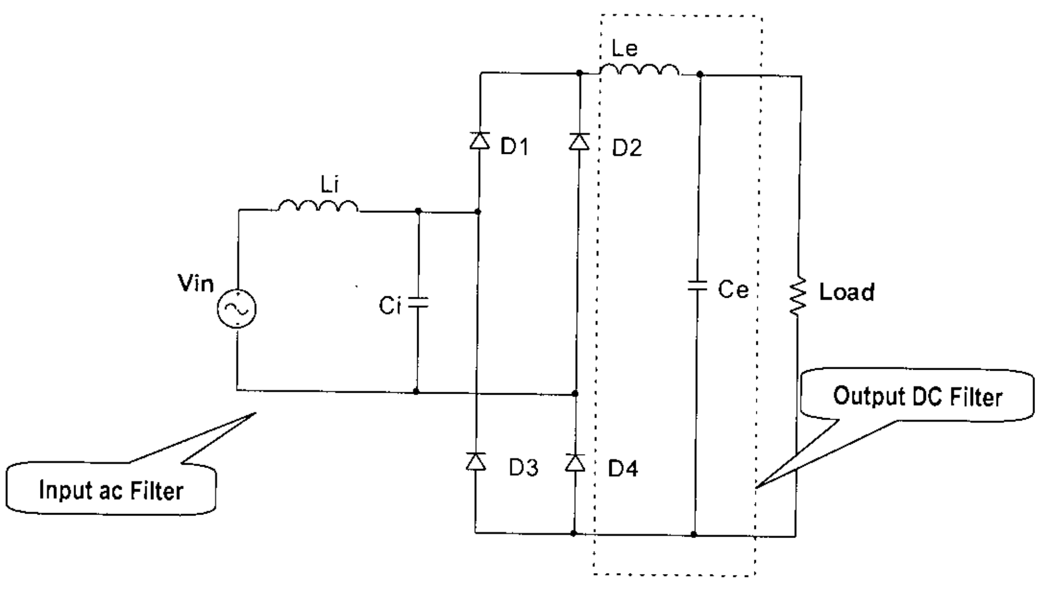


Figure-2.2: Single Phase Full-bridge Rectifier with input and output Passive Filters.

Since only passive elements like R, L and C is used in such type of filtering, they are named as *passive filters*. Usually the filter design requires determining the magnitudes and frequencies of the harmonics. The simplest approach is to add an inductor on the ac side of the rectifier bridge. This added inductor results in a higher effective value of ac-side inductance L_i which improves the power factor and reduces harmonics. The impact of ac side passive filtering are,

- Improved current waveform and the power factor improves from very poor to acceptable range.
- The output voltage V_{dc} is dependent on the output load and is substantially (around 10%) lower compared to the no-inductance case.
- Inductance L_e together with dc-side filter capacitor form a low-pass filter, and therefore, peak-to-peak ripple in the rectified output voltage v_{dc} is less.
- The overall energy remains essentially the same.

In general, passive solution offers reliable, rugged and quick reduction of harmonic current. They are insensitive to line surges and spike. But, passive filters suffer from some disadvantages as,

- Passive filter components (L, C) operate at low frequency (50 or 60 Hz) and as a result their sizes are relatively large.
- Passive filters lack voltage regulation and their dynamic response is poor.
- Passive filters cannot improve both input power factor and input current shape at the same time.
- For large loads harmonic series and/or parallel resonances between the passive filter and the power system impedance may occur at a lower frequency than each tuned frequency. Moreover, a passive filter may sink specific harmonic currents form other nonlinear loads on the same feeder and/or from the power system. This may make the passive filter overloaded and ineffective.

2.3.2 Rectifier with Output *L* or *C* filter and Resistive load :

A full-bridge diode rectifier with output LC filter and with resistive load is shown in Fig-2.3 (no input filter is used). The input voltage V_{in} has peak amplitude of 310 V with a frequency of 50 Hz. The output of the full wave rectifier contains both ac and dc components as shown in Fig-2.3. A majority of applications, which cannot tolerate a high voltage ripple, necessitates further processing of the rectified output. The undesirable ac components, i.e. the ripple, can be minimized using filters.

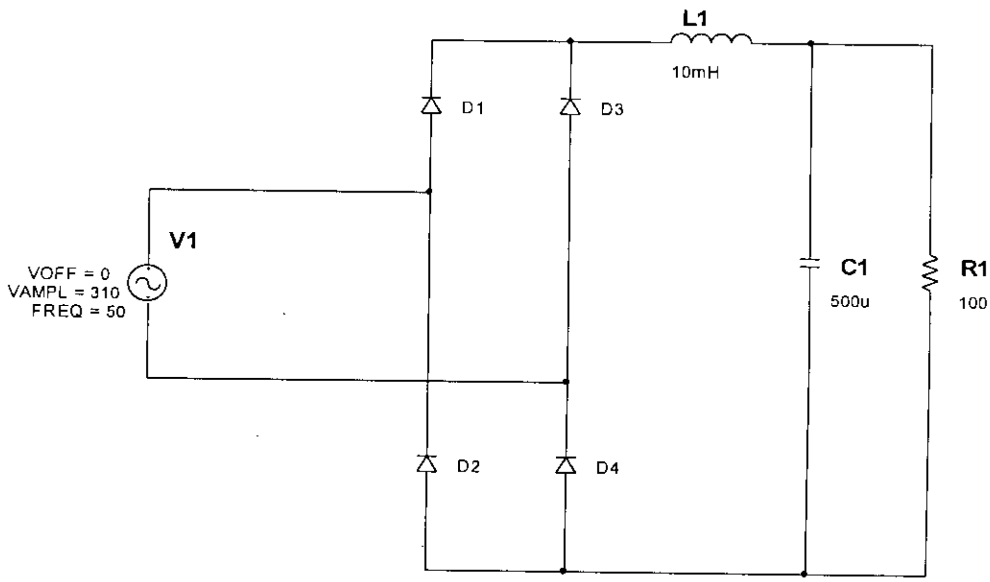


Figure-2.3: Schematic of a Single Phase Full-bridge Rectifier with output Filter.

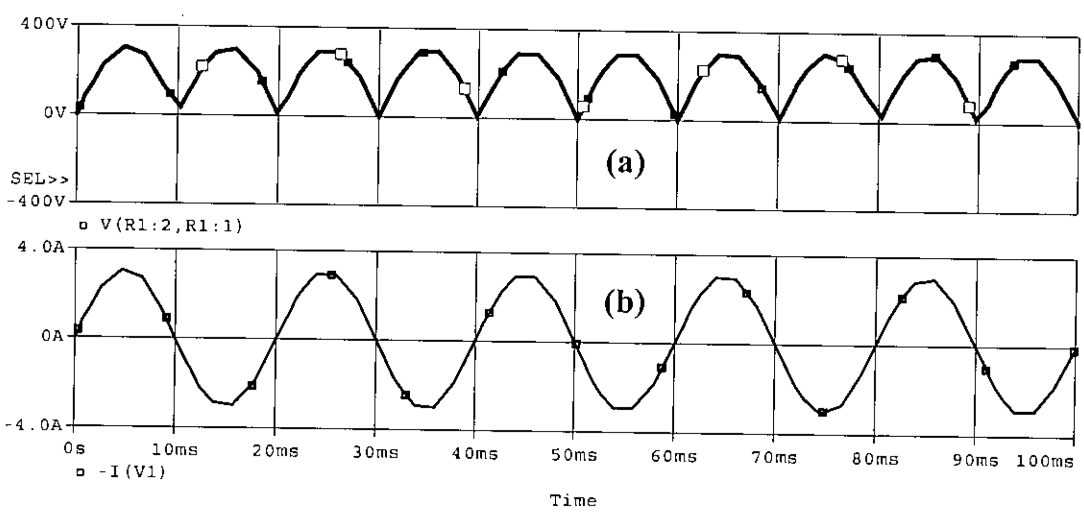


Figure-2.3(a) Output voltage and
(b) Input Current of a Rectifier **without any output Filter**.

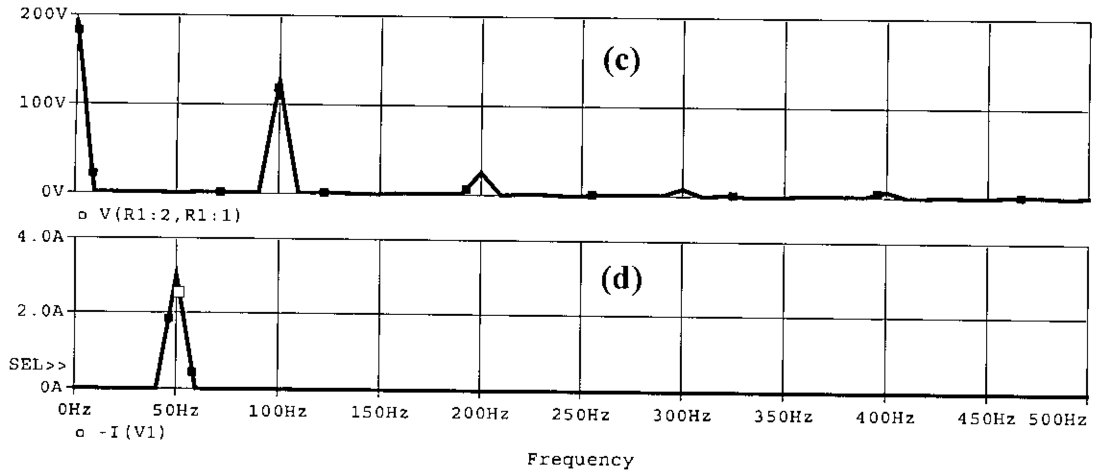


Figure-2.3 Harmonics of Waveforms of Fig-2.3(a) and (b)
(c) Output **Voltage harmonics** and
(d) Input **Current harmonics** of the rectifier.

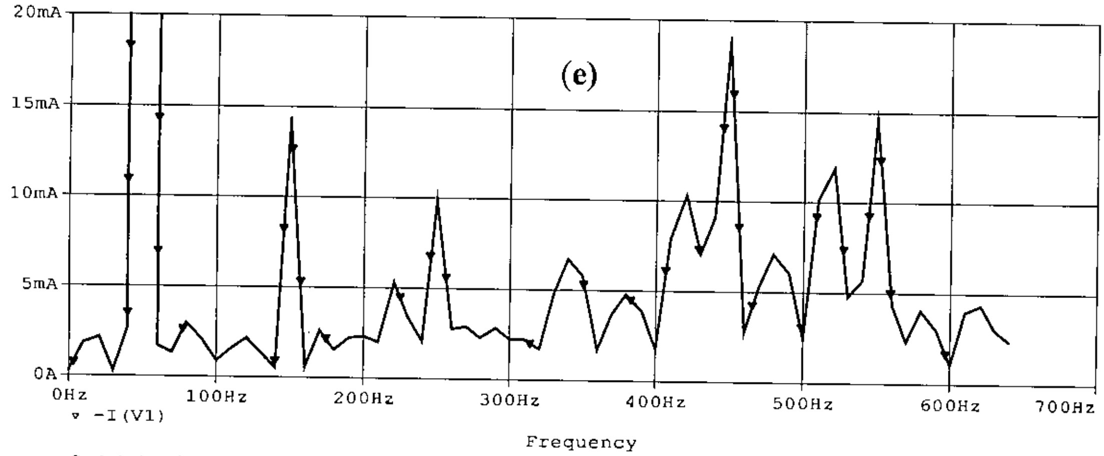


Figure-2.3(e) close-up view of **Input Current harmonics**.

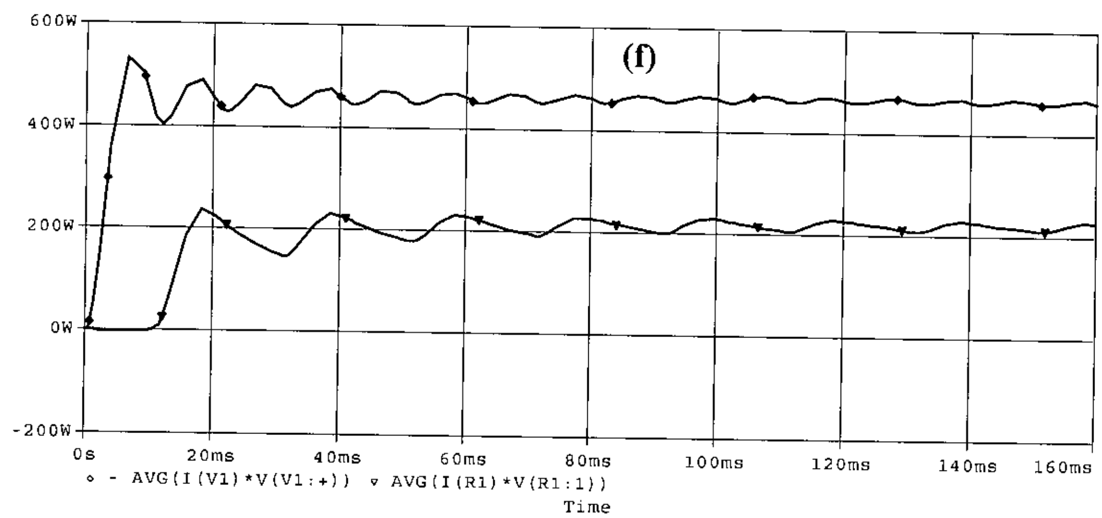


Figure-2.3(f) Average P_{in} and P_{out}; **Efficiency = 47%** (approx.); **(without filter)**

From the Figures-2.3(a) and 2.3(c) we find that the output is a pulsating dc with maximum ripple containing even harmonics. The current waveform is nearly sinusoidal.

In order to reduce the ripple of output voltage a filter capacitor may be used. The output is shown in Fig-2.4(a). The output voltage ripple decreases with increase in capacitor value. The ripple also depends on output load.

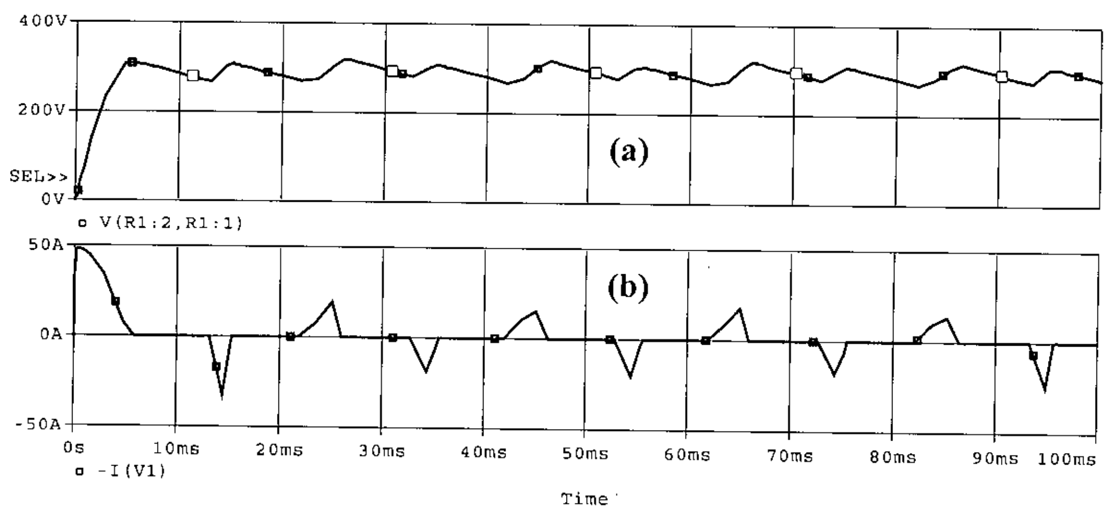


Figure-2.4(a) Output voltage and
(b) Input Current with **C = 500μF**, $R_{load} = 100\ \Omega$.

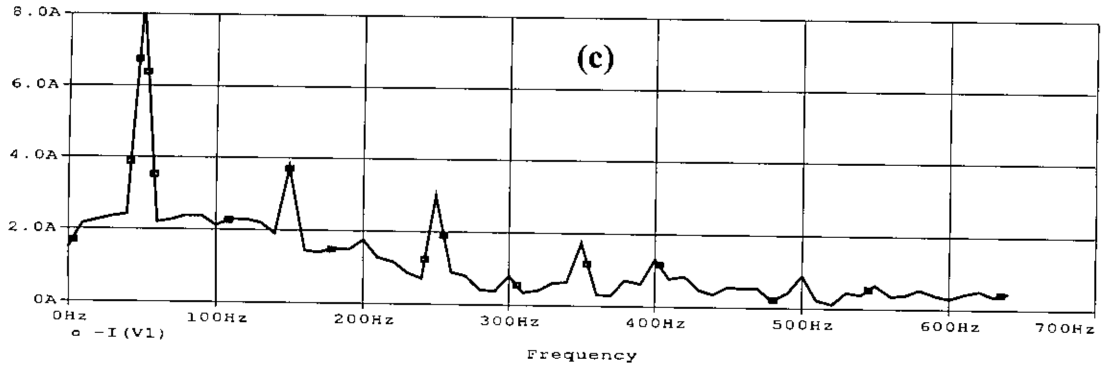


Figure-2.4(c) Input Current **harmonics** (with output **Capacitor = 500μF**).

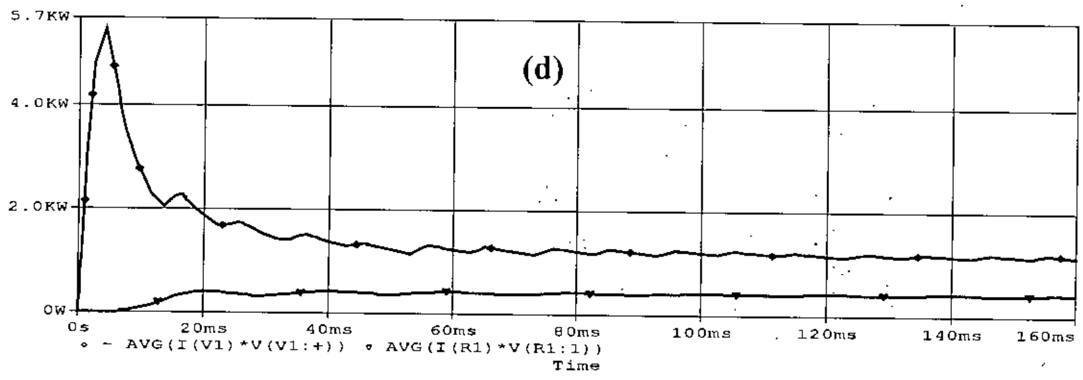


Figure-2.4(d) Average P_{in} and P_{out}; **Efficiency** = **36%** (approx.); (**C_{out}** = **500μF** and R_{load} = 100 Ω).

Figure-2.5(a) and 2.5(b) reveals that addition of output filter capacitor improves output voltage ripple but it deteriorates the input current wave-shape. Figures-2.5 also show the effect of increasing output capacitance value on input current and output voltage.

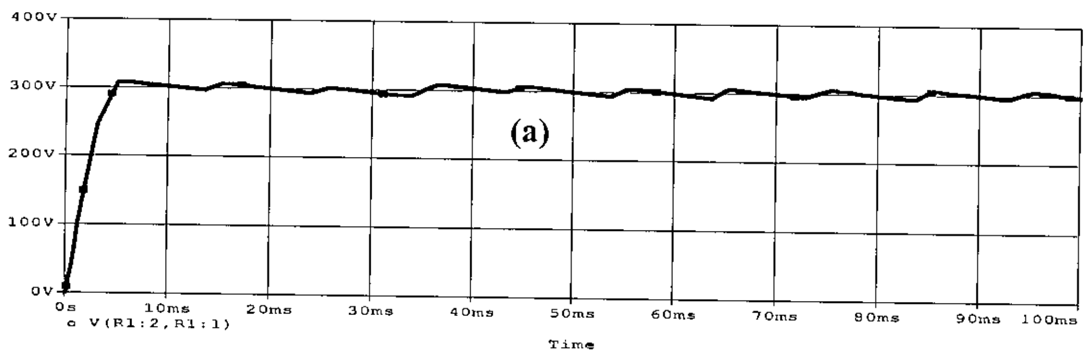


Figure-2.5(a) **Output voltage** of a Rectifier with **C=2000μF**, R_{load} = 100 Ω

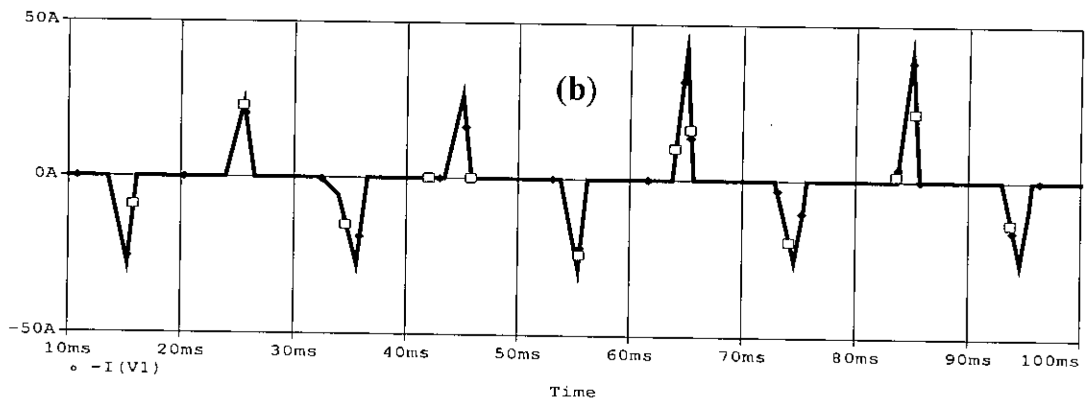


Figure-2.5(b) **Input Current** wave-shape (with output **Capacitor** = **2000μF**).

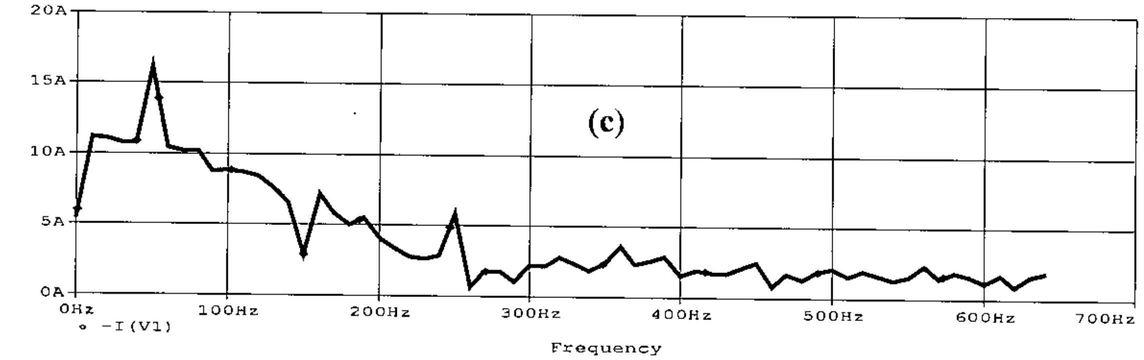


Figure-2.5(c) Input Current **harmonics** (with $\mathbf{C_{out}}$ = **2000μF**, R_{load} = 100 Ω).

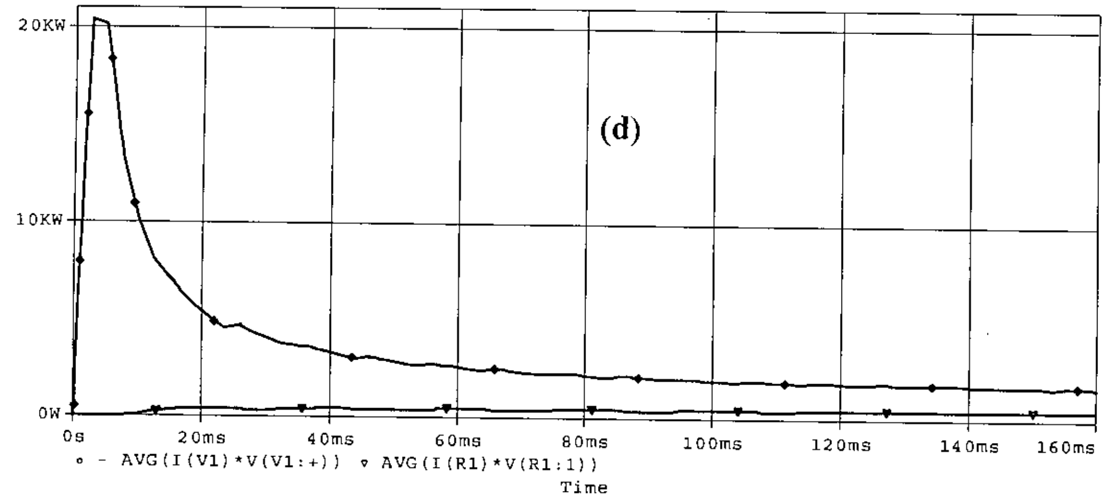


Figure-2.5(d) Average P_{in} and P_{out}; **Efficiency** = **26%** (approx.); ($\mathbf{C_{out}}$ = **2000μF** and R_{load} = 100 Ω).

Effect of adding only an inductor, L filter, at the output of the full-bridge rectifier has been studied and depicted in figures-2.6 and .27.

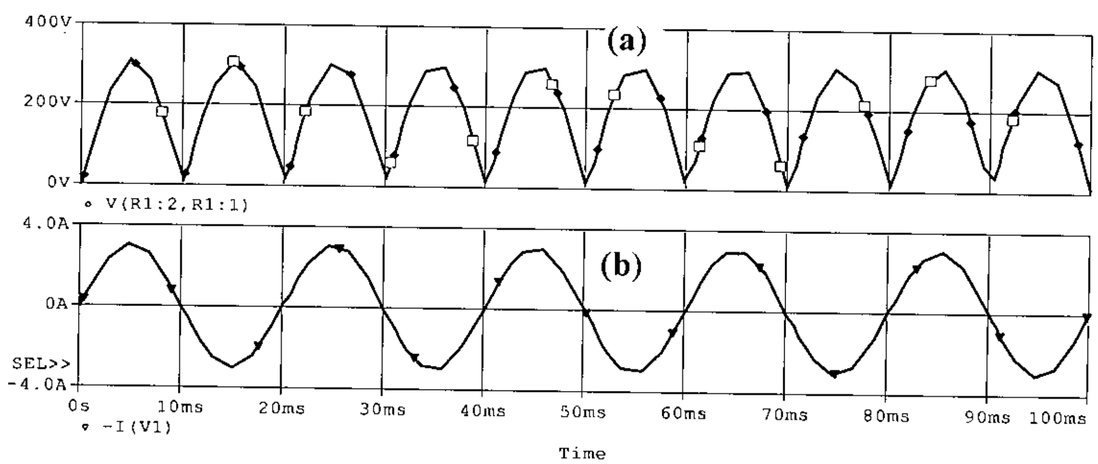


Figure-2.6(a) Output voltage and
(b) Input Current with **L** = **10mH** only.

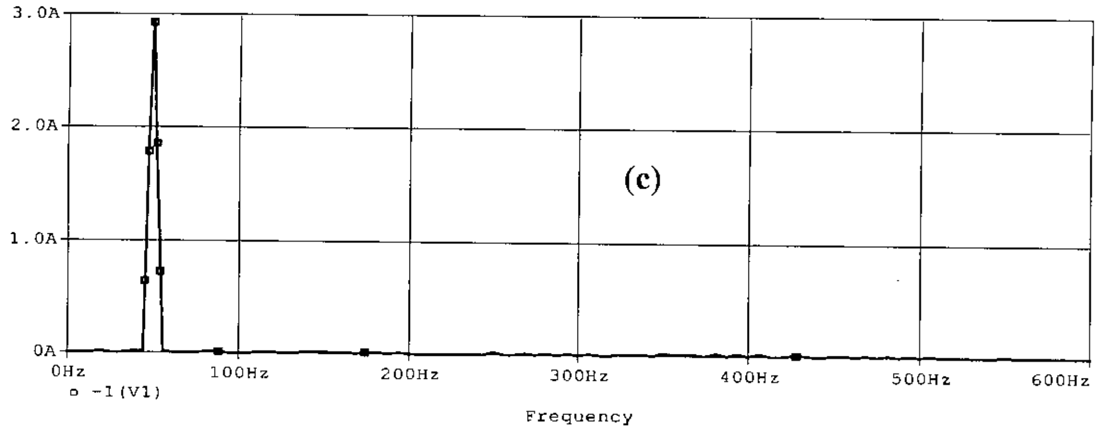


Figure-2.6(c) Input Current **harmonics** (with L_{out} = **10mH** and R_{load} = 100 Ω).

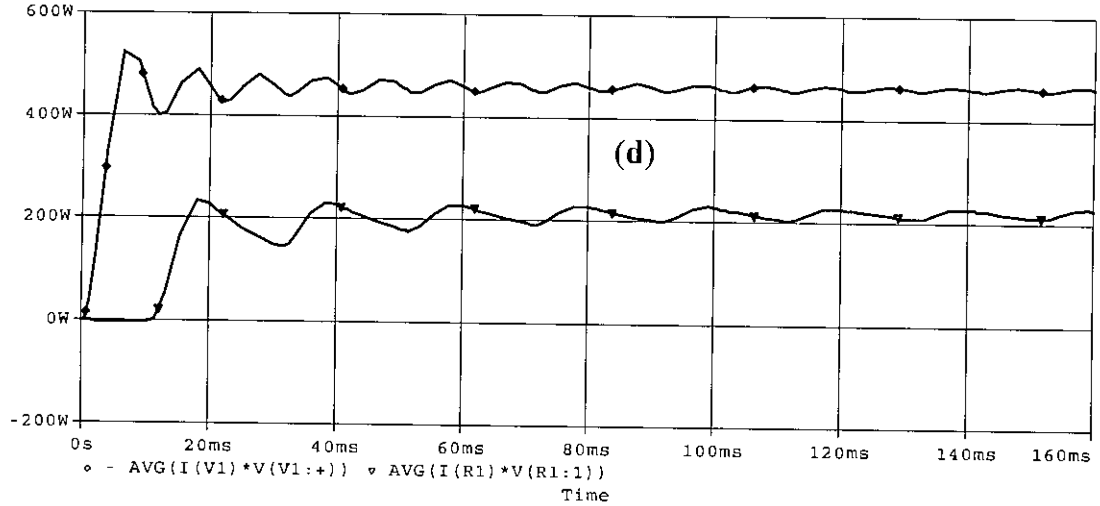


Figure-2.6(d) Average P_{in} and P_{out}; **Efficiency = 49%** (approx.); (L_{out} = **10mH** and R_{load} = 100 Ω).

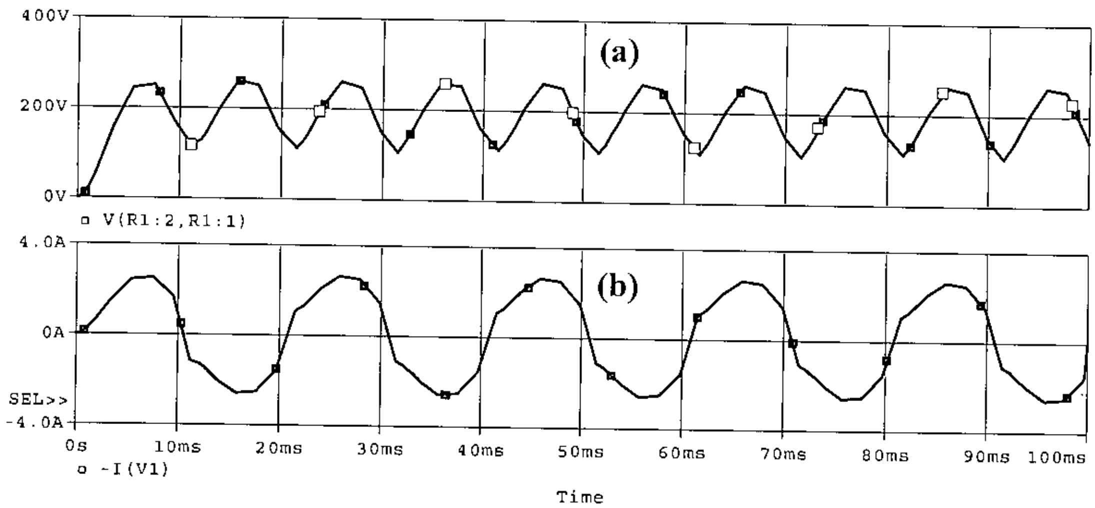


Figure-2.7(a) Output voltage and
(b) Input Current with **L = 200mH** only

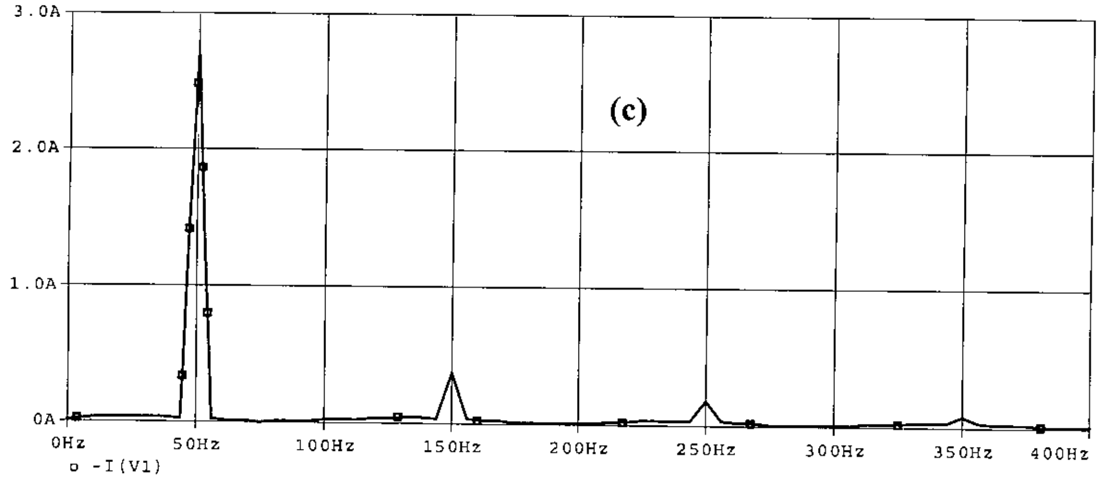


Figure-2.7(c) Input Current **harmonics** (with $\mathbf{L_{out}}$ = **200mH** and R_{load} = 100 Ω).

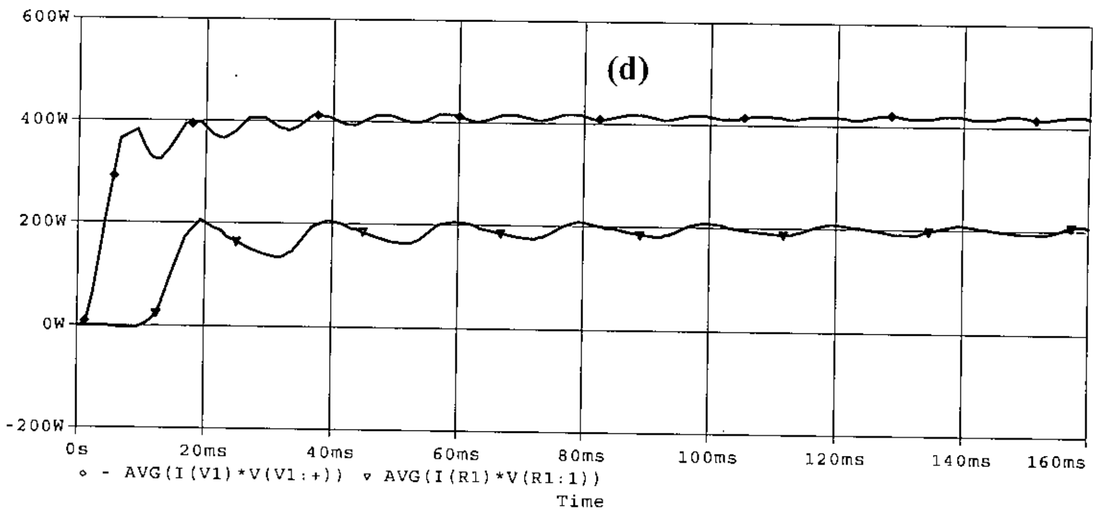


Figure-2.7(d) Average P_{in} and P_{out}; **Efficiency = 52%** (approx.); ($\mathbf{L_{out}}$ = **200mH** and R_{load} = 100 Ω).

Comparison between input current and output voltage waveforms at two different inductances (10mH and 200mH) shows that ripple at output voltage decreases with increase in inductor value with deteriorating input power factor and increasing input harmonics. A proportional effect of load resistance with output ripple also exists here. But the dc output is not as smooth as found using capacitor filter.

2.3.3 Rectifier with Output *LC* filter and Resistive load :

In order to get less ripple in output voltage, to make input current close to sinusoidal and to make the filter load independent, LC filter is introduced at the output stage of the full-bridge rectifier. Analysis on LC output filter with resistive load is discussed in following paragraphs.

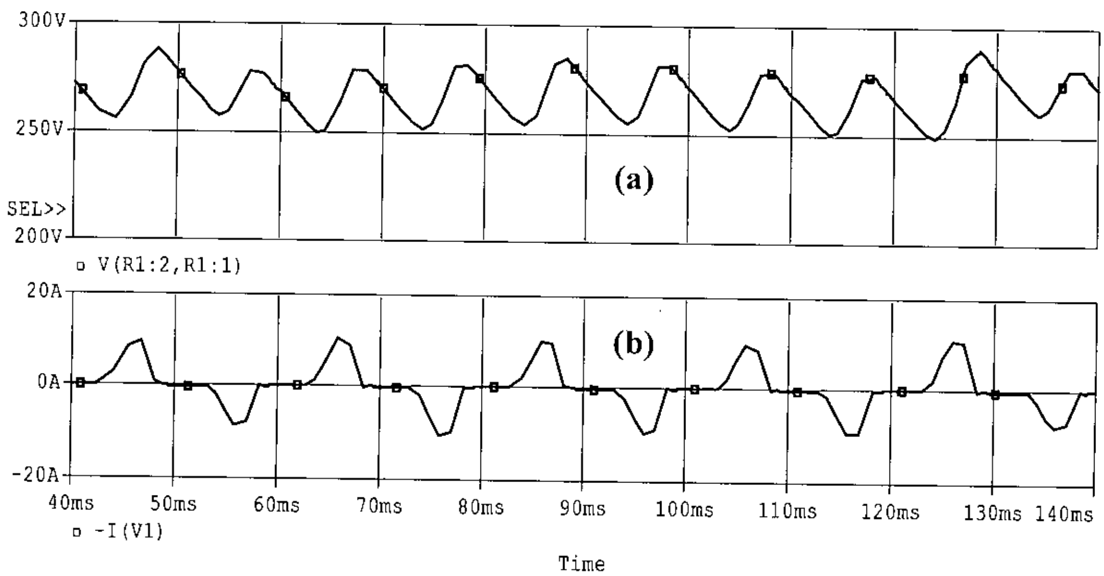


Figure-2.8(a) Output voltage and
(b) Input Current; **L=10mH, C=500μF**, R=100Ω

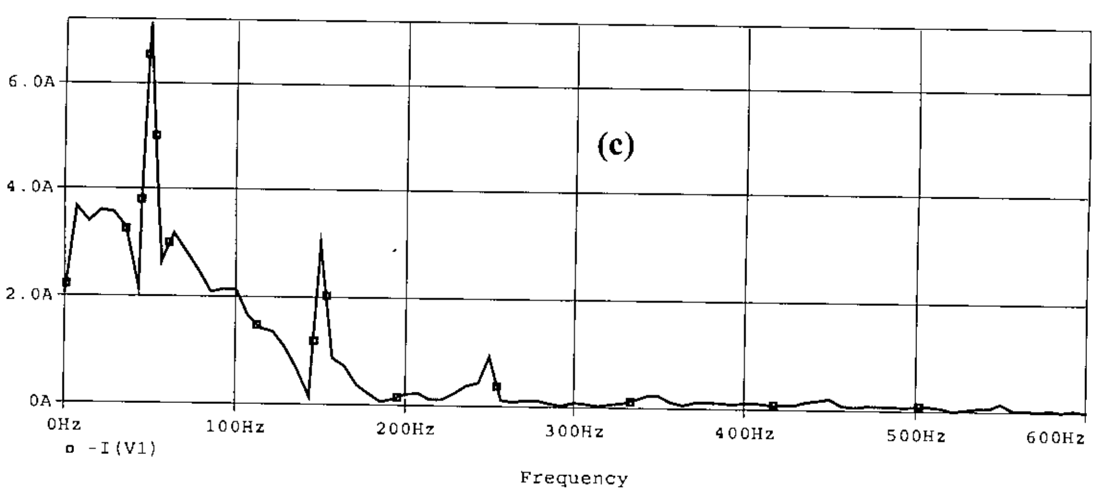


Figure-2.8(c) Input Current harmonics (with $\mathbf{C_{out} = 500\mu F}$, $\mathbf{L_{out} = 10mH}$ and R_{load} = 100 Ω).

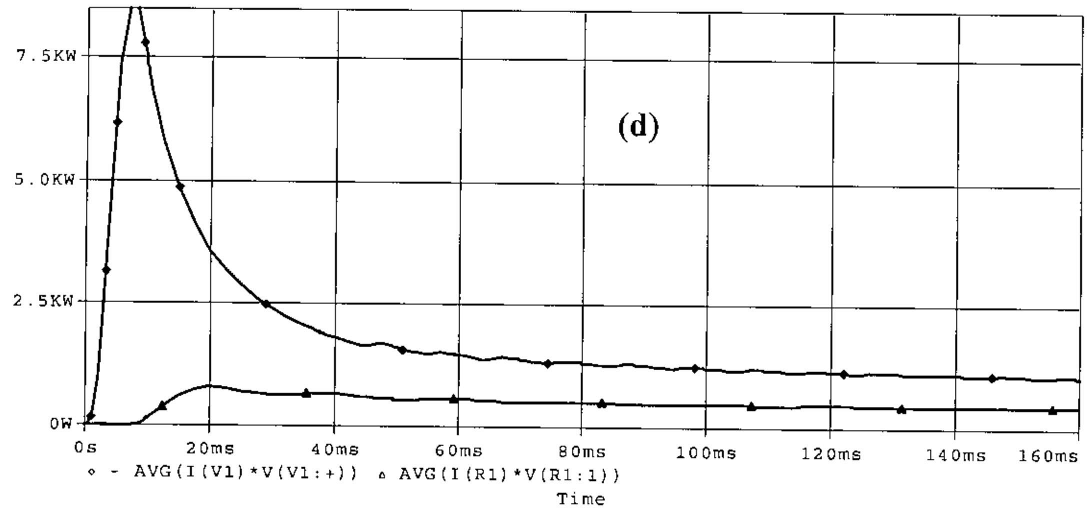


Figure-2.8(d) Average P_{in} and P_{out}; **Efficiency** = **40%** (approx.); (**C_{out}** = **500μF, L_{out} = 10mH** and R_{load} = 100 Ω).

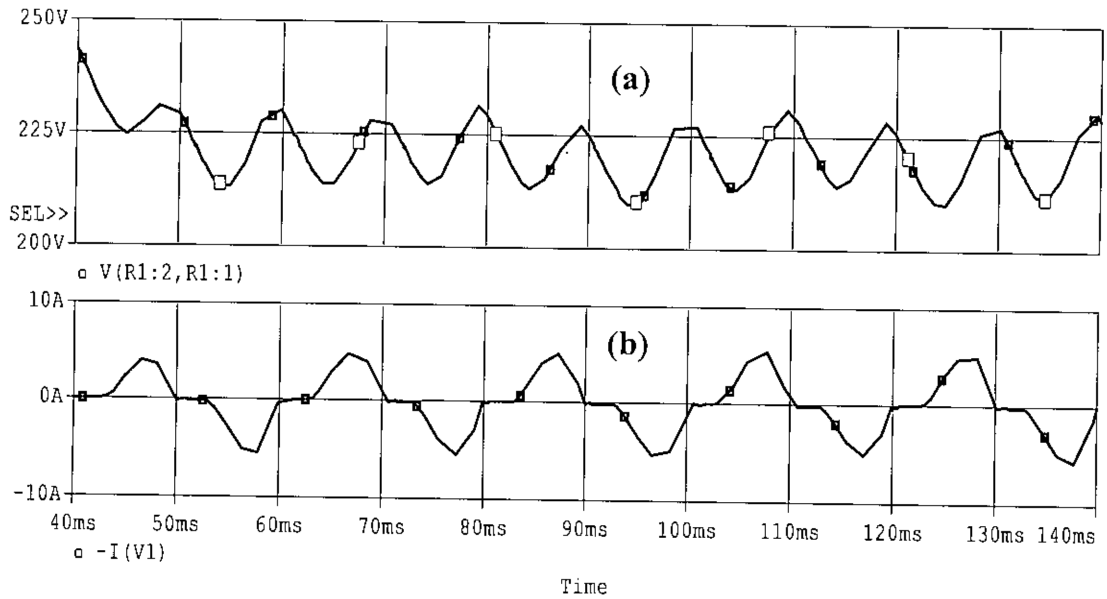


Figure-2.9(a) Output voltage and
(b) Input Current; **L=50mH, C=500μF**, R=100Ω

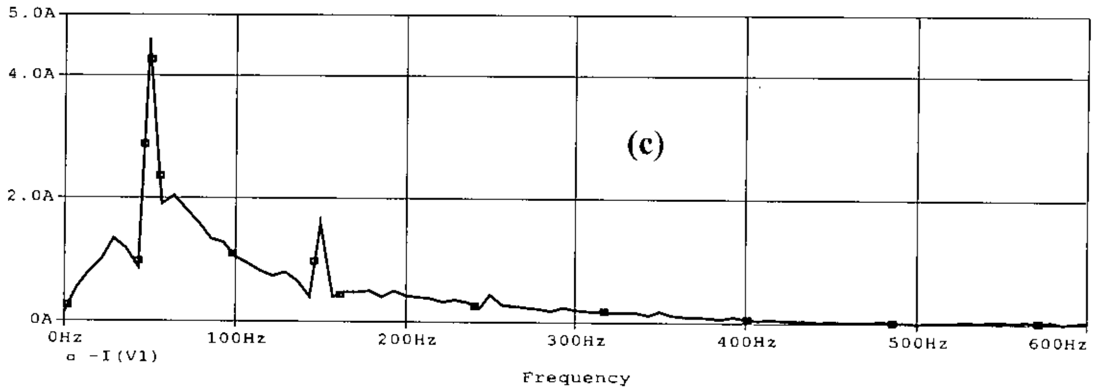


Figure-2.9(c) Input Current harmonics (with $\mathbf{C_{out} = 500\mu F}$, $\mathbf{L_{out} = 50mH}$ and R_{load} = 100 Ω).

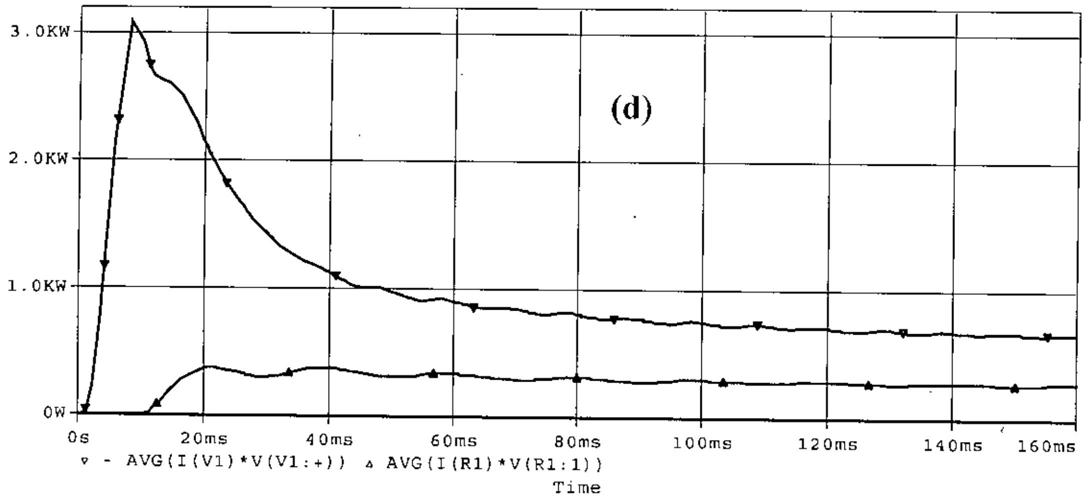


Figure-2.9(d) Average P_{in} and P_{out}; **Efficiency = 41%** (approx.); (C_{out} = 500μF, L_{out} = 50mH and R_{load} = 100 Ω).

It is observed that without filtering the input current THD is small and within limit but the ripple in output voltage is maximum.

Use of only *C-filter* at the output stage results smoother dc output voltage. But this suffers from poor efficiency and very large THD (in the order of 70%) in the input current.

Only *L-filter* at the output provides better THD in input current than C-filter, but ripples in output voltage remains large and output voltage is less than that of C-filter. L-filter provides rectification efficiency around 50%.

LC-filter shows larger output voltage and output power at the cost of increase in harmonic contents in input current.

All these observations are presented in tabular form in ***Table-2.1.***

Table–2.1: Input current, Output voltage and THD at different Output filter values:

	No Output Filter	Capacitor only C_{out}=500u	Capacitor only C_{out}=2000u	Inductor only L_{out}=10mH	Inductor only L_{out}=200mH	LC filter L=10mH, C=500u	LC filter L=50mH, C=500u
I_1	**3.01 A**	**8 A**	**17 A**	**3 A**	**2.75 A**	**7.2 A**	**4.25 A**
I_2	1 mA	2.1 A	8.9 A	4.2 mA	24 mA	2.1 A	1.05 A
I_3	14 mA	3.9 A	2.3 A	5 mA	310 mA	3 A	1.58 A
I_4	2.2 mA	1.7 A	4 A	4 mA	30 mA	0.2 A	0.41 A
I_5	10.5 mA	3.2 A	6.2 A	20 mA	155 mA	1 A	0.45 A
I_6	2.2 mA	0.7 A	2.1 A	2.8 mA	22 mA	0.07 A	0.21 A
I_7	6.8 mA	1.8 A	3.8 A	17 mA	65 mA	0.21 A	0.18 A
I_8	1.8 mA	1.25 A	1.7 A	3 mA	20 mA	0.1 A	0.07 A
I_9	18.8 mA	0.5 A	2.2 A	17.2 mA	41 mA	0.2 A	0.05 A
I_{10}	2.1 mA	0.9 A	2 A	1.5 mA	9 mA	0.1 A	0.01 A
I_{11}	14.5 mA	0.6 A	2.2 A	6 mA	8 mA	0.17 A	0.02 A
%THD	**1.015%**	**78.52%**	**77.67%**	**1.10%**	**13.03%**	**53.04%**	**47.37%**
$V_{dc\ (avg)}$ (approx.)	**197.3 V**	**280 V**	**300 V**	**185 V**	**195 V**	**265 V**	**218 V**
$P_{out(avg)}$	**210 w**	**450 w**	**480 w**	**215 w**	**200 w**	**490 w**	**255 w**
Efficiency	**47%**	**36%**	**26%**	**49%**	**52%**	**40%**	**41 %**

The THD in the current is defined as (in equation 2.11),

$$\%THD_i = 100 \times \frac{\sqrt{Is^2 - I1^2}}{I1};$$

Where $I_s^2 = \sum I_n^2,\ n = 1,2,3,\ldots n$ and I_1 = Fundamental component of input current.

From the above table and respective output figures it is observed that circuit arrangement with no output filter provides good THD but contains high ripple in rectified output voltage. Use of L-filter at the output stage also provides tolerable input current harmonics but suffers from high ripple in the output voltage. Use of C and LC filters provide better rectified output voltage with less ripple content but contains huge harmonics in intput current and also has poor efficiency.

2.3.4 Rectifier with *Input-Output LC filter* and Resistive load :

In order to get less ripple in output voltage and to improve input current wave shape, passive LC-filter is introduced at the input side of the rectifier. Following paragraph will find related parameters to evaluate the effect of addition of LC-filter of different L and C value. Simulations have been carried out for filter components at output stage of the full-bridge rectifier having values of – L_{out} = 10 mH, C_{out} = 500 μF and R_{load} = 100 Ω. Typical representative simulation results are presented in figures 2.10 – 2.13.

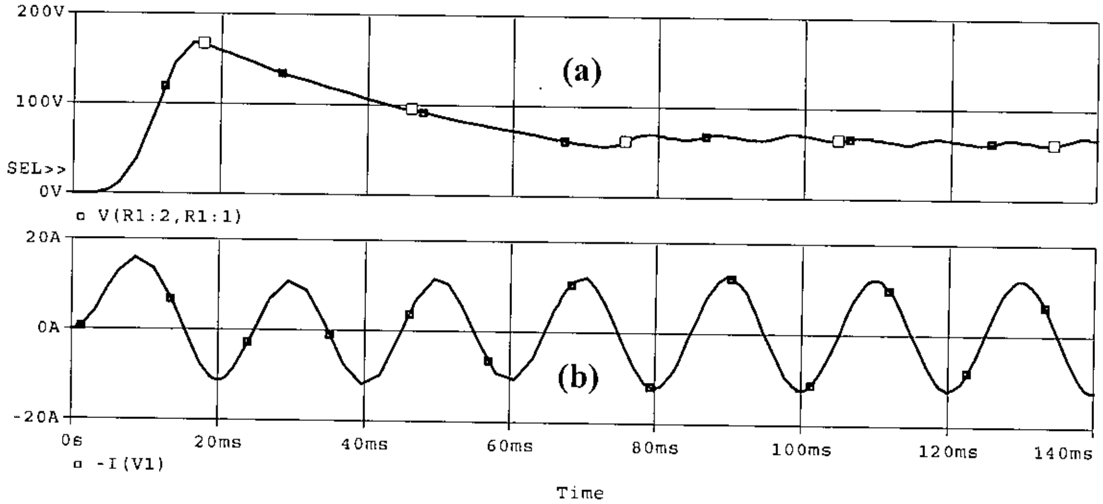


Figure-2.10(a) Output voltage and
(b) Input Current; (L_{out} = 10mH, C_{out} = 500μF, R=100Ω , C_{in} = 500μF, L_{in1} = 100mH and L_{in2} = 10mH).

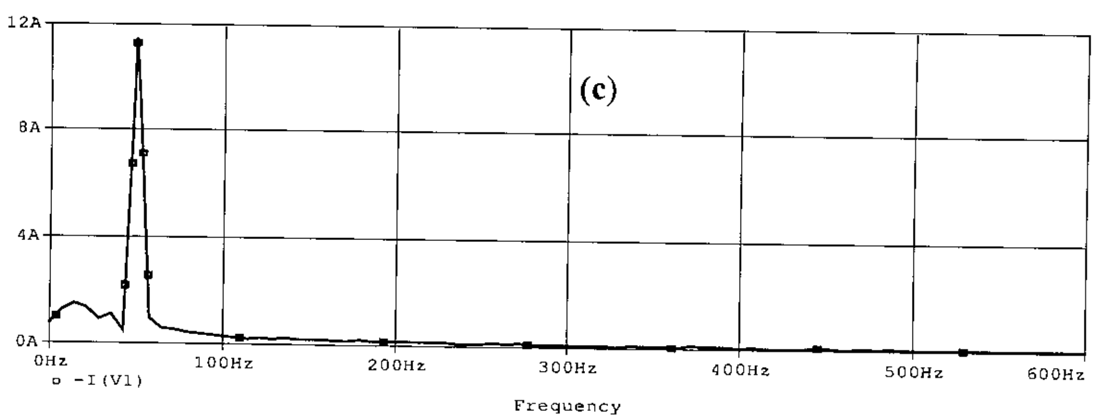


Figure-2.10(c) Input Current harmonics; (L_{out} = 10mH, C_{out} = 500μF, R=100Ω , C_{in} = 500μF, L_{in1} = 100mH and L_{in2} = 10mH).

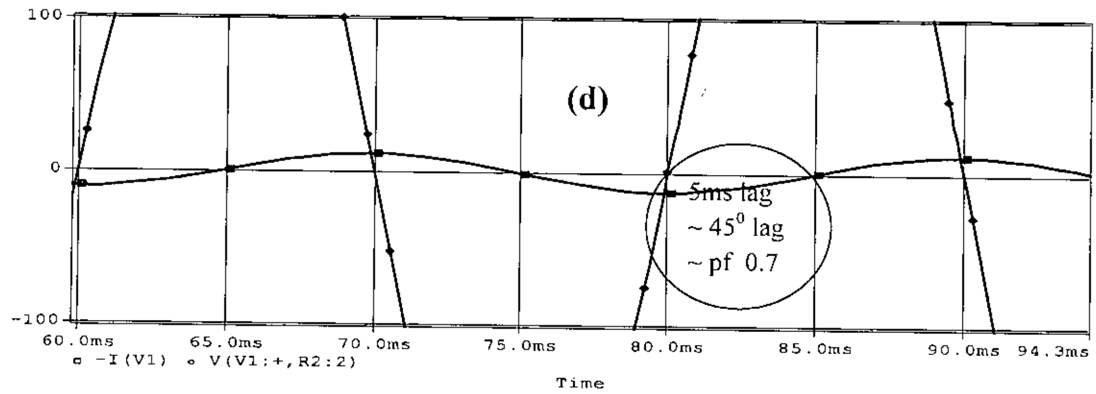


Figure-2.10(d) v_{in} and i_{in}; Close-up view showing **Power Factor = 0.7**; (L_{out} = 10mH, C_{out} = 500μF, R = 100Ω , C_{in} = 500μF, L_{in1} = 100mH and L_{in2} = 10mH).

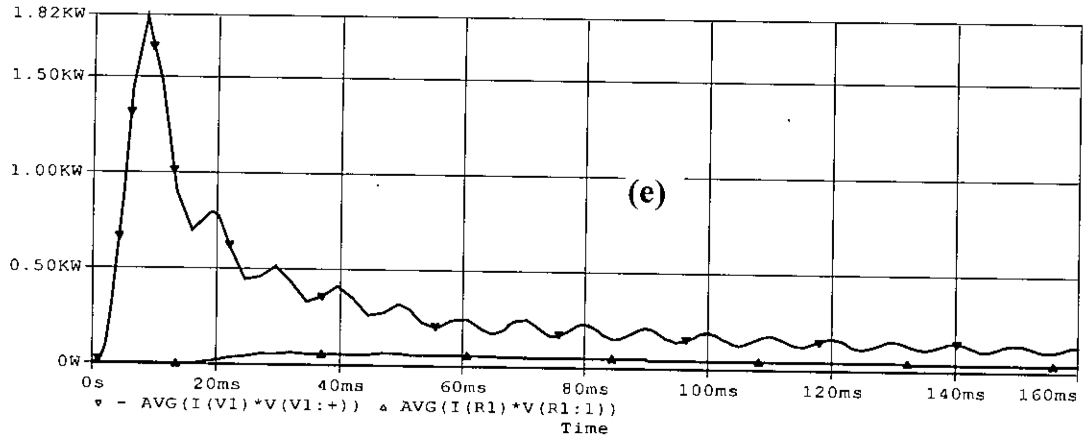


Figure-2.10(e) Average P_{in} and P_{out}; **Efficiency = 28%** (approx.); (L_{out} = 10mH, C_{out} = 500μF, R = 100Ω , C_{in} = 500μF, L_{in1} = 100mH and L_{in2} = 10mH).

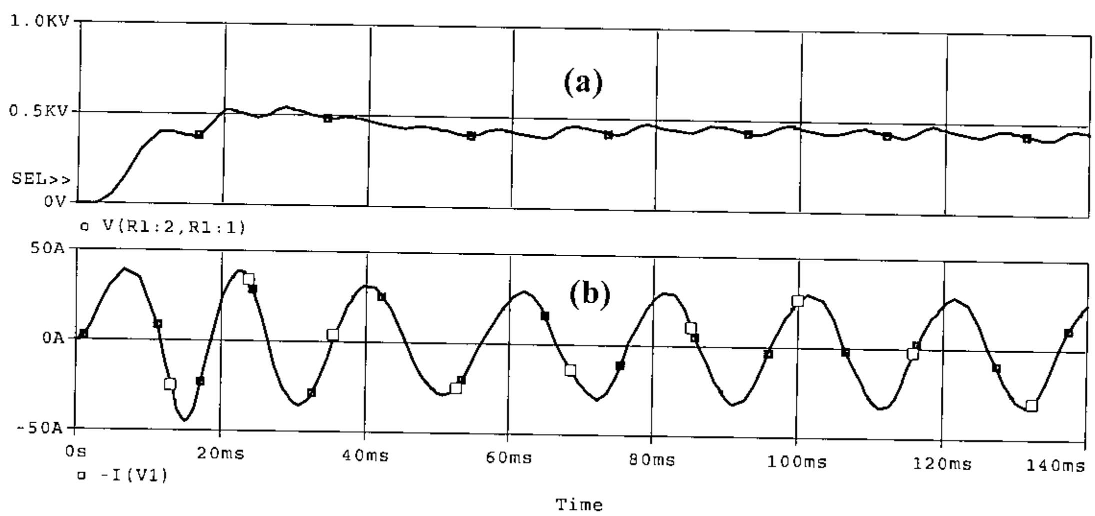


Figure-2.11(a) Output voltage and

(b) Input Current; (L_{out} = 10mH, C_{out} = 500μF, R=100Ω , **C_{in} = 200μF, L_{in1} = 20mH and L_{in2} = 1mH**).

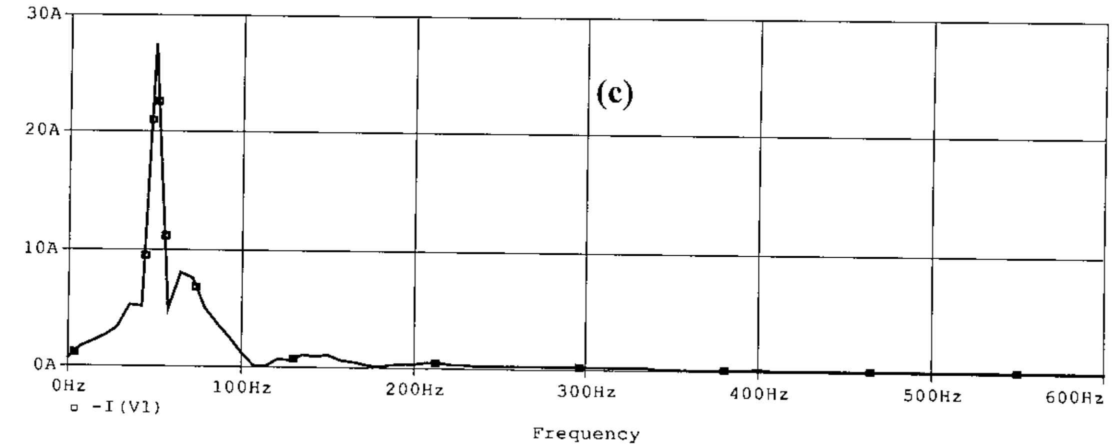


Figure-2.11(c) Input Current harmonics; (L_{out} = 10mH, C_{out} = 500μF, R=100Ω , C_{in} = 200μF, L_{in1} = 20mH and L_{in2} = 1mH).

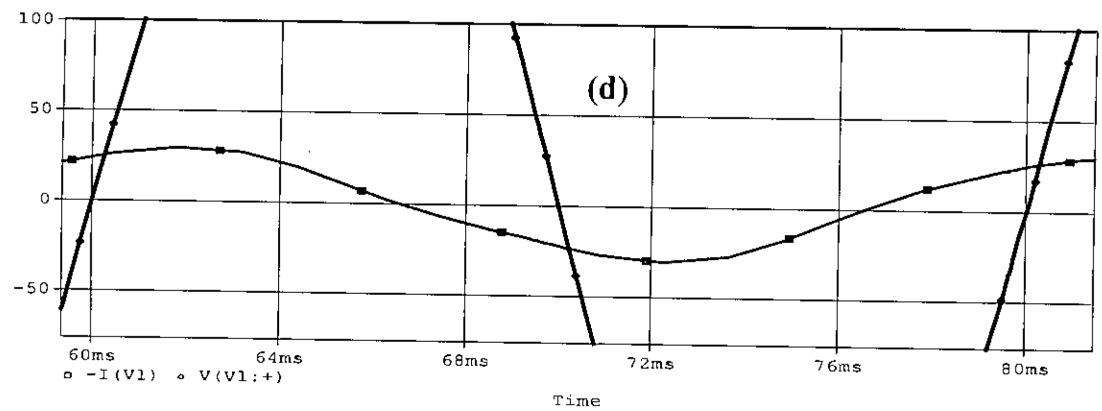


Figure-2.11(d) v_{in} and i_{in}; Close-up view showing Power Factor = **0.85 leading**; (L_{out} = 10mH, C_{out} = 500μF, R = 100Ω , C_{in} = 200μF, L_{in1} = 20mH and L_{in2} = 1mH).

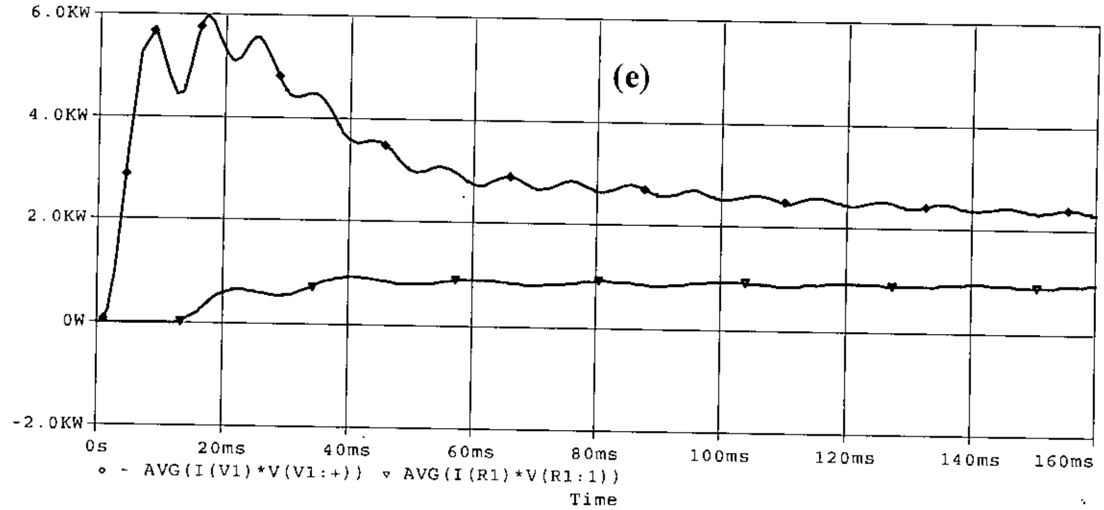


Figure-2.11(e) Average P_{in} and P_{out}; **Efficiency = 42%** (approx.); (L_{out} = 10mH, C_{out} = 500μF, R = 100Ω , C_{in} = 200μF, L_{in1} = 20mH and L_{in2} = 1mH).

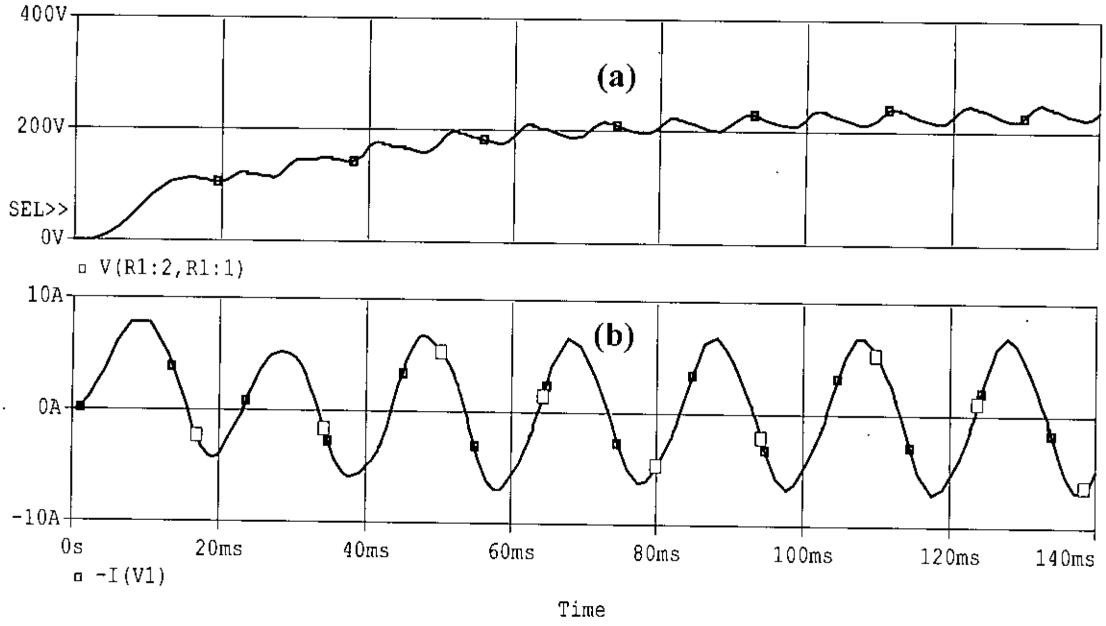


Figure-2.12(a) Output voltage and
b) Input Current; (L_{out} = 10mH, C_{out} = 500μF, R=100Ω , C_{in} = 50μF, L_{in1} = 200mH and L_{in2} = 1mH).

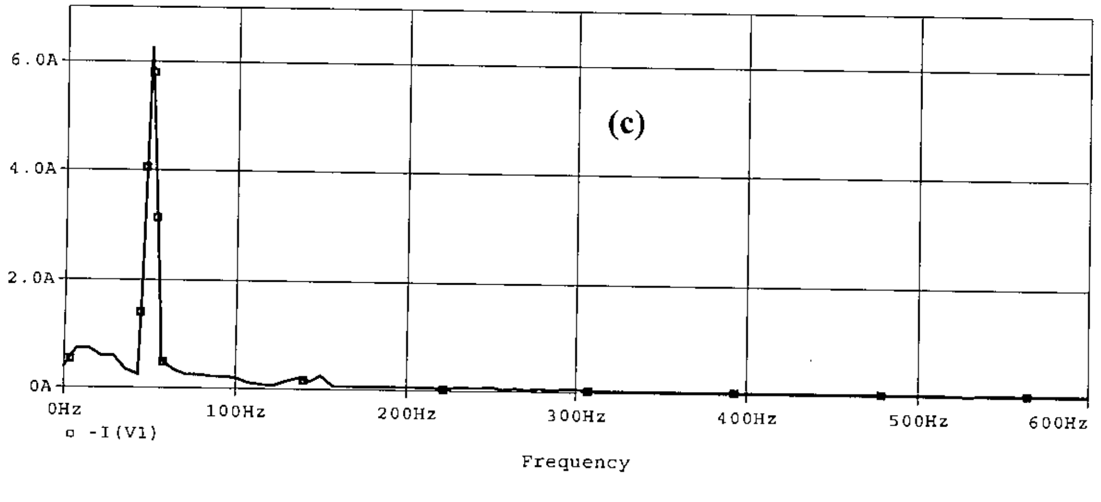


Figure-2.12(c) Input Current harmonics; (L_{out} = 10mH, C_{out} = 500μF, R=100Ω , C_{in} = 50μF, L_{in1} = 200mH and L_{in2} = 1mH).

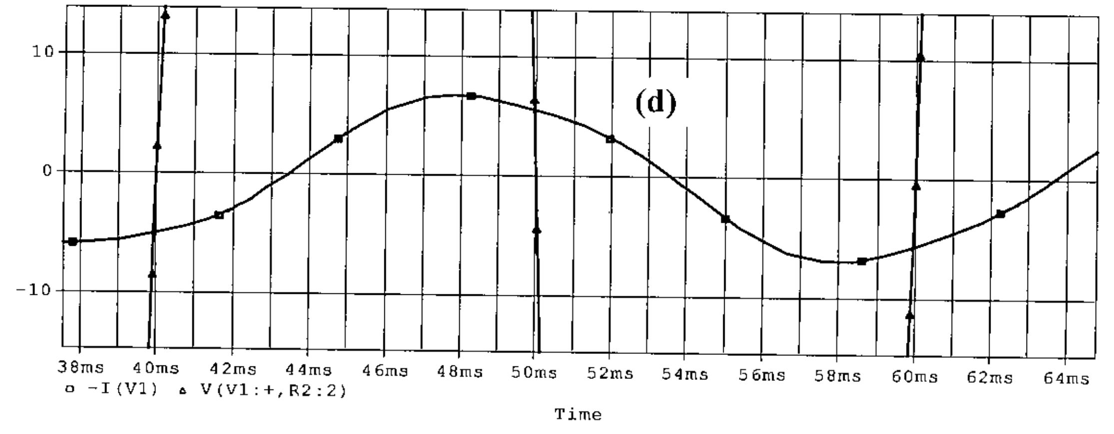


Figure-2.12(d) v_{in} and i_{in}; Close-up view showing **Power Factor = 0.85**; (L_{out} = 10mH, C_{out} = 500μF, R = 100Ω , C_{in} = 50μF, L_{in1} = 200mH and L_{in2} = 1mH).

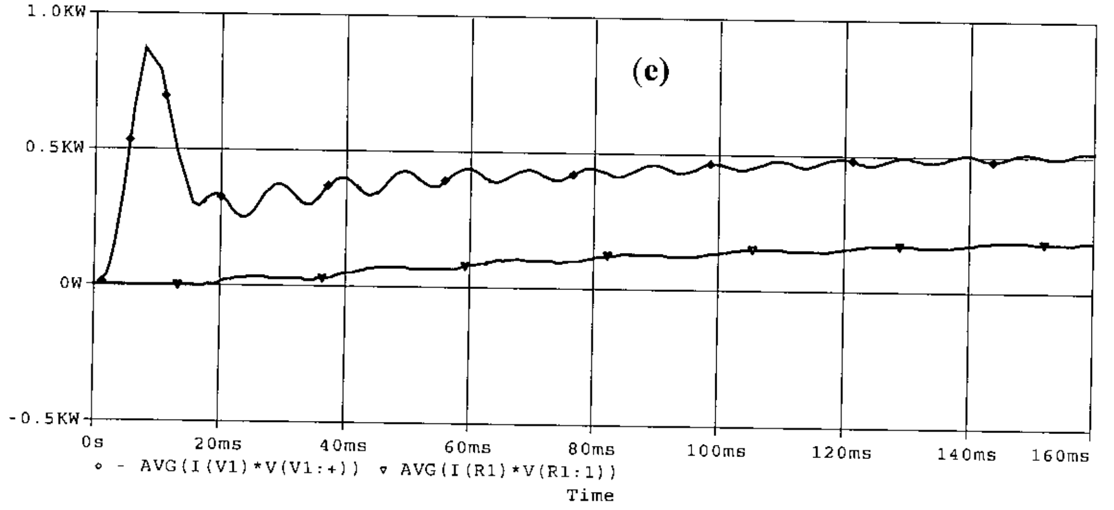


Figure-2.12(e) Average P_{in} and P_{out}; **Efficiency = 32%** (approx.); (L_{out} = 10mH, C_{out} = 500μF, R = 100Ω , C_{in} = 50μF, L_{in1} = 200mH and L_{in2} = 1mH).

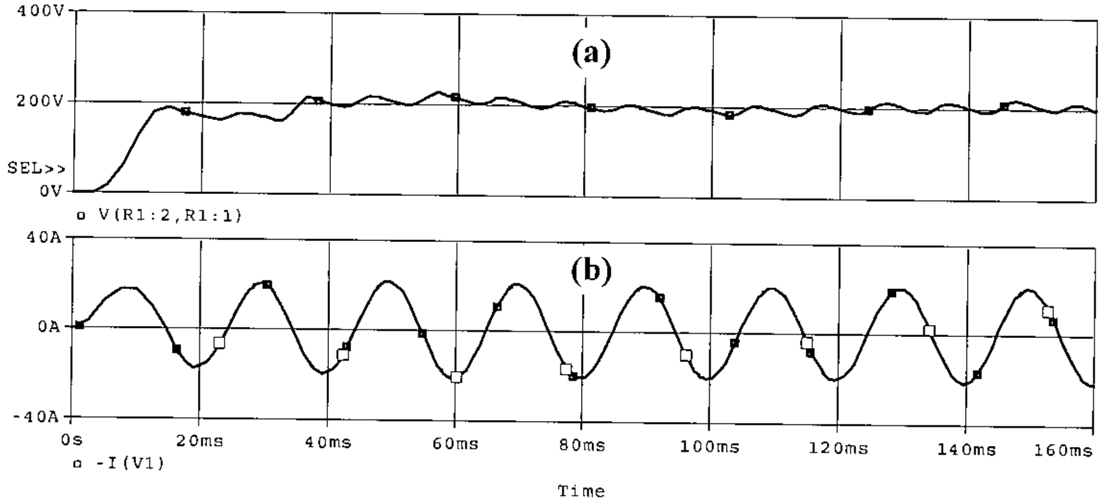


Figure-2.13(a) Output voltage and
(b) Input Current; (C_{in} = 300μF, L_{in1} = 80mH and L_{in2} = 1mH).

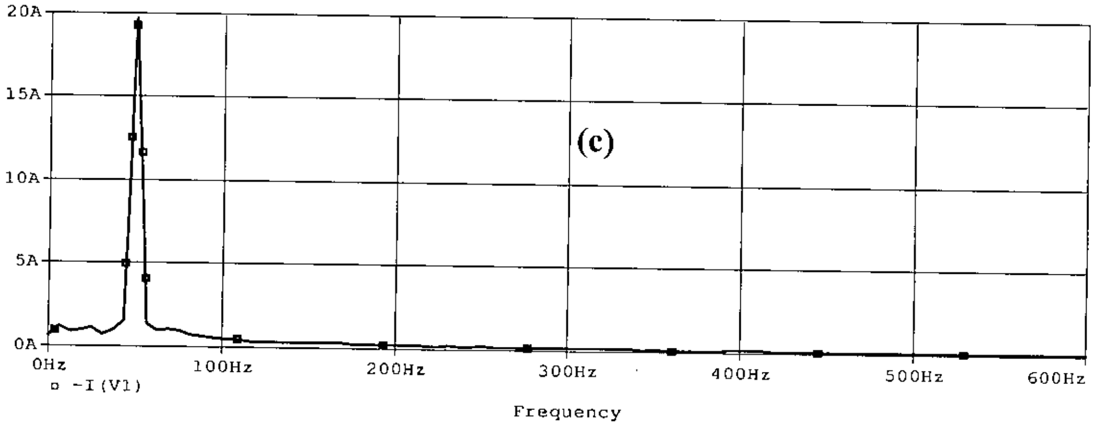


Figure-2.13(c) Input Current harmonics; (L_{out} = 10mH, C_{out} = 500μF, R=100Ω , C_{in} = 300μF, L_{in1} = 80mH and L_{in2} = 1mH).

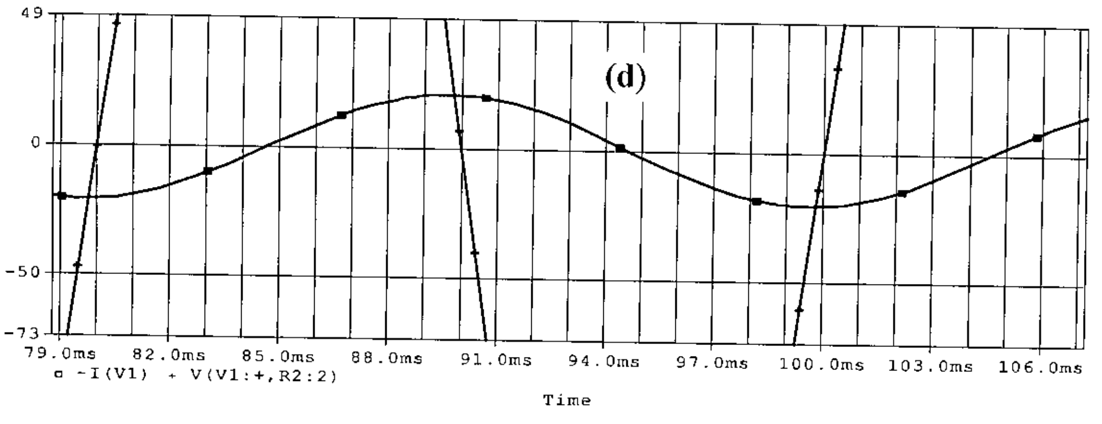


Figure-2.13(d) v_{in} and i_{in}; Close-up view showing **Power Factor = 0.75**; (L_{out} = 10mH, C_{out} = 500μF, R = 100Ω , C_{in} = 300μF, L_{in1} = 80mH and L_{in2} = 1mH).

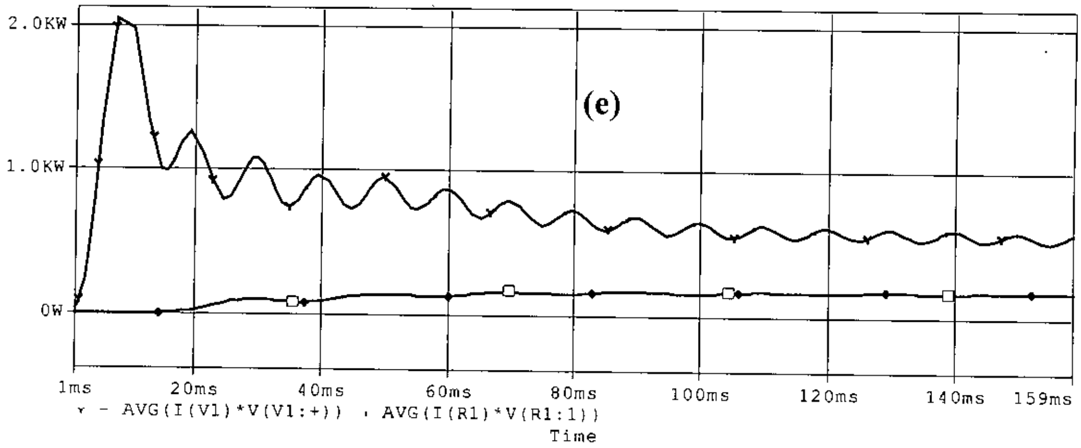


Figure-2.13(e) Average P_{in} and P_{out}; **Efficiency = 32%** (approx.); (L_{out} = 10mH, C_{out} = 500μF, R = 100Ω , C_{in} = 300μF, L_{in1} = 80mH and L_{in2} = 1mH).

From these simulation results we find that the shape of input current and output voltage ripple improves after using LC-filter at the input stage of the rectifier with the cost of deteriorating input power factor. It is also found that only odd harmonic contents are dominating in input current spectrum, since the waveform is symmetrical about the X-axis.

The input current magnitude depends on the input L and C combination. At lower values of input inductor the input current becomes leading providing a higher output voltage than input voltage. Efficiency found in these observations are not satisfactory though THD in input current is in tolerable limit. To achieve a good combination of input-output passive filter we have to use large inductors and capacitors as filter component which will make the physical device bulky in size. Regulation of output voltage is also not possible with the help of passive filters.

The observations made from simulated studies in Section-2.3.4 are listed in the ***Table-2.2.***

Table – 2.2: Input current, Output voltage and THD at different Input filter values when L_{out} = 10mH, C_{out} = 500μF, R = 100Ω:

	L_{in1} = 100mH, L_{in2} = 10mH, C_{in} = 500μF	L_{in1} = 200mH, L_{in2} = 1mH, C_{in} = 50μF	L_{in1} = 80mH, L_{in2} = 1mH, C_{in} = 300μF	L_{in1} = 20mH, L_{in2} = 1mH, C_{in} = 200μF
I_1	**11.4 A**	**6.25 A**	**19.5 A**	**27.8 A**
I_2	0.3 A	180 mA	0.47 A	1.4 A
I_3	180 mA	260 mA	0.31 A	1.1 A
I_4	142 mA	68 mA	0.21 A	0.37 A
I_5	120 mA	76 mA	0.23 A	0.21 A
I_6	100 mA	46 mA	0.15 A	0.20 A
I_7	98 mA	25 mA	0.11 A	0.10 A
I_8	52 mA	37 mA	0.12 A	0.096 A
I_9	60 mA	20 mA	0.1 A	0.14 A
I_{10}	56 mA	28 mA	0.098 A	0.16 A
I_{11}	60 mA	30 mA	0.095 A	0.13 A
%THD	**3.82%**	**5.46%**	**3.59%**	**6.70%**
Power Factor	**0.7 lagging**	**0.85 lagging**	**0.75 lagging**	**0.85 leading**
$V_{dc\,(avg)}$ (approx.)	**65 V**	**210 V**	**200 V**	**430 V**
%Efficiency (approx.)	**28%**	**40%**	**32%**	**42%**

From the Table-2.2 and corresponding figures (from Fig.-2.10 to Fig.-2.13) it is observed that different combination of LC filters, used in the input side of the rectifier, provide different THD and power factors. Almost all these configurations have THD within or near to specified limit but they have input power factor in the order of 0.7 or 0.8 and also have poor rectification efficiency.

2.4 Active Power Factor Correction (PFC)

In active power factor correction method, static 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 choice of the active power electronic converter is based on the following consideration:

- In general, electrical isolation between the utility input and the output of the power electronic system (e.g. rectifier) either is not needed (e.g. in ac and dc motor drives) or it can be provided in the second converter stage, as in the switch-mode dc power supplies.
- In most applications it is acceptable, and in many cases desirable, to stabilize the dc voltage V_{dc} slightly in excess of the peak of the maximum of the ac input voltage.
- The input current drawn should ideally be at a unity power factor so that the power electronic interface emulates a resistor supplied by the utility source. This also implies that the power flow is always unidirectional, from the utility source to the power electronic equipment.
- The cost, power losses, and size of the current shaping circuit should be as small as possible.

Based on these considerations, a line-frequency transformer isolation is ruled out. The output voltage is usually regulated for variations. According to switching frequency used, active PFC solutions may be classified into low-frequency and high-frequency active PFC circuits. In most cases it is acceptable to have $V_d > V_{s(max)}$, where $V_{s(max)}$ is the peak of ac input voltage; so current shaping circuit in that case is a step-up *(boost)* dc-dc converter. We can also use a *buck* converter, then the output voltage will be lower and while using a *buck-boost* converter output voltage can be either higher or lower than $V_{s(max)}$

2.4.1 Active Input Current Shaping: Principle of Operation

The principle of operation of active input current shaping is straightforward. At the utility input, the current i_s is desired to be sinusoidal and in phase with v_s as shown in Figure-2.14(b). Therefore, at the full-bridge rectifier output in Figure-2.14(a) have the same waveform as shown in Fig-2.14(c). In practice the power losses in the rectifier bridge and the step-up dc-dc converter are fairly small. These are neglected in the following study.

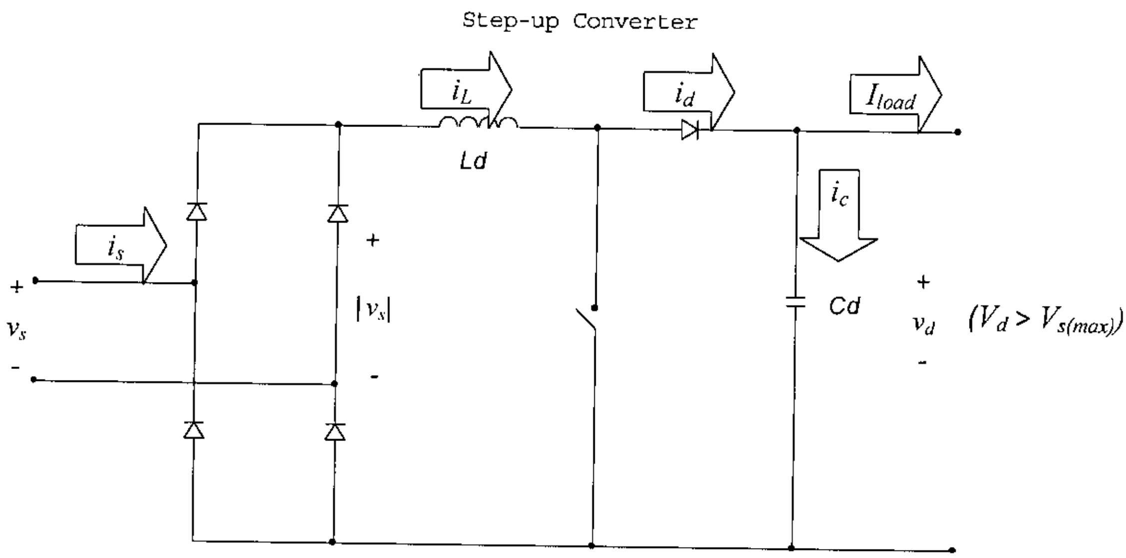


Figure-2.14(a) Schematic of Active PFC using Step-up Converter.

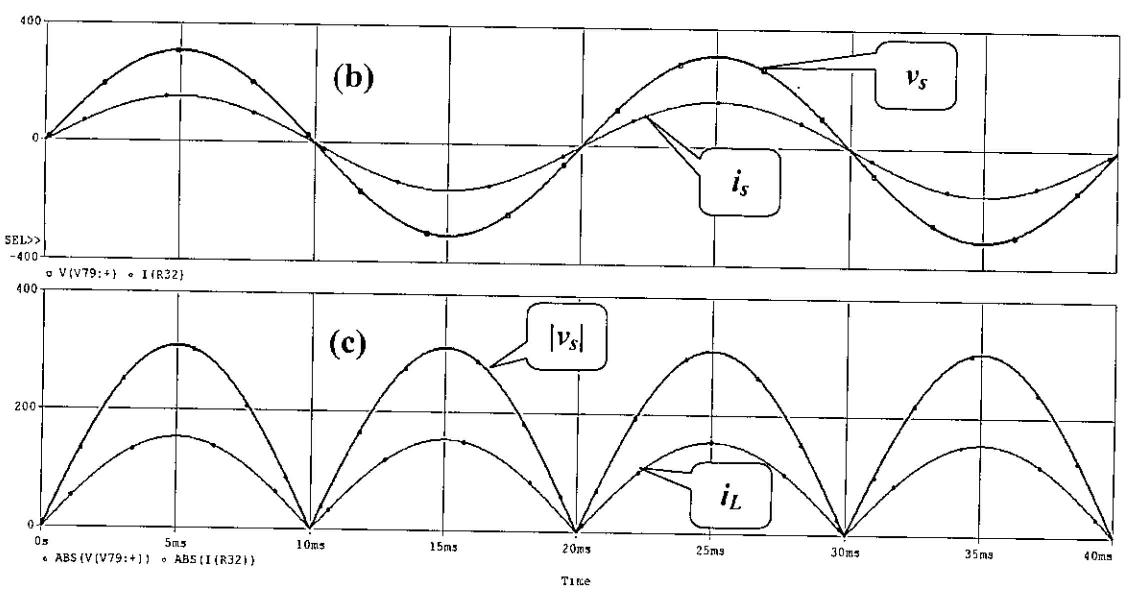


Figure-2.14(b) line voltage and Current, (c) v_s and i_L waveforms.

From the figures 2.14(a)-(c), the iput power $p_{in}(t)$ from ac source is,

$$p_{in}(t) = V_{s(max)}|sin\ \omega t|.\ I_{s(max)}|sin\ \omega t|$$

$$= V_s I_s - V_s I_s cos2\omega t \text{ ; where, } V_s, I_s \text{ are rms input values.} \qquad 2.14$$

Because of a fairly large capacitance C_d, the voltage v_d can be initially assumed to be dc. That is, $v_d(t) = V_d$. Therefore, the output power is,

$$p_d(t) = V_d i_d(t) \qquad 2.15$$

From Fig-2.14a $$i_d(t) = I_{load} + i_c(t) \qquad 2.16$$

If the step-up converter in Fig-2.14a is idealized and can be assumed to be operating at a switching frequency approaching infinity, then required inductance L_d would be negligibly small. This allows the assumption that,

$$p_{in}(t) = p_d(t)$$

$$or, \quad V_s I_s - V_s I_s cos2\omega t = V_d\ i_d(t)$$

$$or, \quad i_d(t) = \frac{Vs\ Is}{Vd} - \frac{Vs\ Is}{Vd}\ cos2\omega t \qquad 2.17$$

now from Eq-2.16 and Eq-2.17 we get the average value of i_d as,

$$I_d = I_{load} = \frac{Vs\ Is}{Vd}\ , \qquad 2.18$$

and the current through the capacitor as,

$$i_c(t) = -\frac{Vs\ Is}{Vd}\ cos2\omega t = -I_d\, cos2\omega t. \qquad 2.19$$

Even though this analysis is carried out by assuming the voltage across the capacitor to be ripple-free dc, the ripple in v_d can be estimated from the above relation of $i_c(t)$ as,

$$v_{d,ripple}(t) \approx \frac{1}{Cd}\int ic\ dt = \frac{Id}{2\omega Cd}\ sin2\omega t \qquad \text{Eq-2.20}$$

which can be kept low by selecting a suitably large value of C_d . A series-tuned LC filter tuned for twice the ac frequency according to Eq-2.20 may be put in parallel with C_d to minimize the ripple in the dc voltage. In this case, the switching frequency components of currents in i_d and the high frequency components in the load current will also flow through C_d.

Since the input current to the step-up converter is to be shaped, the step-up converter usually is operated in a current-regulated mode. There are various ways to implement the current-mode control of the step-up converter such as,

a) Constant frequency control,
b) Constant tolerance-band control,
c) Variable tolerance-band control and
d) Discontinuous current control.

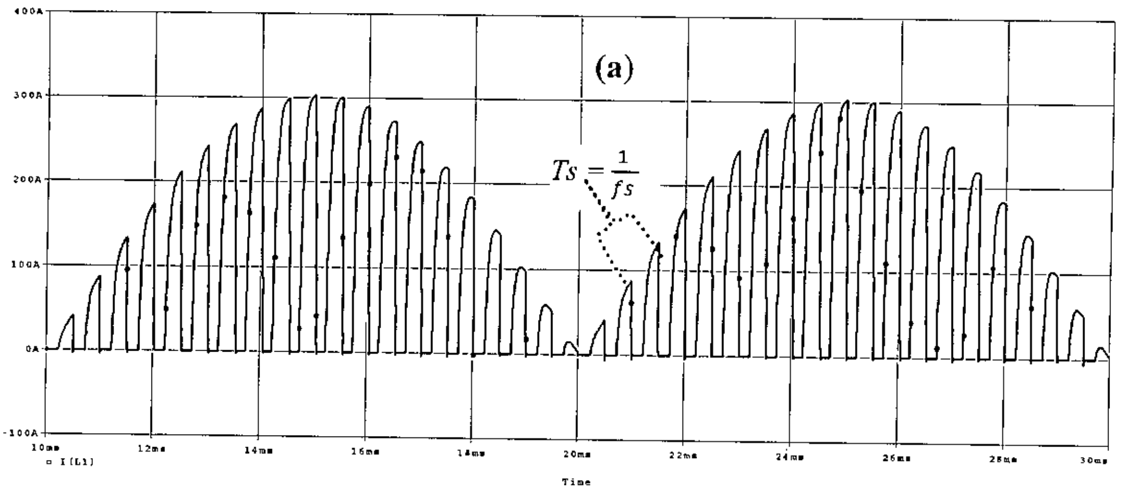


Figure-2.15(a) waveform of i_L (showing a full line voltage period = 20 mille-sec)

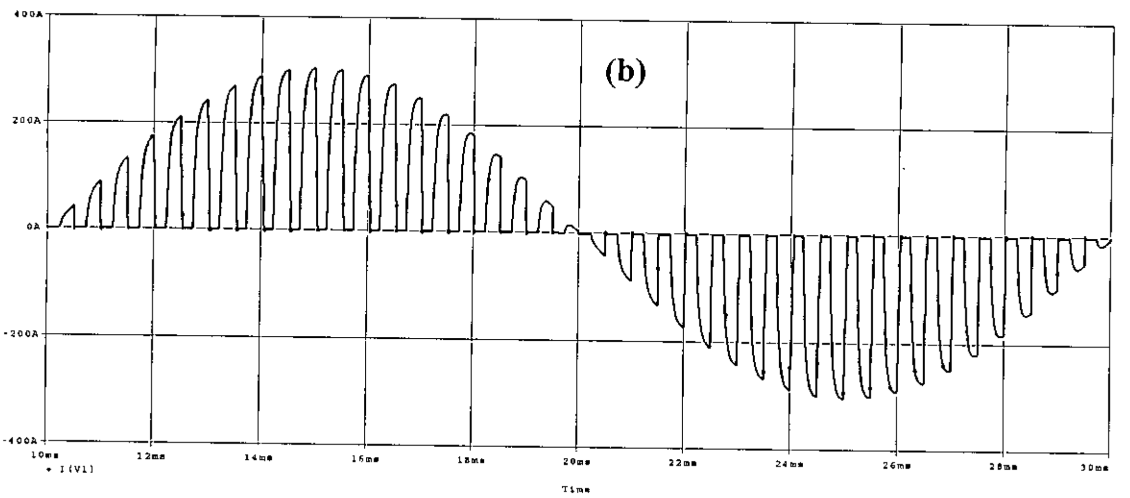


Figure-2.15(b) waveform of i_s in Constant Frequency Control (f_s = 2kHz).

Out of these the first one – Constant frequency control is easier and effective one. Here, the switching frequency f_s is kept constant. When i_L reaches the value i_L^* (i_L^* is the reference or desired value of i_L), the switch in the step-up converter is turned-off. The switch is turned on by a clock at a fixed frequency f_s, which results in i_L as shown in Fig-2.15(a).

During a switching-frequency time period T_s, the output voltage is assumed to be constant as V_d and the input voltage to the step-up converter is assumed to be constant at that instant of time; I_{ripple} is the peak-to-peak ripple current around the envelop during one time period of the switching frequency. From Fig-2.14(a) and ***"volt-second balance"*** of an inductor the following equations can be written as,

$$t_{on} = \frac{Ld\ Iripple}{|vs|}, \qquad 2.21$$

$$and, \quad t_{off} = \frac{Ld\ Iripple}{Vd-|vs|}. \qquad 2.22$$

where, t_{on} is the on-interval and t_{off} is the off-interval of the switch. Thus the switching frequency f_s can be expressed as,

$$f_s = \frac{1}{Ts} = \frac{1}{ton+toff}$$

$$or, \quad f_s = \frac{(Vd-|vs|).|vs|}{Ld.Iripple.Vd} \qquad 2.23$$

in a constant-frequency control scheme, f_s is constant and hence,

$$I_{ripple} = \frac{(Vd-|vs|).|vs|}{Ld.fs.Vd} \qquad 2.24$$

$$or, \quad I_{ripple} = \frac{\left(1-\frac{|vs|}{Vd}\right).\frac{|vs|}{Vd}}{Ld.fs} \qquad 2.25$$

from Equation-2.25 it is obvious that in a step-up converter $\frac{|vs|}{Vd}$ must be *less than* or *equal to* 1 which requires,

$$\frac{|vs|}{Vd} \leq 1 \qquad \text{or,} \qquad |v_s| \leq V_d \qquad 2.26$$

From Equation-2.24 the maximum ripple current is given as,

$$I_{ripple(max)} = \frac{Vd}{4.Ld.fs}; \quad when\ |v_s| = 0.5\ V_d \qquad 2.27$$

2.4.2 Active Input Current Shaping by Boost Regulator and no input LC filter :

In active input current shaping technique using boost regulator, a boost converter is placed between input and output stage of a full-bridge rectifier. Usually high switching frequency (in this experiment we used $f_s = 40\ kHz$) is used to operate the boost switch S_b in order to reduce the size of L, C components. In this section no input passive filter is used.

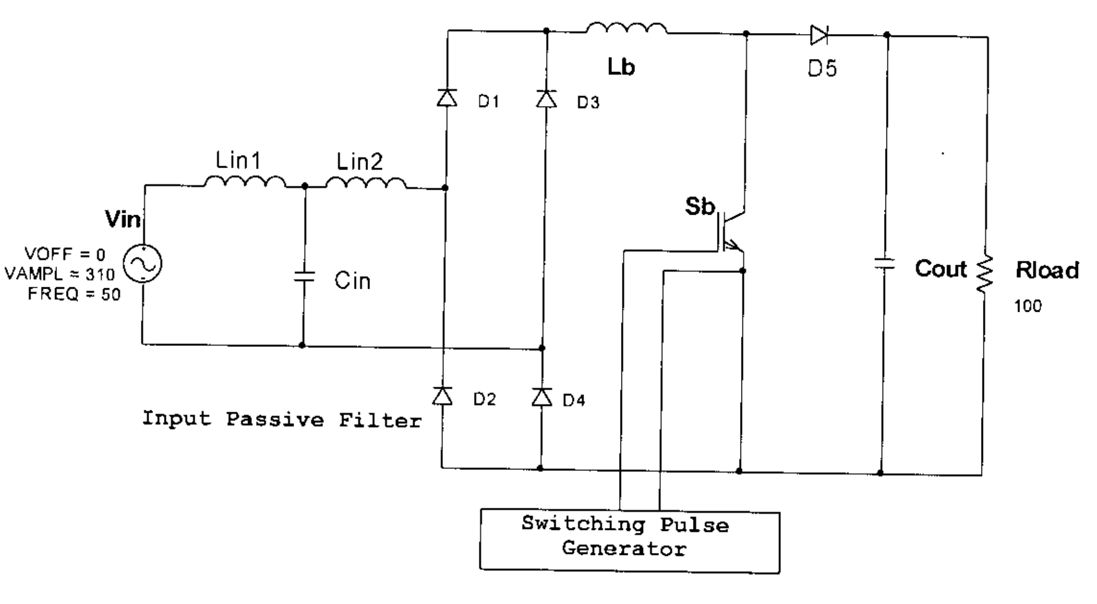


Figure-2.16 Schematic of a full-bridge rectifier with Boost regulator with resistive load.

The input current here starts to conduct in discontinuous conduction mode and the wave shape follows the input voltage but have high frequency harmonics. Figures 2.16-2.18 show the effect of changing the duty cycle of the boost switch at different stages.

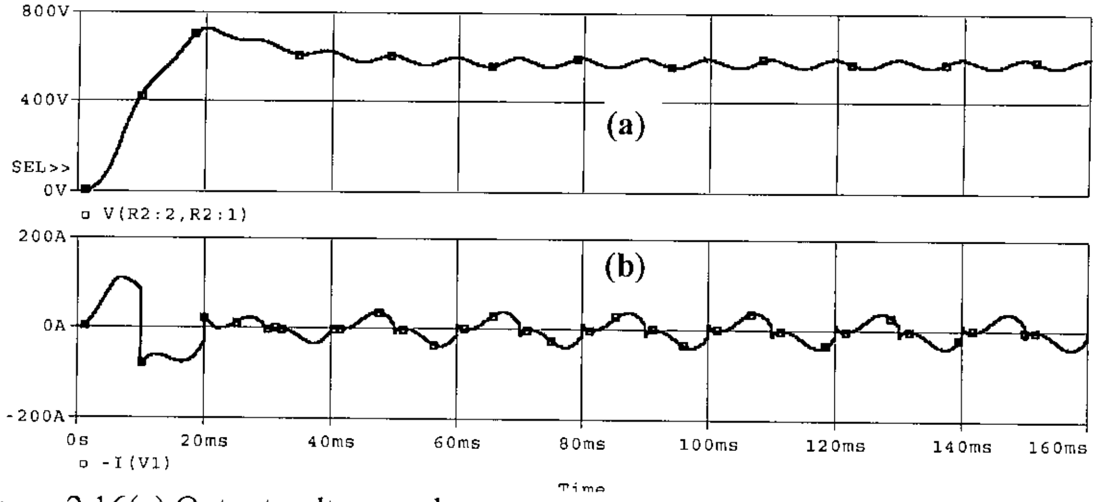


Figure-2.16(a) Output voltage and

(b) Input Current; (L_b = 10mH, C_{out} = 500μF, R=100Ω , $\mathbf{T_{on}}$ = **7μsec**, Period = 25μsec and f_s = 40kHz).

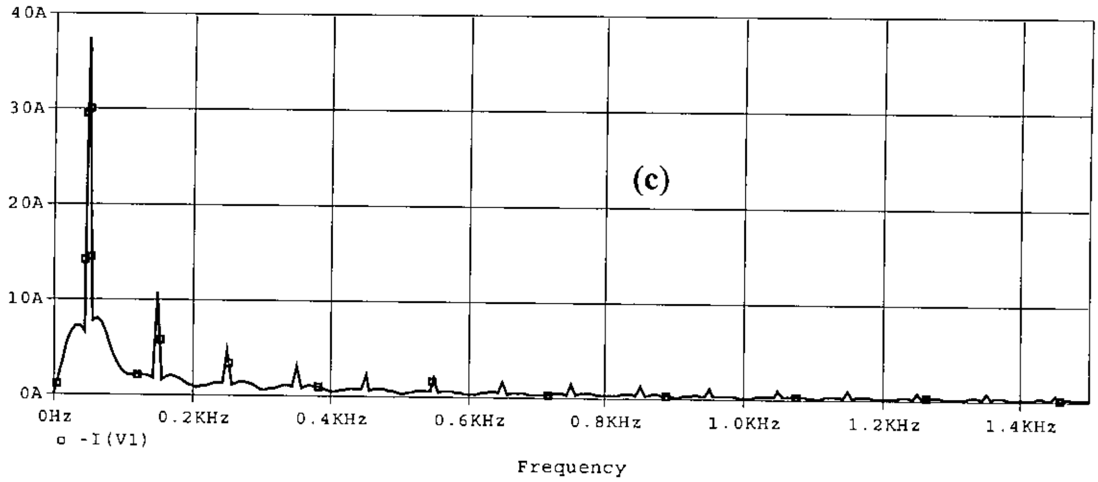


Figure-2.16(c) Input Current harmonics; (L_b = 10mH, C_{out} = 500μF, R=100Ω , $\mathbf{T_{on}}$ = **7μsec**, Period = 25μsec and f_s = 40kHz).

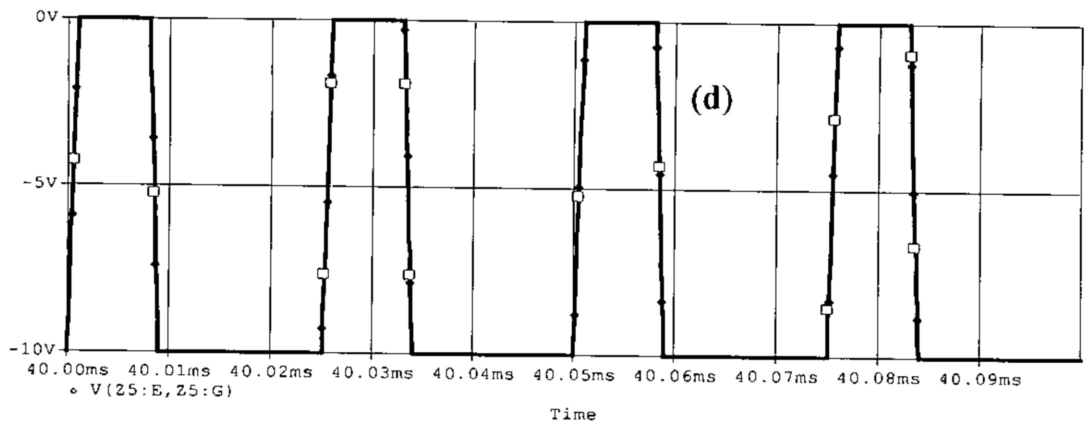


Figure-2.16(d) Gate pulse of Boost switch; ($\mathbf{T_{on}}$ = **7μsec**, Period = 25μsec).

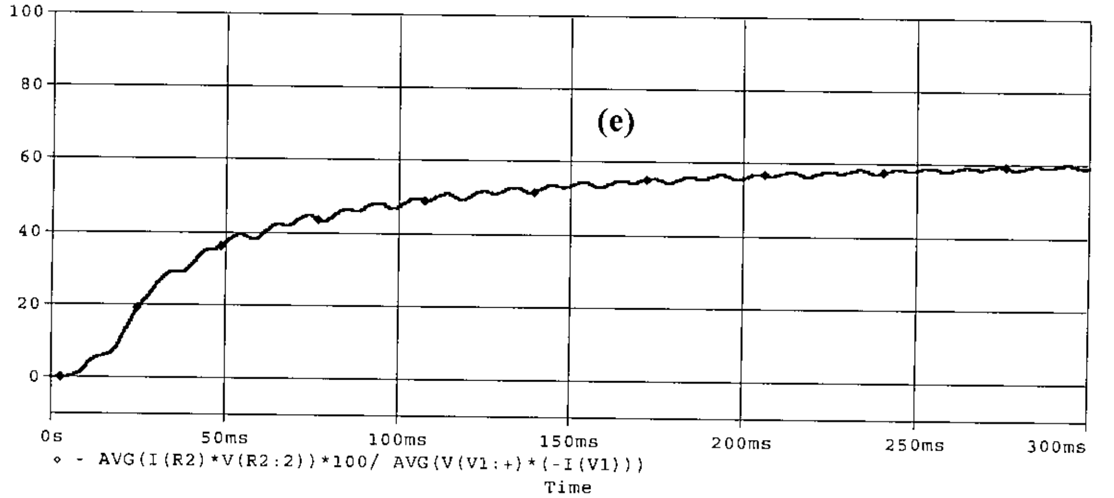


Figure-2.16(e) Average P_{in} and P_{out}; Efficiency = **60%** (approx.); (L_b = 10mH, C_{out} = 500μF, R=100Ω , $\mathbf{T_{on}}$ = **7μsec**, Period = 25μsec and f_s= 40kHz).

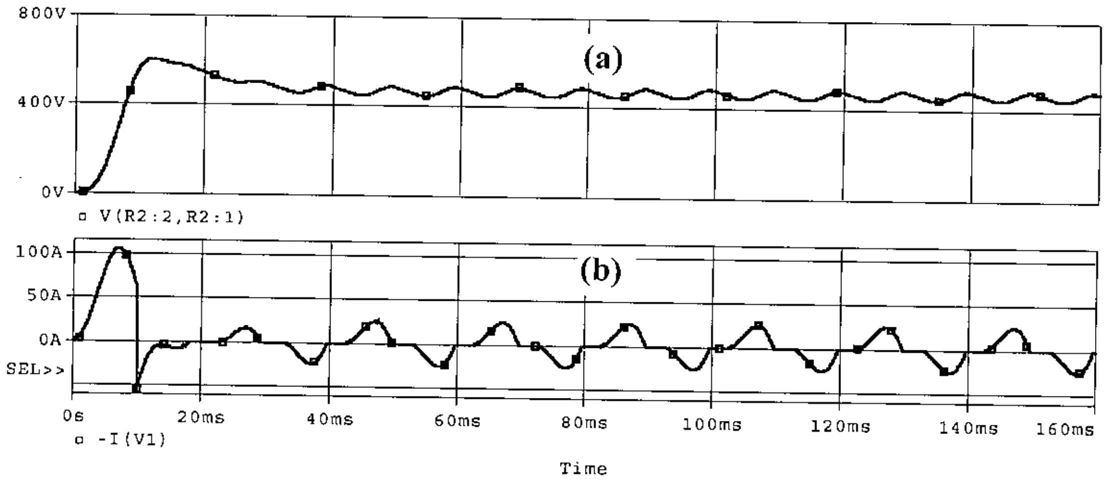


Figure-2.17(a) Output voltage and
(b) Input Current; (L_b = 10mH, C_{out} = 500μF, R=100Ω , T_{on} = 11μsec, Period = 25μsec and f_s= 40kHz).

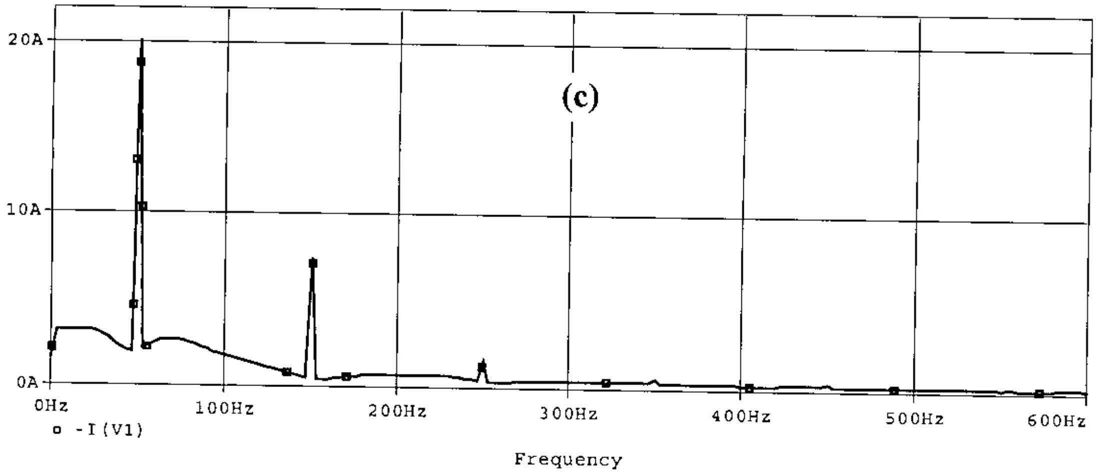


Figure-2.17(c) Input Current harmonics; (L_b = 10mH, C_{out} = 500μF, R=100Ω , $\mathbf{T_{on}}$ = **11μsec**, Period = 25μsec and f_s= 40kHz).

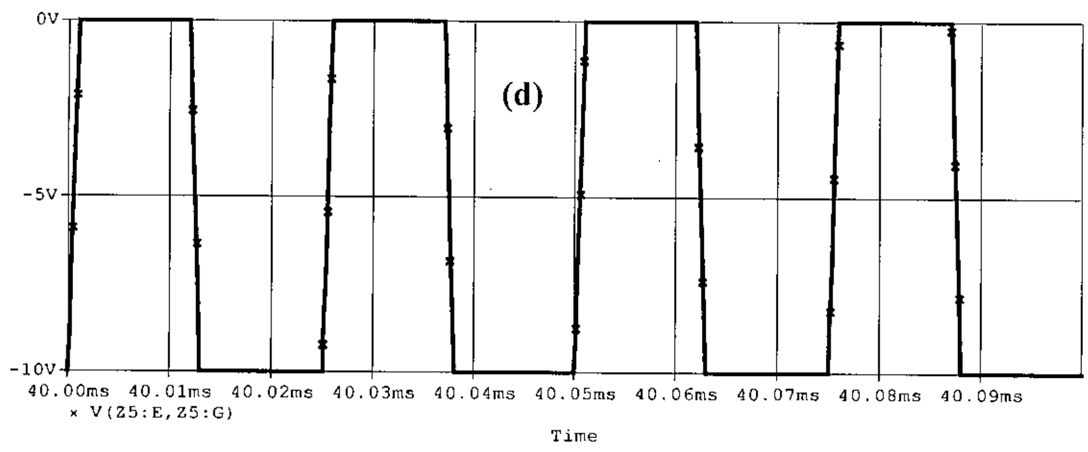


Figure-2.17(d) Gate pulse of Boost switch; (**T_{on} = 11μsec**, Period = 25μsec).

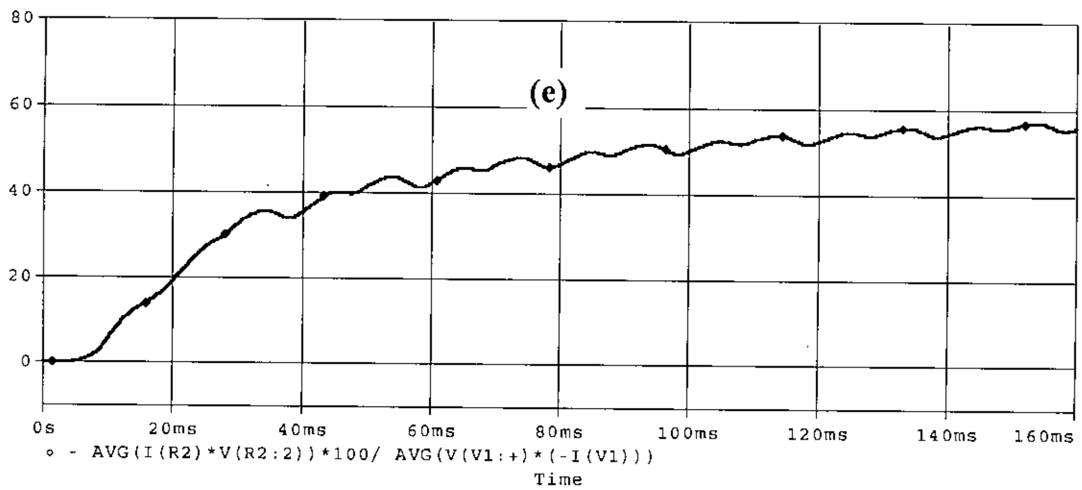


Figure-2.17(e) Average P_{in} and P_{out}; **Efficiency = 56%** (approx.); (L_b = 10mH, C_{out} = 500μF, R=100Ω , **T_{on} = 11μsec**, Period = 25μsec and f_s = 40kHz).

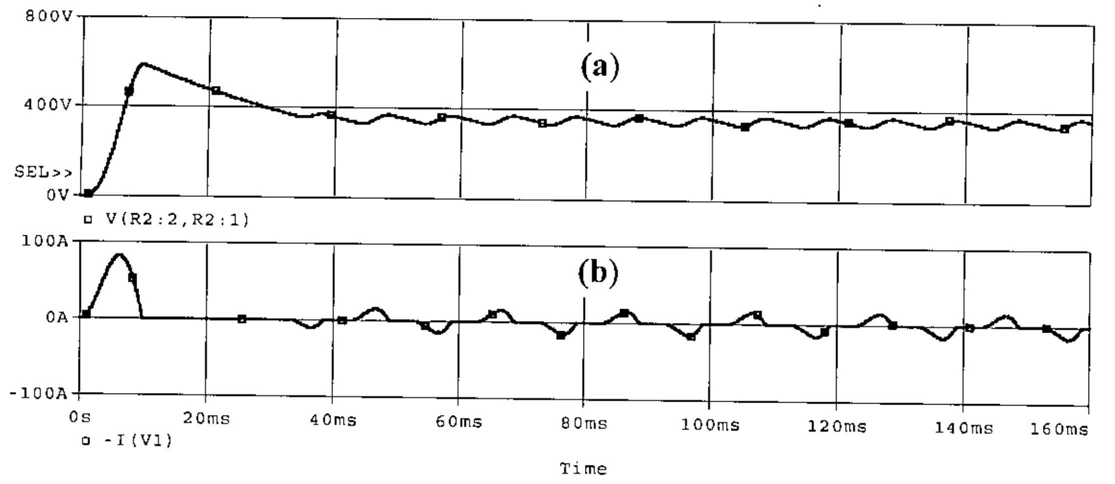


Figure-2.18(a) Output voltage and
(b) Input Current; (L_b= 10mH, C_{out}= 500μF, R=100Ω , $\mathbf{T_{on}}$ **= 17μsec**, Period= 25μsec and f_s= 40kHz).

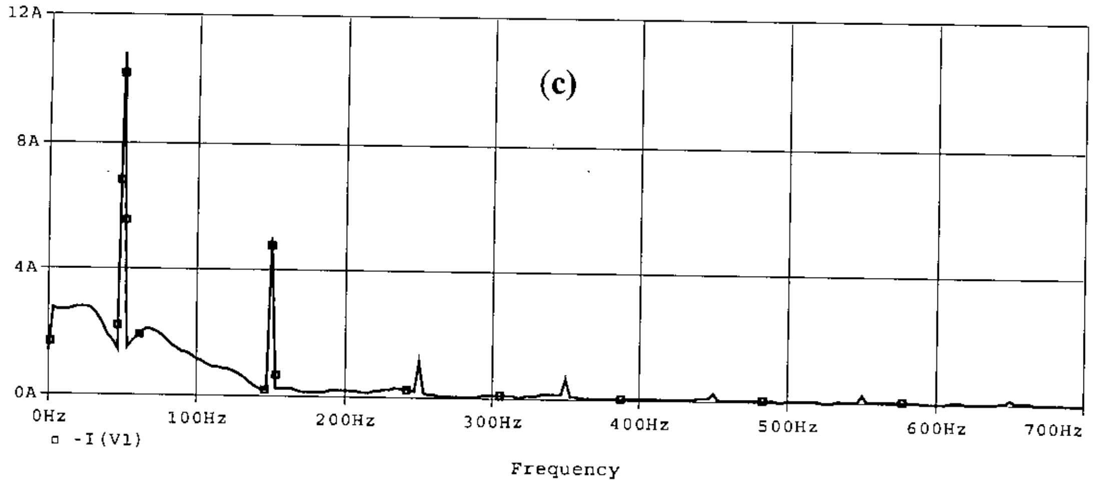


Figure-2.18(c) Input Current harmonics; (L_b= 10mH, C_{out}= 500μF, R=100Ω , $\mathbf{T_{on}}$ **= 17μsec**, Period= 25μsec and f_s= 40kHz).

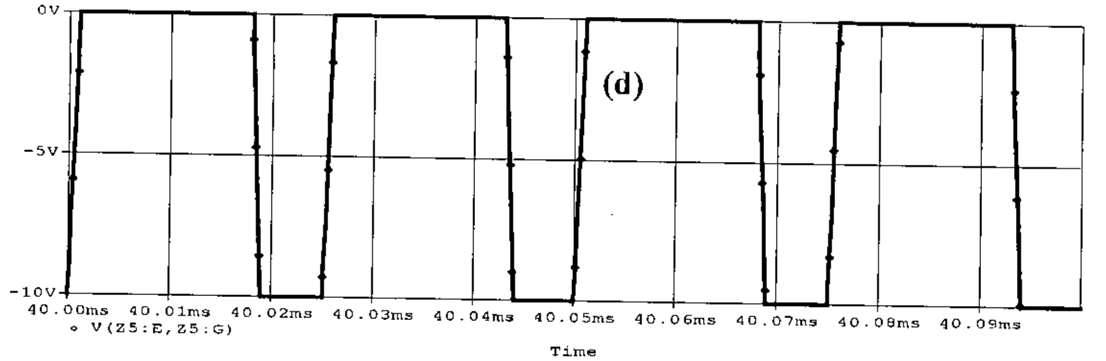


Figure-2.18(d) Gate pulse of Boost switch; ($\mathbf{T_{on}}$ **= 17μsec**, Period= 25μsec).

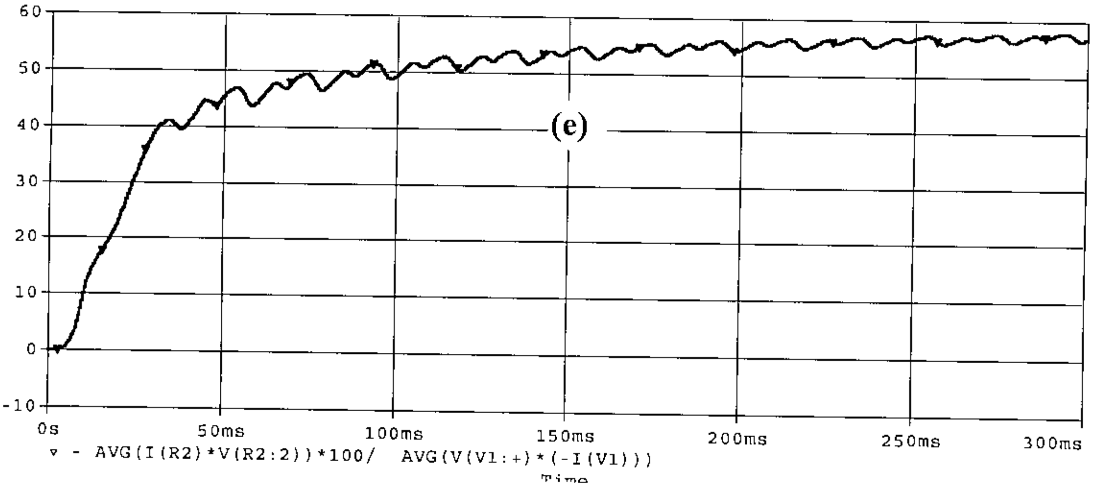


Figure-2.18(e) Average P_{in} and P_{out}; **Efficiency = 57%** (approx.); (L_b= 10mH, C_{out} = 500μF, R=100Ω , $\mathbf{T_{on}}$ **= 17μsec**, Period= 25μsec and f_s= 40kHz).

2.4.3 Boost Regulator with input-output filter :

In order to improve the input current wave-shape of the boost regulated rectifier, input passive filter is added as shown in Figure-2.19. Simulated waveforms and their spectrum are shown in Figs-2.19-2.21 for various duty cycles. In Fig-2.19 the Boost Converter is placed at the input side of the line.

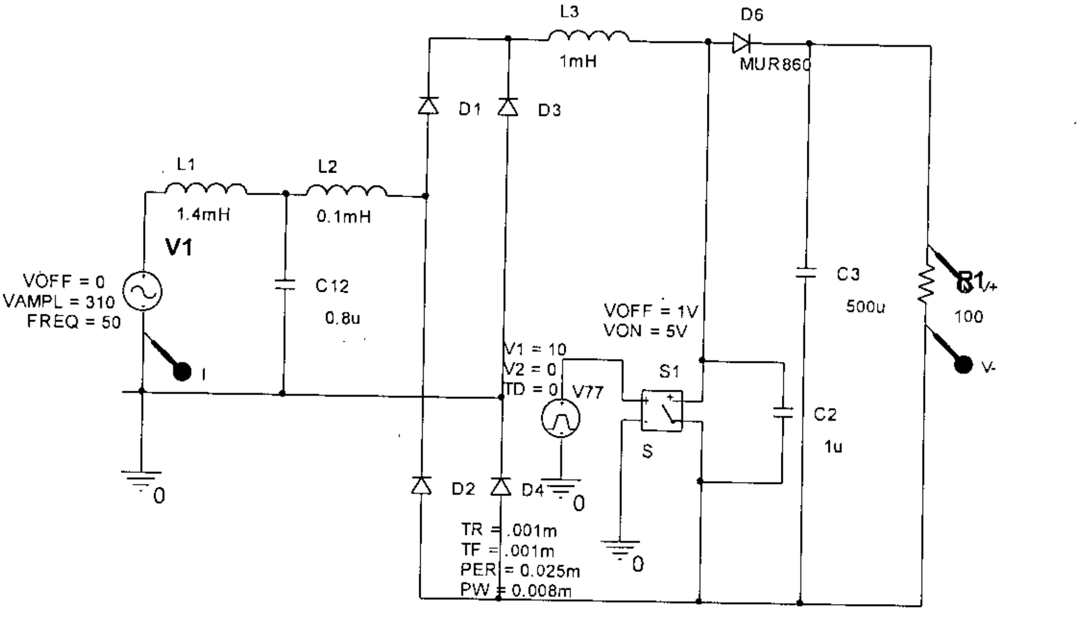


Fig.-2.19 Schematic of a Boost rectifier with input-output filter and resistive load.

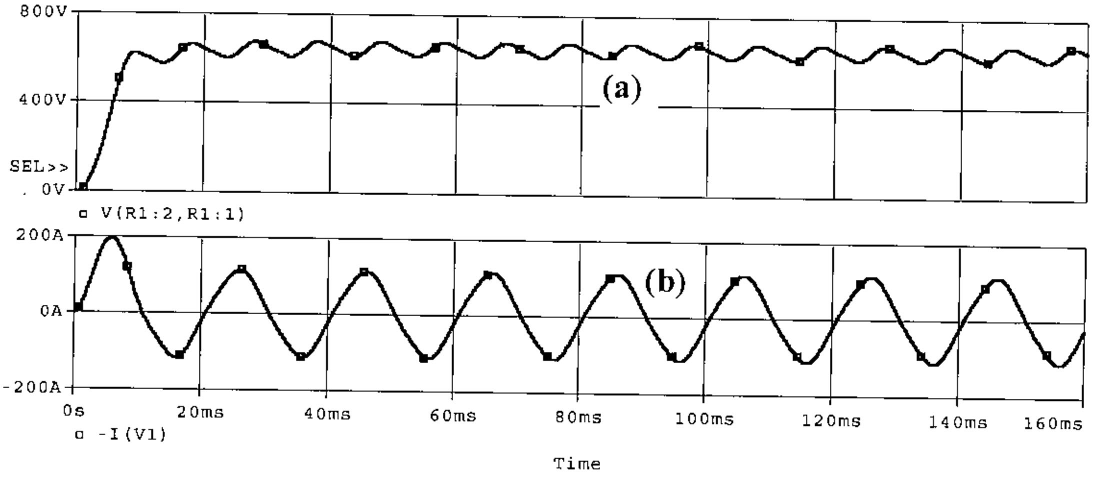


Figure-2.19(a) Output voltage and
(b) Input Current found from the circuit shown above; (C_{out} = 500μF, R=100Ω , $\mathbf{T_{on}}$ = **8μsec**, Period = 25μsec and f_s= 40kHz).

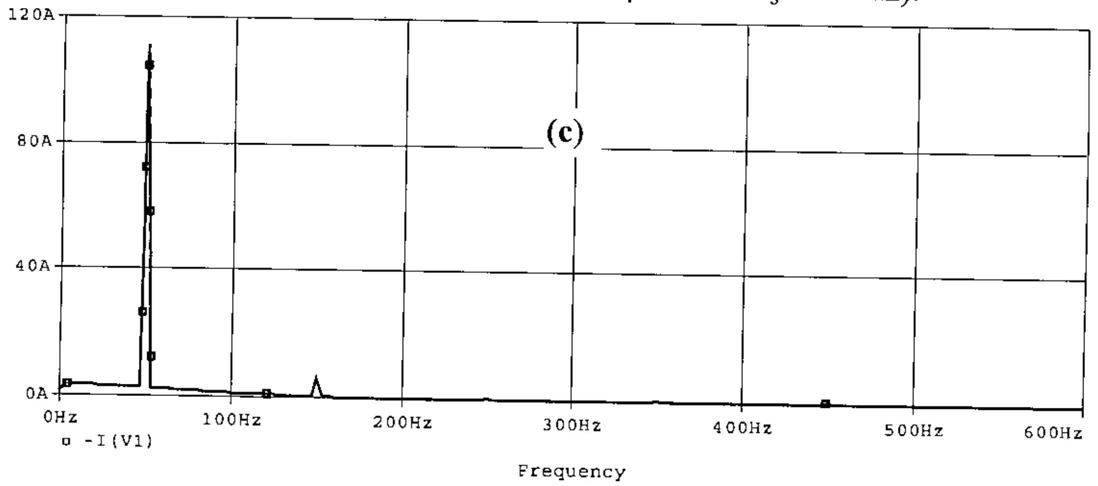


Figure-2.19(c) Input Current harmonics for the circuit shown above, THD = 5.35%; (C_{out} = 500μF, R=100Ω , $\mathbf{T_{on}}$ = **8μsec**, Period = 25μsec and f_s= 40kHz).

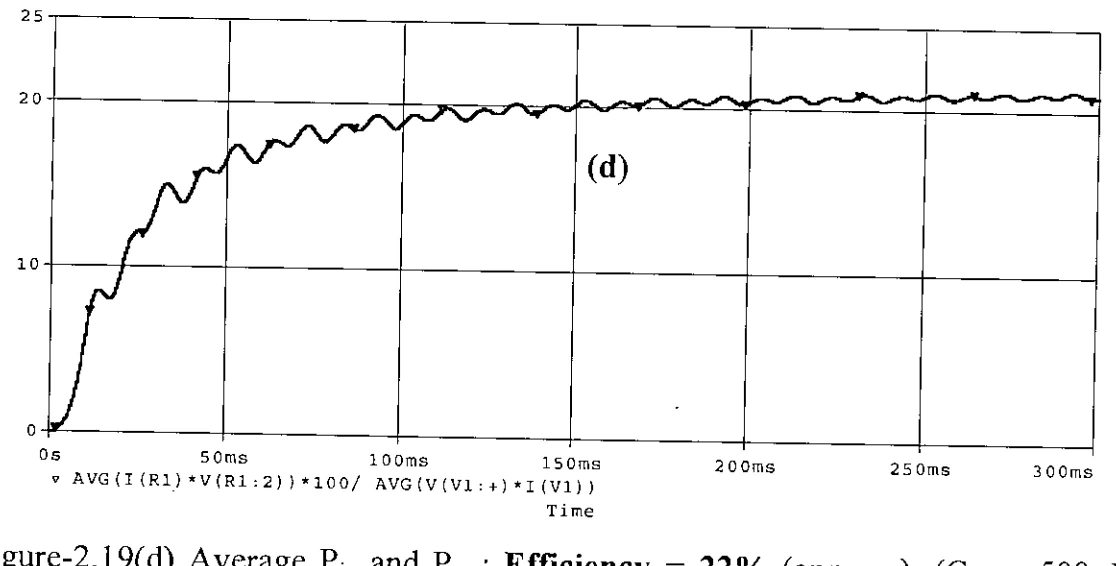


Figure-2.19(d) Average P_{in} and P_{out}; **Efficiency = 22%** (approx.); (C_{out} = 500μF, R=100Ω , T_{on} = 8μsec, Period = 25μsec and f_s= 40kHz).

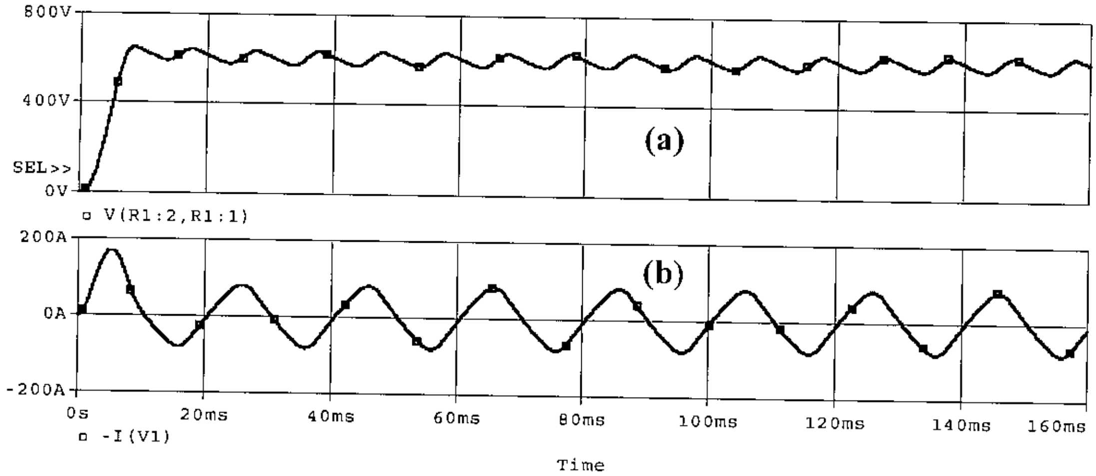


Figure-2.20(a) Output voltage and

(b)Input Current found from the circuit shown above; (C_{out} = 500μF, R=100Ω , $\mathbf{T_{on}}$ **= 11μsec**, Period = 25μsec and f_s= 40kHz).

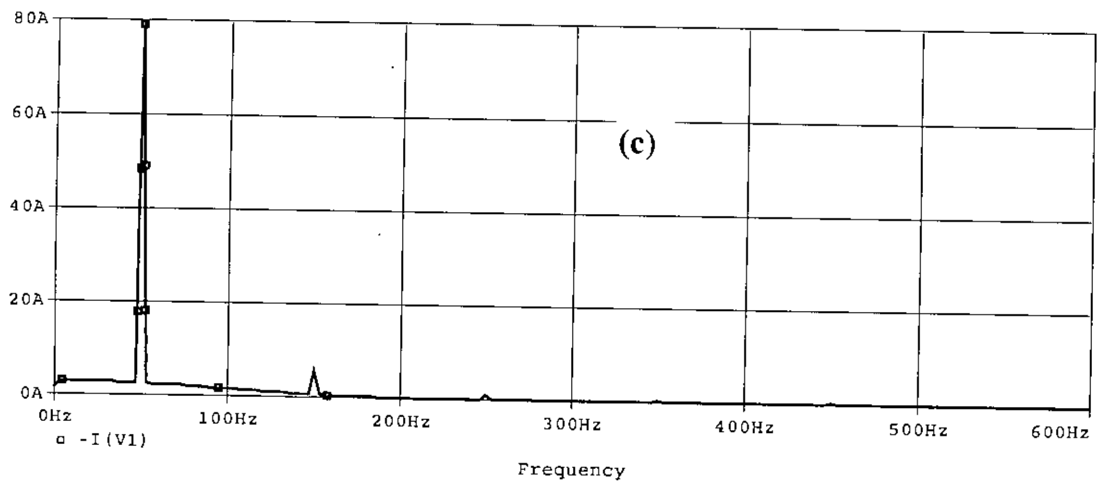


Figure-2.20(c) Input Current harmonics for the circuit shown above, THD = 7.08%; (C_{out} = 500μF, R=100Ω , $\mathbf{T_{on}}$ **= 11μsec**, Period = 25μsec and f_s= 40kHz).

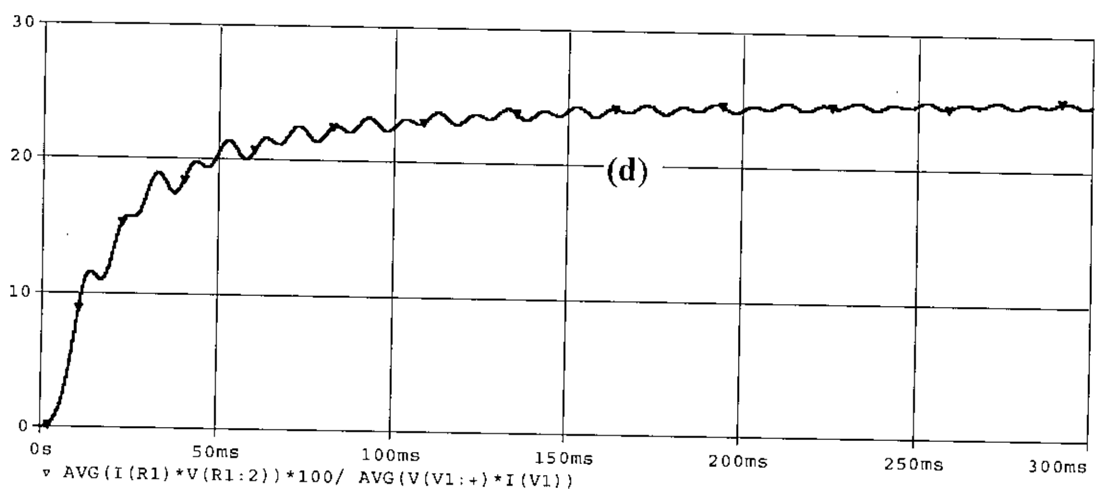


Figure-2.20(d) Average P_{in} and P_{out}; **Efficiency = 25%** (approx.); (C_{out} = 500μF, R=100Ω , $\mathbf{T_{on}}$ **= 11μsec**, Period = 25μsec and f_s= 40kHz).

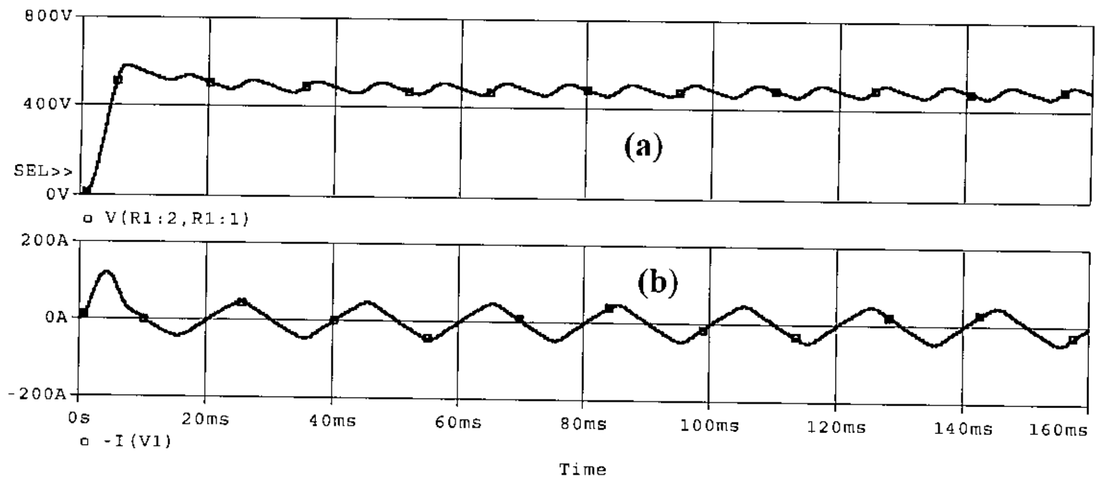


Figure-2.21(a) Output voltage and
(b)Input Current found from the circuit shown above; (C_{out} = 500μF, R=100Ω , $\mathbf{T_{on}}$ = **17μsec**, Period = 25μsec and f_s= 40kHz).

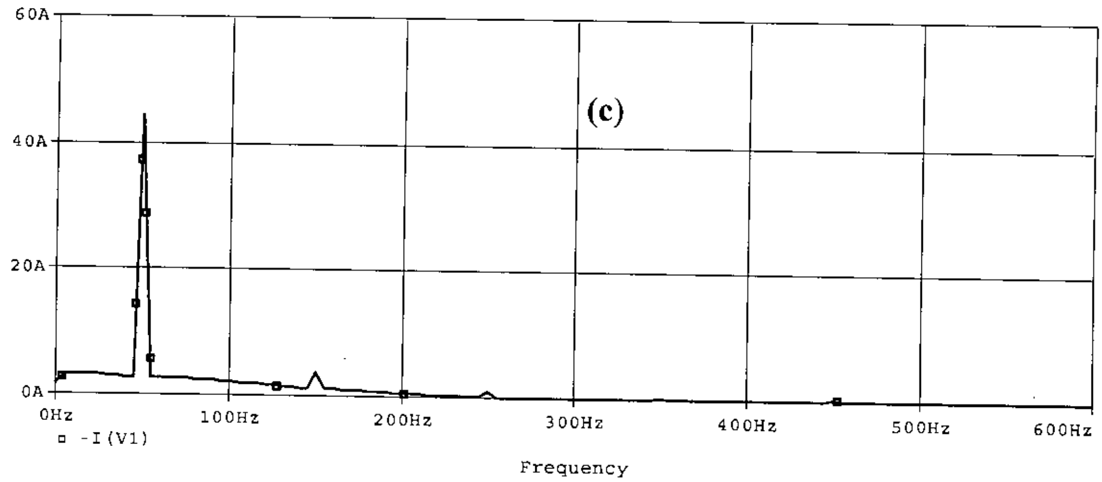


Figure-2.21(c) Input Current harmonics for the circuit shown above; (C_{out} = 500μF, R=100Ω , $\mathbf{T_{on}}$ = **17μsec**, Period = 25μsec and f_s= 40kHz).

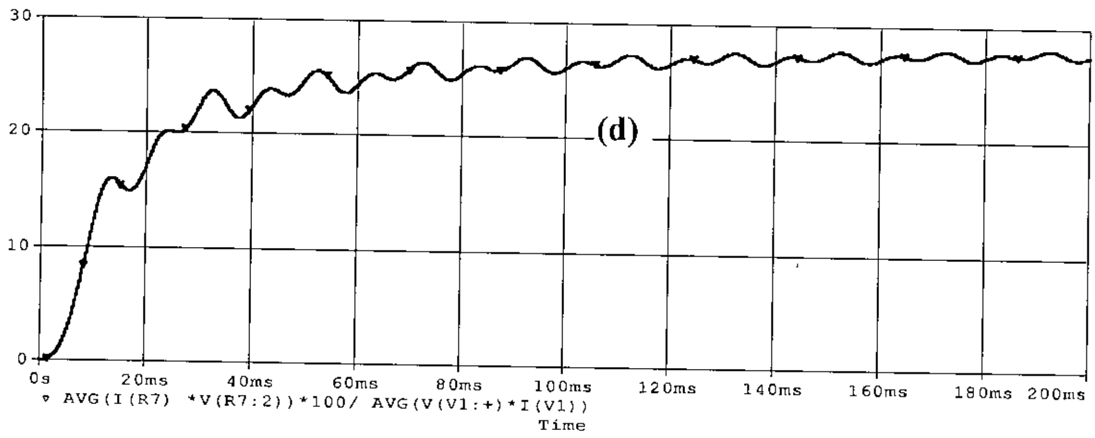


Figure-2.21(d) Average P_{in} and P_{out}; **Efficiency = 27%** (approx.); (C_{out} = 500μF, R=100Ω , $\mathbf{T_{on}}$ = **17μsec**, Period = 25μsec and f_s= 40kHz).

All these observations made from simulations (from fig-2.16 to fig-2.21) are provided in ***Table-2.3.***

Table – 2.3: Input current, Output voltage, THD and Efficiency at different values T_{on} of **Boost** switch:

	Boost circuit with no Input Filter			Boost Rectifier circuit with input-output filter		
	T_{on} = 7μsec	T_{on} = 11μsec	T_{on} = 17μsec	T_{on} = 8μsec	T_{on} = 11μsec	T_{on} = 17μsec
I_1	**38.95** A	**22** A	**12** A	**111** A	**80** A	**43.5 A**
I_2	2.5 A	2.25 A	2.1 A	1.1 A	1.6 A	1.45 A
I_3	10.5 A	7.58 A	4.8 A	5.8 A	5.3 A	3.55 A
I_4	0.4 A	0.52 A	0.18 A	0.05 A	0.05 A	0.4 A
I_5	4.85 A	1.51 A	1.1 A	0.56 A	1.2 A	1 A
I_6	0.25 A	0.5 A	0.22 A	0.06 A	0.04 A	0.05 A
I_7	3 A	0.72 A	0.26 A	0.27 A	0.2 A	0.14 A
I_8	0.3 A	0.48 A	0.15 A	0.07 A	0.03 A	0.005 A
I_9	2.45 A	0.5 A	0.21 A	0.28 A	0.15 A	0.013A
%THD	**32.41%**	**37.06%**	**44.8%**	**5.35%**	**7.08%**	**8.8%**
$V_{dc\,(avg)}$ (approx.)	**580 V**	**472 V**	**355 V**	**645 V**	**600 V**	**490 V**
Efficiency	**60%**	**56%**	**57%**	**22%**	**25%**	**27%**

From the above table it is found that total harmonic distortion in input current is reduced significantly with the addition of passive filter at input side and change in duty cycle affects very little on efficiency. In terms of efficiency boost circuits with input filter do not provide satisfactory result. Since a resistive load is considered for all configurations, almost all circuits provide power factor as good as unity.

In the active current shaping circuit using a step-up dc-dc converter, the following observations are made,

- The output voltage v_d across the capacitor C_d contains ripple at twice the line frequency.
- A higher switching frequency allows a lower value of L_d and an increased ease of filtering high-frequency ripple. However, the switching frequency is chosen as a compromise between the foregoing advantages and the increase switching losses.
- If rectifier output voltage V_d is much larger than 10% beyond peak input ac voltage $V_{in(max)}$, this will cause efficiency to decline.
- A small filter capacitor may be used across the output of the diode rectifier bridge to prevent the ripple in i_L from entering the utility system. An EMI filter at the input is still required as in a conventional circuit without the active current shaping.

In addition to an almost sinusoidal input waveform at nearly unity power factor, the other advantages of an active current shaping can be summarized as follows,

- The dc output voltage V_d can be stabilized to a nearly constant value for large variations in the line voltage. Thus, the volt-ampere ratings of the semiconductor devices in the converter fed from V_d are significantly reduced.
- Because of the absence of large peaks in the input current, the size to the EMI filter components is smaller.

2.4.4 Buck-Boost Regulator – Principle of Operation:

Buck-boost converter is a combination of Buck and Boost regulator which can provide an output voltage that may be less than or greater that the input voltage. The output voltage polarity is opposite to that of the input voltage. So, this regulator is also known as an inverting regulator. The circuit arrangement of a buck-boost regulator is shown in the following figure.

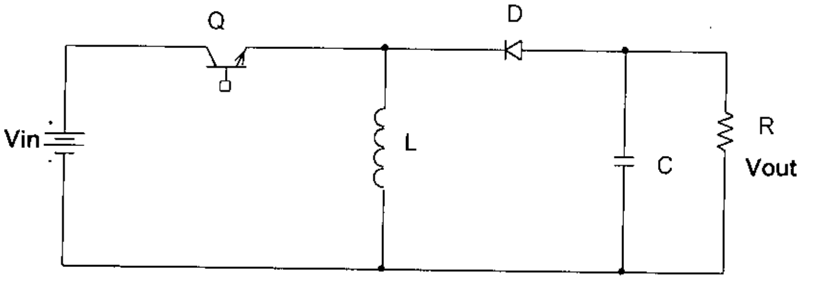


Figure-2.22 Schematic of a Buck-boost Regulator.

In dc-dc conversion, the switch Q of Buck-boost converter is turned on and off by the pulse-width modulated control voltage. For analysis of the above circuit it may be assumed that the transistor and the diode have no voltage drop during the respective on-phases.

During the on-time of the transistor T_{on}, there is an input voltage V_{in} applied across the inductor L. Inductor current I_L increases linearly and energy is transferred to the inductor. During the blocking phase T_{off} of the transistor, current I_L continues to flow through the inductor and transfer the energy to the capacitor C.

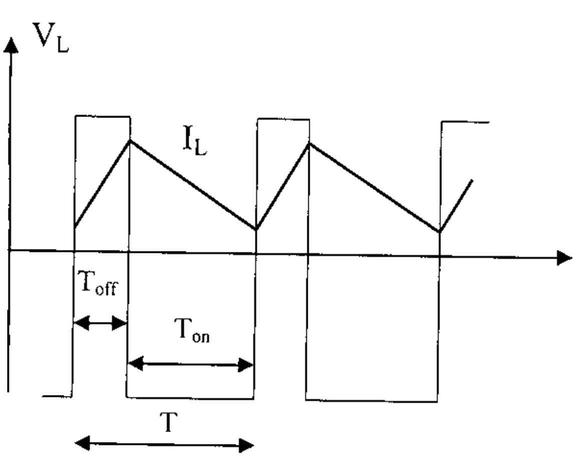


Figure-2.23 Waveform of a Buck-boost converter.

In ideal relationship inductor, diode, capacitor and switch may be assumed to be loss-less.

From Fig-2.23, at $T = T_{on}$; $V_L = V_{in}$ 2.28

And at $T = T_{off}$; $V_L = - V_{out}$ 2.29

For volt-seconds balance, $V_{in}T_{on} + V_{out}T_{off} = 0$ 2.30

which gives the output to input voltage ratio as follows –

$$\frac{Vout}{Vin} = -\frac{D}{(1-D)} \quad 2.31$$

And corresponding current ratio is –

$$\frac{Iout}{Iin} = -\frac{(1-D)}{D} \quad 2.32$$

where, D is the duty-cycle defined as $D = \frac{Ton}{T}$. Since the value of D is in-between 0 and 1, the output voltage can be varied from lower to higher than input voltage in magnitude. The negative sign in Eqn. 2.31 indicates a reversal of the output voltage.

The above ideal relationship will change in real circuit due to non-ideal components (L, C), switch non-idealities (conduction drop in switches) etc. and thus efficiency will also deviate from 100% of ideal efficiency.

2.4.5 A Practical Buck-Boost Regulator :

Now we'll examine a practical buck-boost regulator and observe their different characteristics at different switching stages.

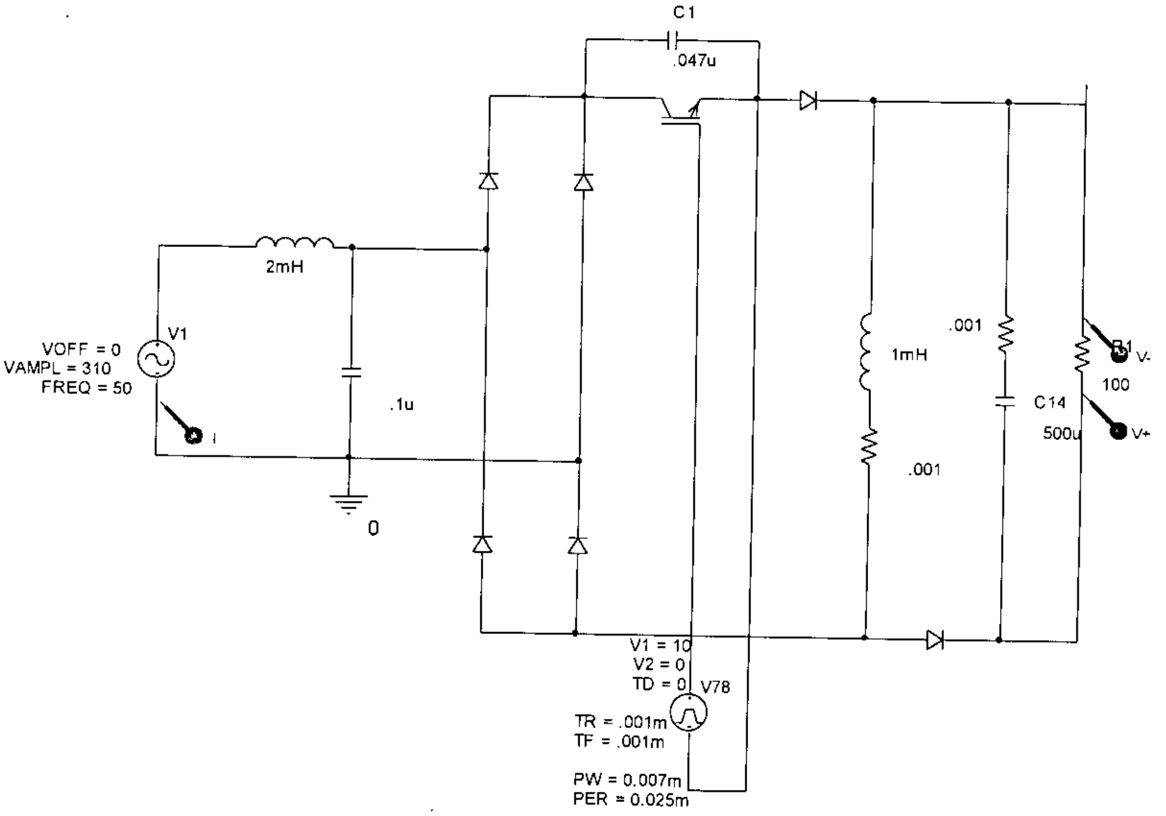


Figure-2.24 A buck-boost circuit arrangement where switching frequency of the transistor, $f_s = 40kHz$ and $T_{on} = 7\mu sec$.

Input current, rectifier output voltage, THD, input power factor, Efficiency etc. are observed graphically and presented in Figures 2.24-2.26. From these figures and observed data we'll be able to choose a better combination comparing to other circuit configurations. Observations of simulated results are provided in *Table-2.4*.

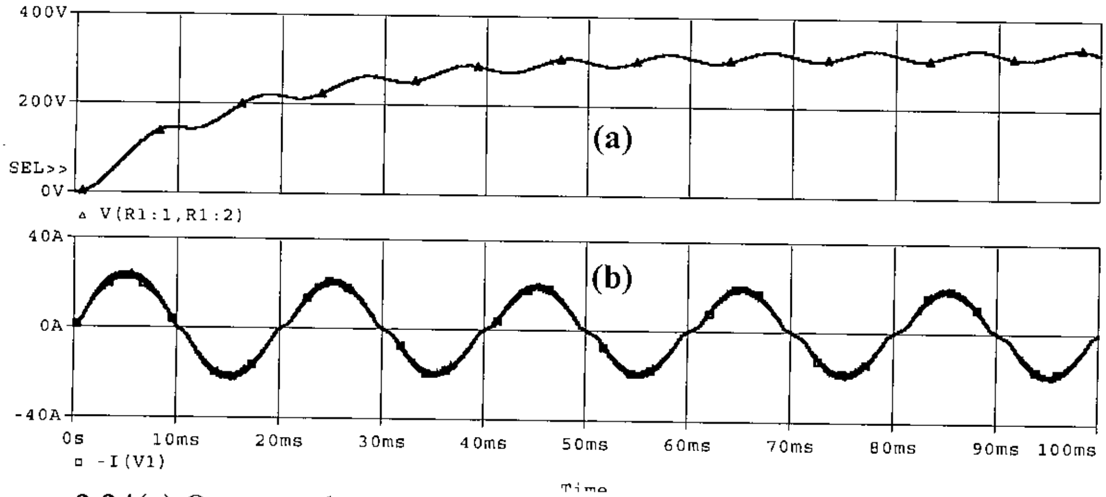


Figure-2.24(a) Output voltage and
(b) Input Current of Buck-boost converter; (L_{bb} = 1mH, C_{out} = 500μF, R=100Ω , $\mathbf{T_{on}}$ = **7μsec**, Period = 25μsec and f_s= 40kHz).

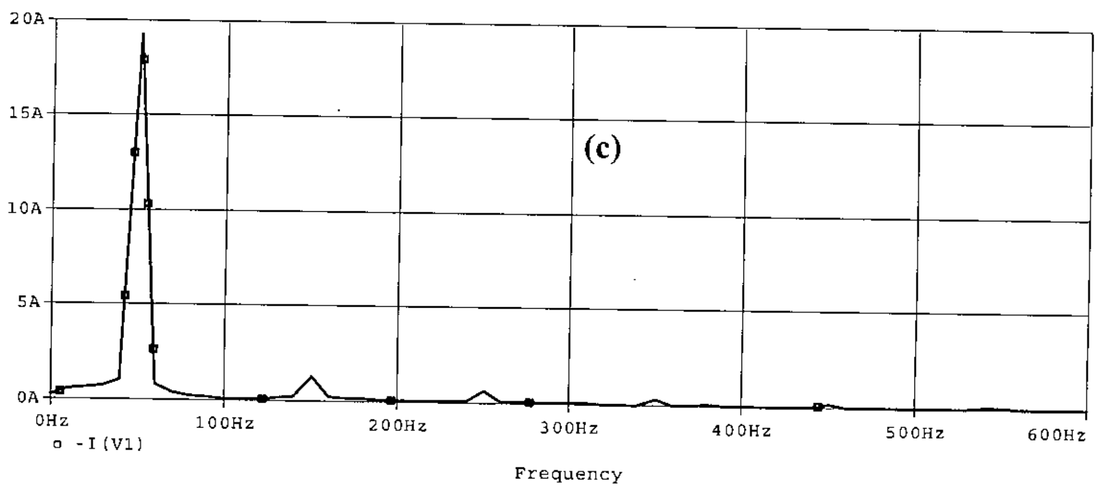


Figure-2.24(c) Input Current harmonics; (L_{bb} = 1mH, C_{out} = 500μF, R=100Ω , $\mathbf{T_{on}}$ = **7μsec**, Period = 25μsec and f_s= 40kHz).

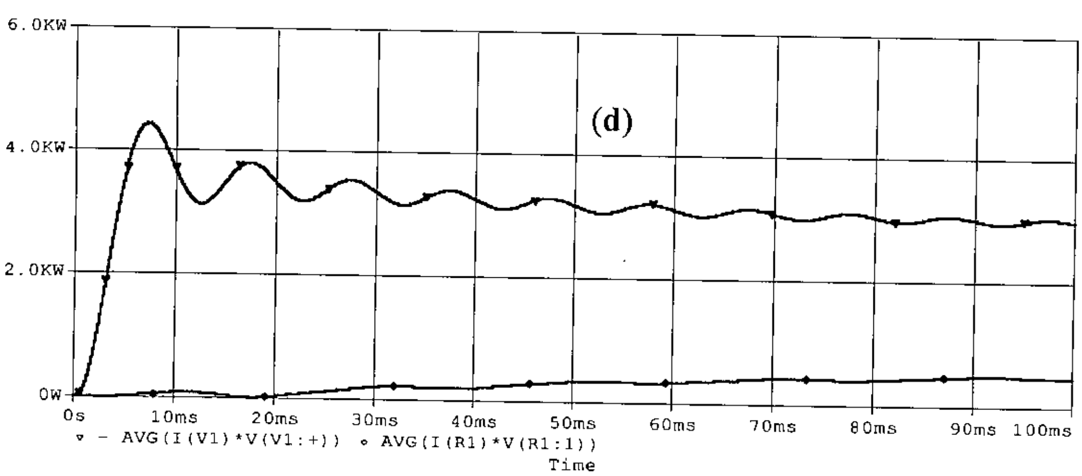


Figure-2.24(d) Output and Input average Power of Buck-boost converter; (L_{bb} = 1mH, C_{out} = 500μF, R=100Ω , $\mathbf{T_{on}}$ = **7μsec**, Period = 25μsec and f_s= 40kHz).

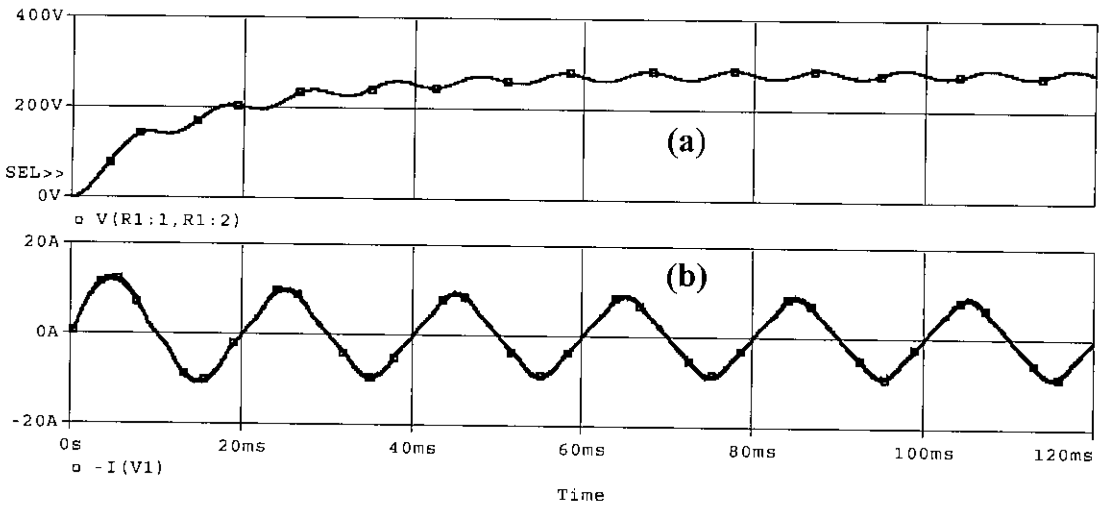


Figure-2.25(a) Output voltage and (b) Input Current of Buck-boost converter; (L_{bb} = 1mH, C_{out} = 500μF, R=100Ω , $\mathbf{T_{on}}$ **= 11μsec**, Period = 25μsec and f_s= 40kHz).

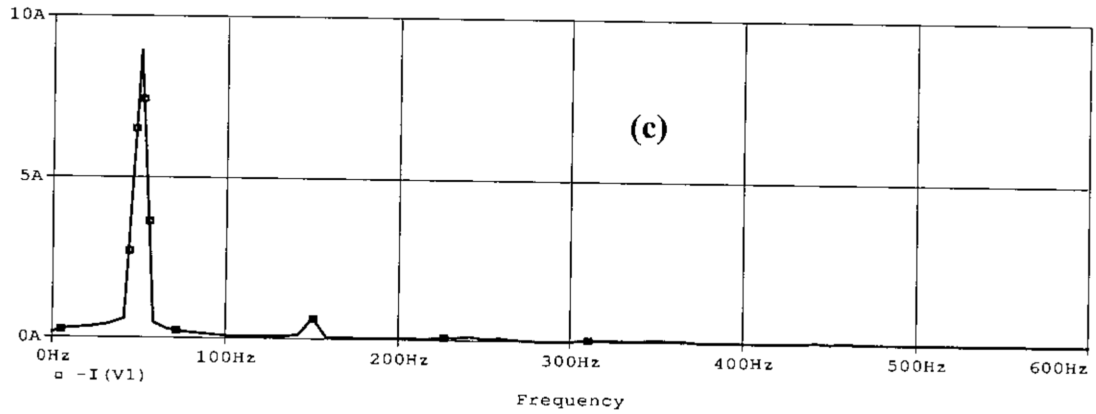


Figure-2.25(c) Input Current harmonics; (L_{bb} = 1mH, C_{out} = 500μF, R=100Ω , $\mathbf{T_{on}}$ = **11μsec**, Period = 25μsec and f_s= 40kHz).

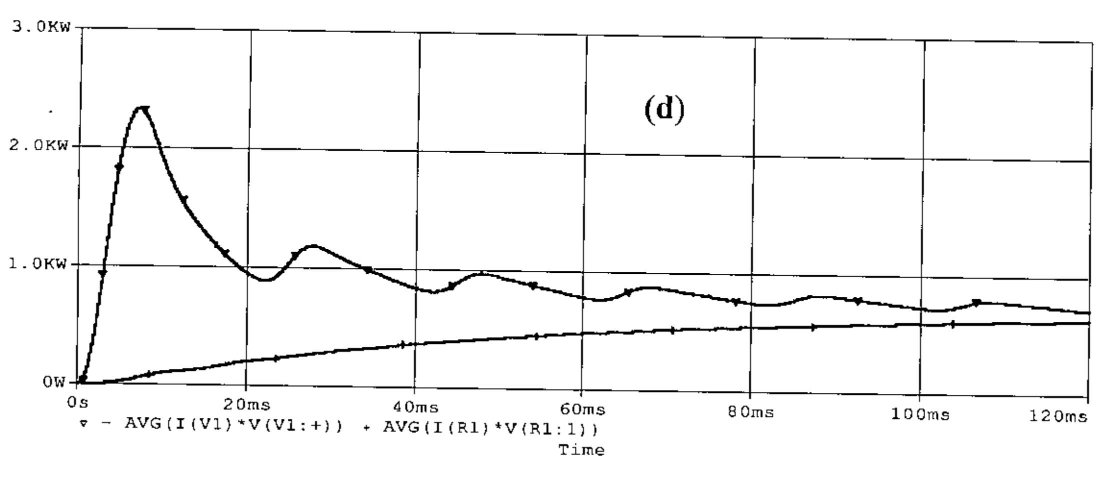


Figure-2.25(d) Output and Input average Power of Buck-boost converter; (L_{bb} = 1mH, C_{out} = 500μF, R=100Ω , $\mathbf{T_{on}}$ = **11μsec**, Period = 25μsec and f_s= 40kHz).

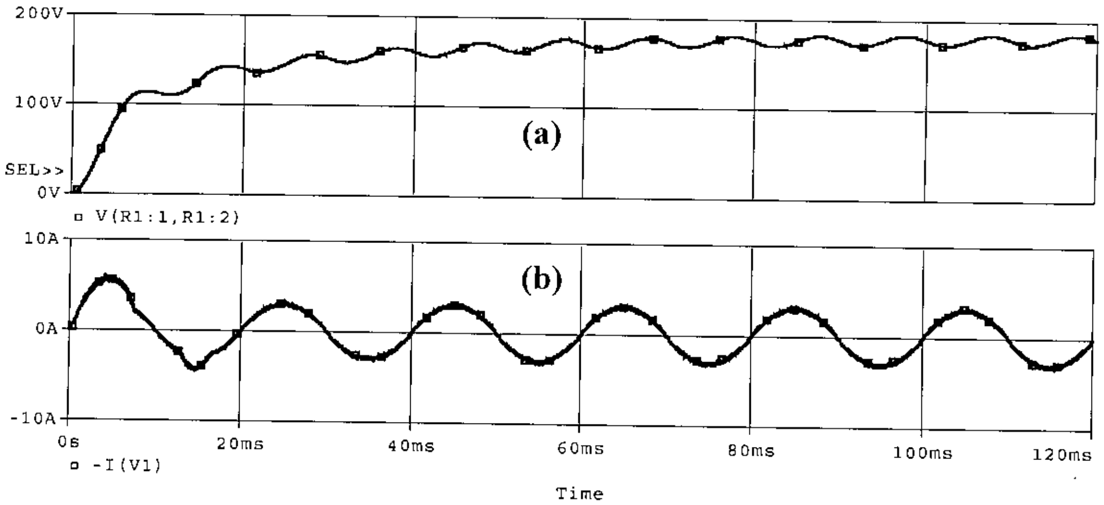


Figure-2.26(a) Output voltage and (b) Input Current of Buck-boost converter; (L_{bb} = 1mH, C_{out} = 500μF, R=100Ω , T_{on} = **17μsec**, Period = 25μsec and f_s= 40kHz).

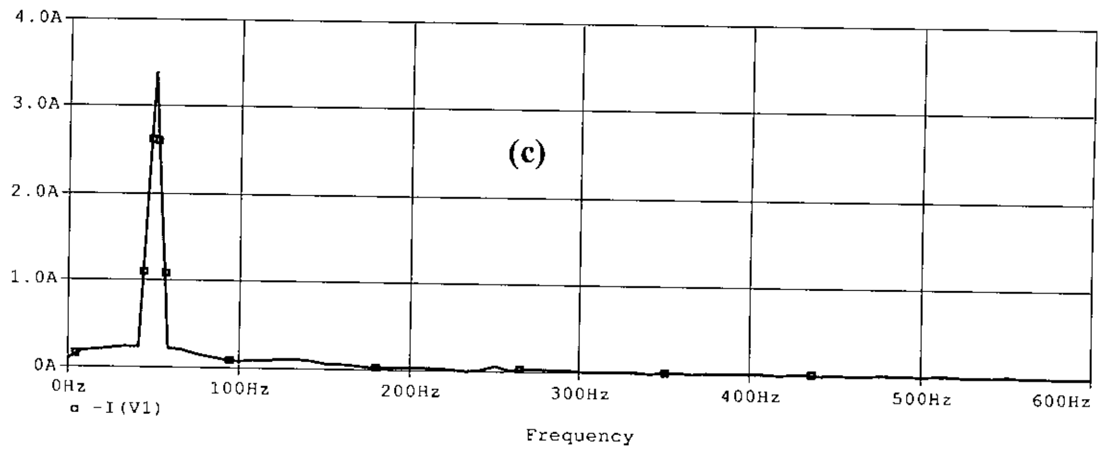


Figure-2.26(c) Input Current harmonics; (L_{bb} = 1mH, C_{out} = 500μF, R=100Ω , T_{on} = **17μsec**, Period = 25μsec and f_s= 40kHz).

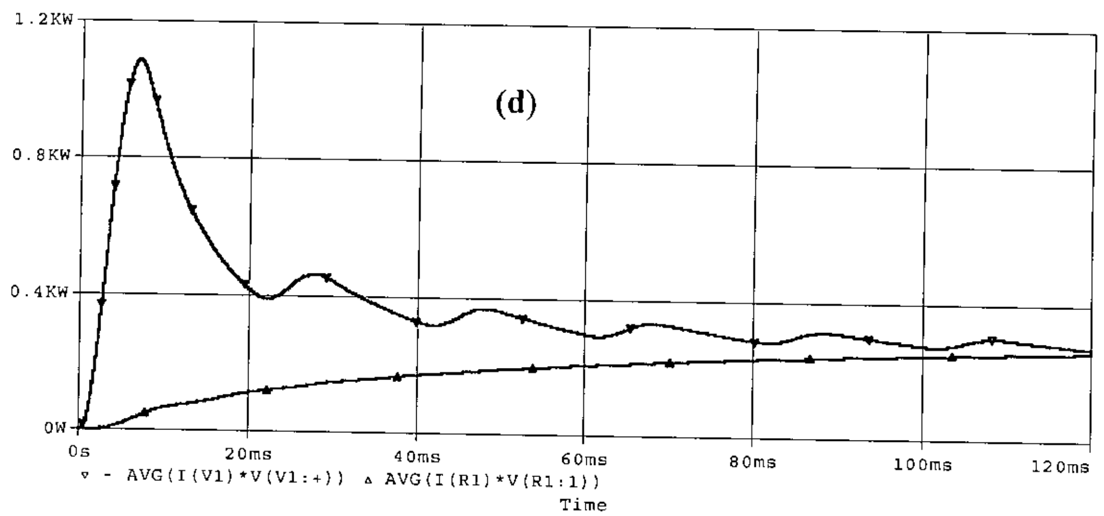


Figure-2.26(d) Output and Input average Power of Buck-boost converter; (L_{bb} = 1mH, C_{out} = 500μF, R=100Ω , T_{on} = **17μsec**, Period = 25μsec and f_s= 40kHz).

Table–2.4: Input current, Output voltage and THD at different values T_{on} of **Buck-boost** switch (L_{bb} = 1mH, C_{out} = 500µF, R = 100Ω):

	T_{on} = 7µsec	T_{on} = 11µsec	T_{on} = 17µsec
I_1	**19.2 A**	**8.9 A**	**3.38 A**
I_2	0.08 A	0.1 A	0.08 A
I_3	1.24 A	0.64 A	0.09 A
I_4	0.071 A	0.052 A	0.03 A
I_5	0.7 A	0.05 A	0.07 A
I_6	0.055 A	0.03 A	0.008 A
I_7	0.36 A	0.07 A	0.02 A
I_8	0.03 A	0.01 A	0.006 A
I_9	0.18 A	0.03 A	0.01 A
I_{10}	0.02 A	0.009 A	0.004 A
I_{11}	0.05 A	0.02 A	0.008 A
%THD	**7.73%**	**7.38%**	**4.28%**
Power Factor	**Nearly unity**	**Nearly unity**	**Nearly unity**
$V_{dc\ (avg)}$ (approx.)	**320 V**	**270 V**	**178 V**
%Efficiency	**17%**	**87%**	**95%**

From the above table it is found that higher duty ratio provides better result both in terms of THD and efficiency. Since at T_{on} = 17µsec we got THD within tolerable limit and good overall efficiency, we can use this circuit for resonant inverter operation.

Chapter 3

Resonant Inverter

3.1 Introduction:

In all pulse-width modulated dc-ac and dc-dc converter topologies, the controllable switches are operated in a switch mode where they are required to turn-on and turn-off the entire load current during each switching. So the switches are subjected to high switching stresses and high switching power loss that increases linearly with the switching frequency of the PWM. Another significant drawback of the switch mode operation is the EMI produced due to large di/dt and dv/dt caused by a switch mode operation.

These shortcomings of switch-mode converters are exacerbated if the switching frequency is increased in order to reduce the converter size and weight and hence to increase the power density. Therefore, to realize high switching frequencies in converters, the aforementioned shortcomings are minimized if each switch in a converter changes its status (from 'on' to 'off' and vice versa) when the voltage across it and / or the current through it is zero at the switching instant. Since most of these converter topologies and switching strategies require some form of LC resonance, these are broadly classified as "resonant converters / inverters".

3.2 Classification of Resonant Inverters:

The resonant converters are defined as the combination of converter topologies and switching strategies that result in zero-voltage and / or zero-current switching. One way to categorize these converters is,

1) Load-resonant converters
   (a) Voltage-source series-resonant converters
      (i) Series-loaded resonant converters

(ii) Parallel-loaded resonant converters

(iii) Hybrid resonant converters

(b) Current-source parallel-resonant converters

(c) Class-E and subclass-E resonant converters.

(2) Resonant Switch Converters

(a) Resonant switch dc-dc converters

(i) Zero-current switching (ZCS) converters

(ii) Zero-voltage switching (ZVS) converters

(b) Zero-voltage switching, clamped-voltage (ZVS-CV) converters

(3) Resonant dc-link converters

(4) High frequency-link integral half-cycle converters.

3.3 A Full-bridge Series Resonant Inverter:

A typical full-bridge series resonant inverter and its current wave-shape through the series resonant branch is shown in Figure-3.1:

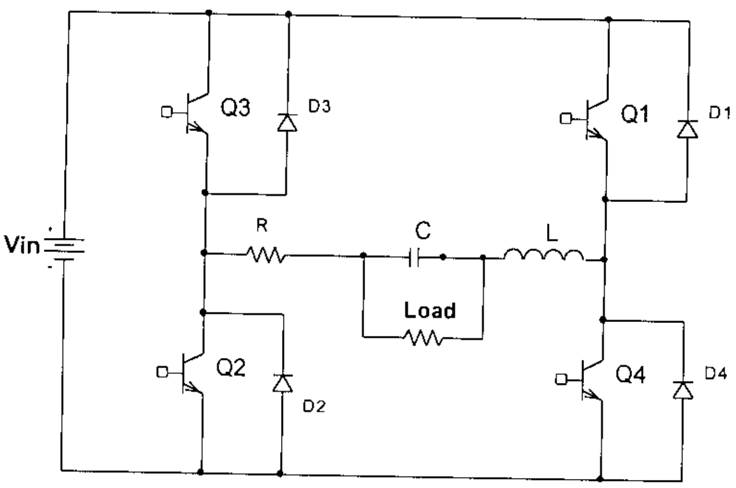


Figure-3.1 A full-bridge Series Resonant Inverter.

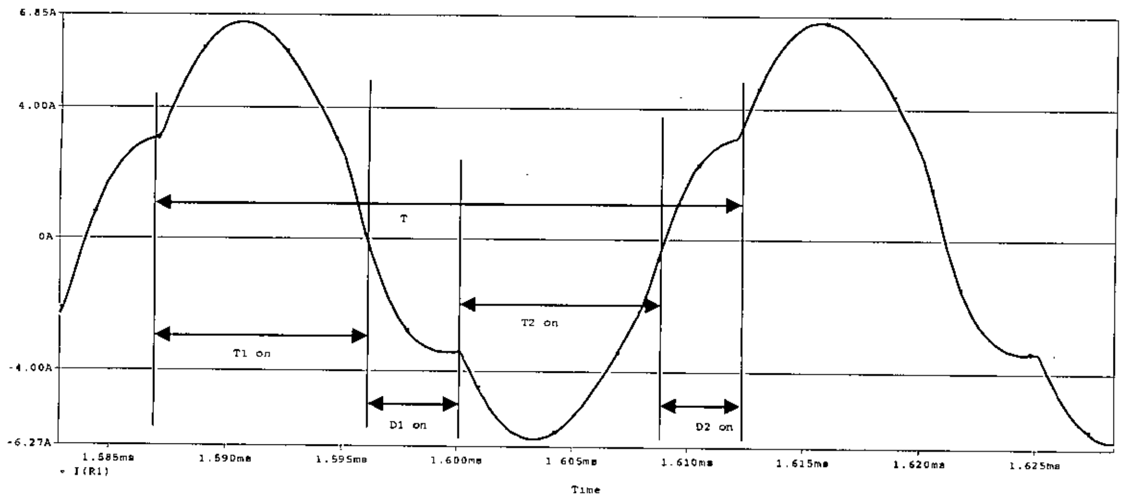


Figure-3.2 Current waveform through Resonant LC branch at overlapping condition.

The full-bridge configuration shown in Fig-3.1 can be operated in two different modes: non-overlapping and overlapping. In a non-overlapping mode, the gate-pulse of the transistor (or MOSFET, IGBT etc.) is delayed until the last current oscillation through a diode has been completed as shown in the figure of current wave form. And in overlapping mode, a transistor is made 'on' while the current in the diode of the other part is still conducting as shown in Fig-3.2. Overlapping operation increases the output frequency and also the output power.

The maximum frequency of resonant inverters are limited due to the turn-off or commutation requirements of the switching device (BJT, MOSFET, IGBT etc.)

$$f_{max} = \frac{1}{2tq} \quad ; \qquad 3.1$$

where, t_q = turn-off time of the switching device.

The inverter can operate (f_o) at resonant frequency f_r, that means –

$$f_o = f_r = \frac{\omega r}{2\pi} \quad ; \qquad 3.2$$

here, ω_r = angular resonant frequency = $\frac{1}{\sqrt{(LC)}}$; 3.3

3.4 Resonant Inverters at Various Switching Condition:

Resonant inverter is examined for different duty cycle of a switching period of 25μsec (i.e switching frequency f_s = 40 kHz). Various input output parameters are also shown in Figures 3.3-3.5.

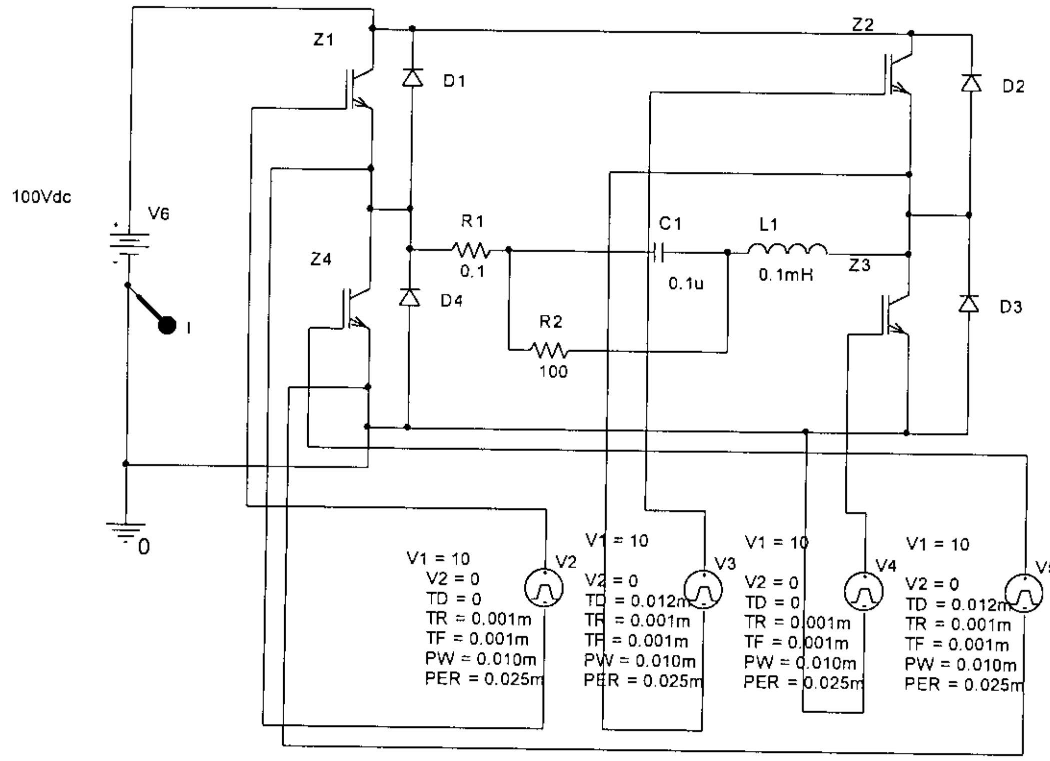


Figure-3.3 Circuit Diagram of a full-bridge Resonant inverter.

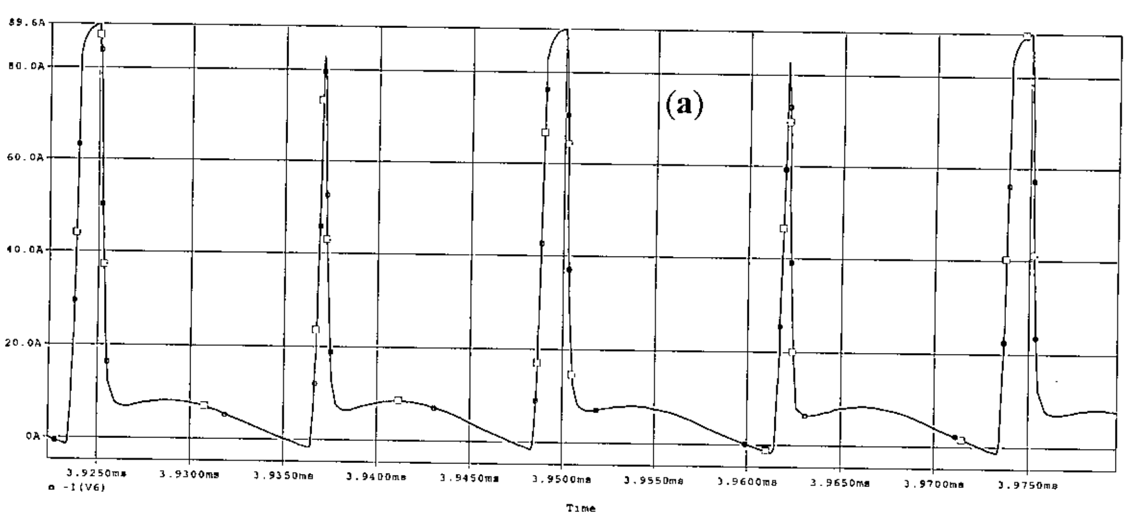


Figure-3.3(a) Input current of Resonant Inverter; when V=100v, **T_{on}=10μsec.**

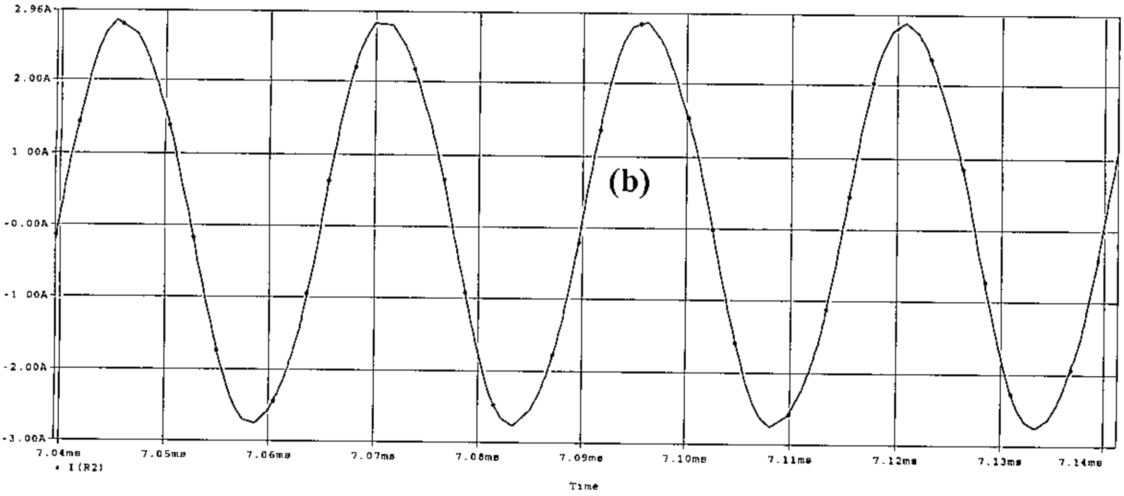


Figure-3.3(b) Resistive load-current; when V=100v, $\mathbf{T_{on}=10\mu sec}$.

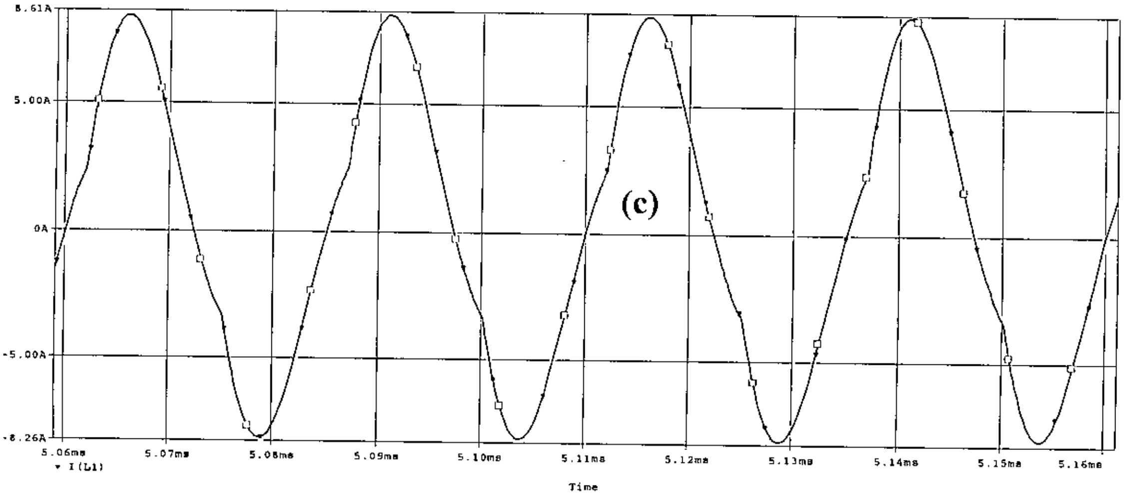


Figure-3.3(c) Current through resonating branch; when V=100v, $\mathbf{T_{on}=10\mu sec}$.

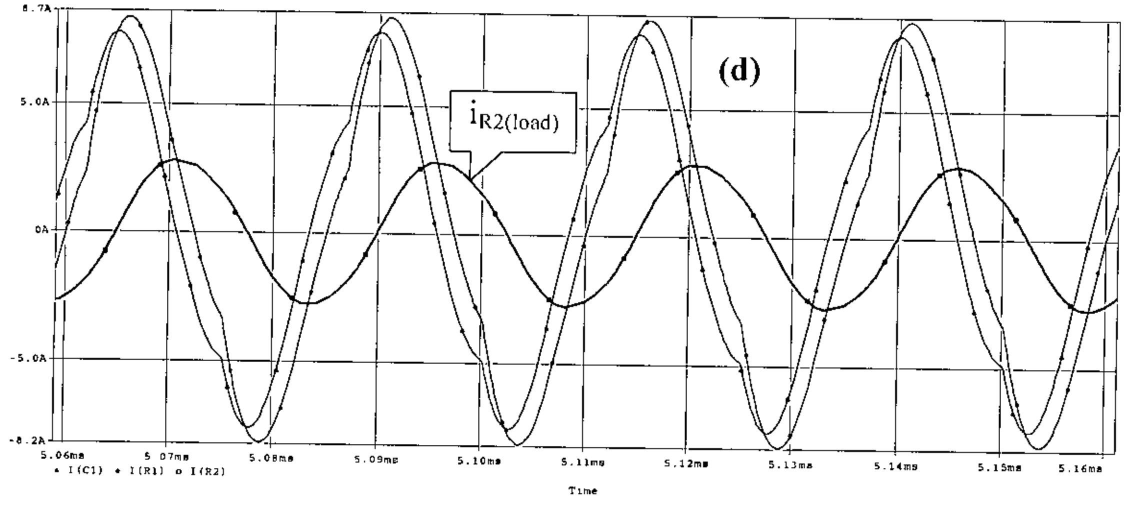


Figure-3.3(d) Waveform of i_{C1}, i_{R1} and i_{R2} as in Fig-3.3; when V=100v, $\mathbf{T_{on}=10\mu sec}$.

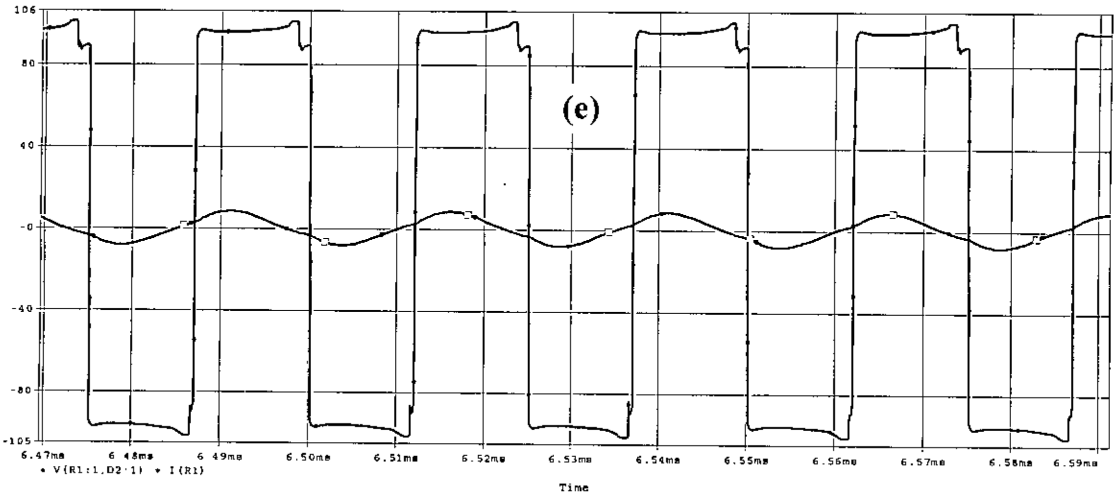
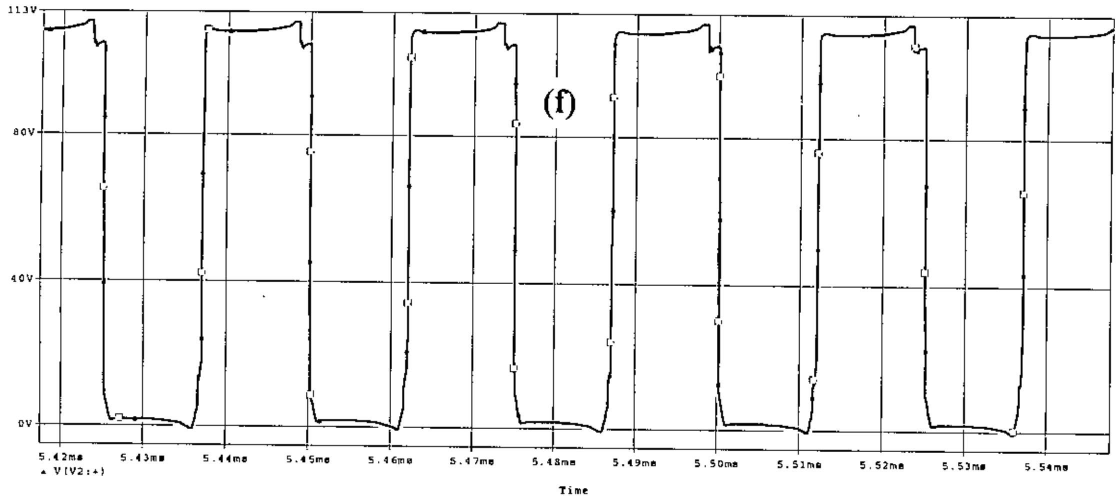


Figure-3.3(e) Voltage and Current wave through resonant branch; when $\mathbf{T_{on}=10\mu sec}$.



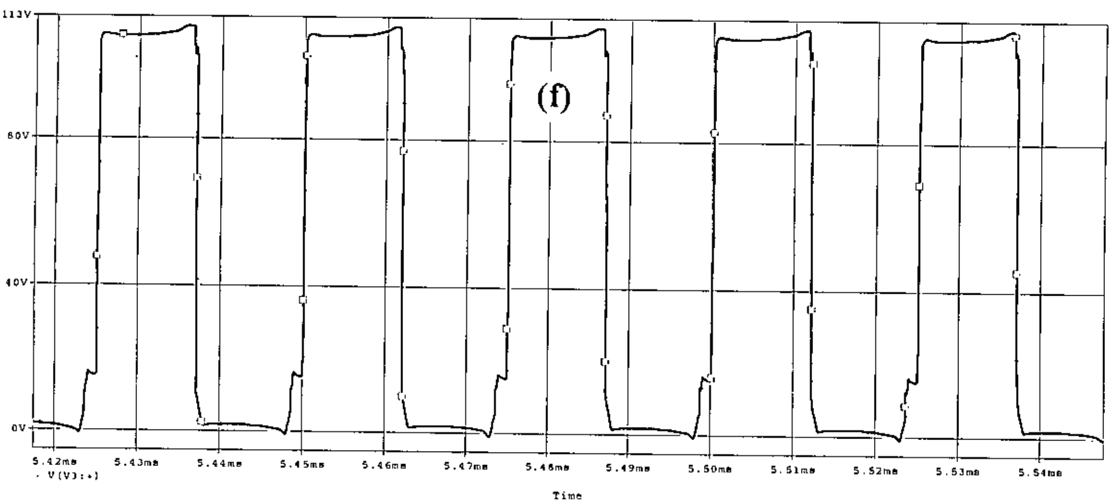


Figure-3.3(f) Alternate Gate-pulse to Switches; when $\mathbf{T_{on}=10\mu sec}$.

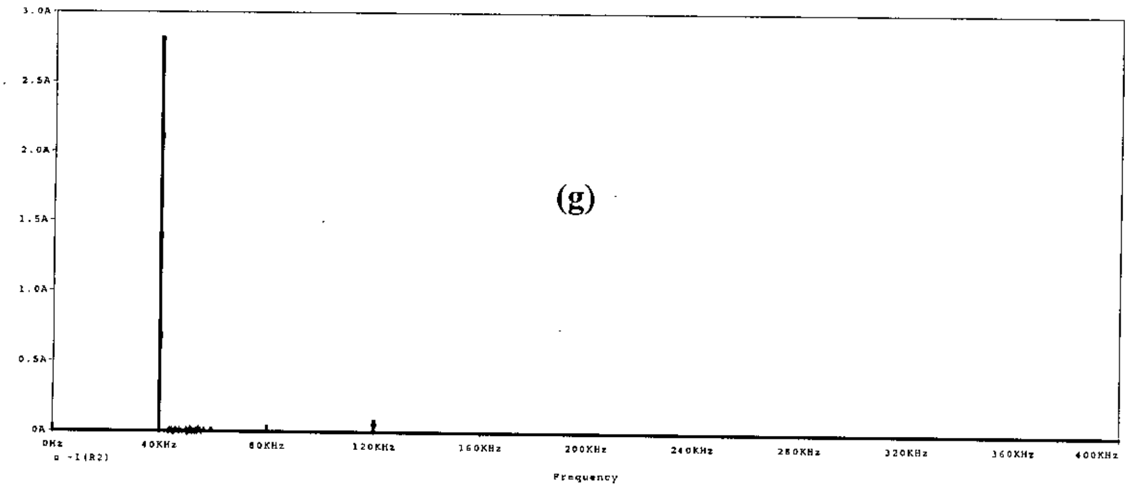


Figure-3.3(g) Load Current (I_{R2}) Harmonics; when $\mathbf{T_{on}=10\mu sec}$.

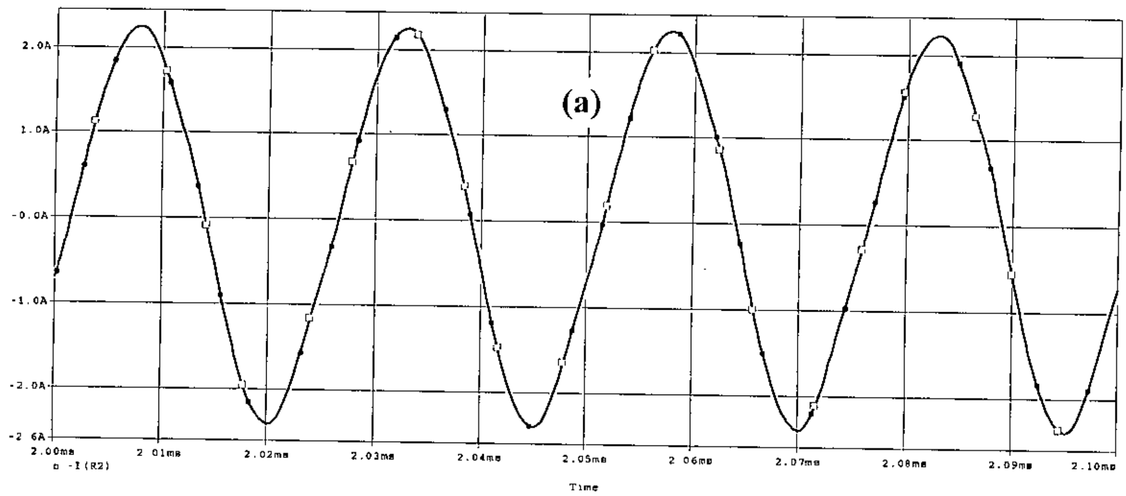


Figure-3.4(a) Resistive load-current; when V=100v, $\mathbf{T_{on}=6\mu sec}$.

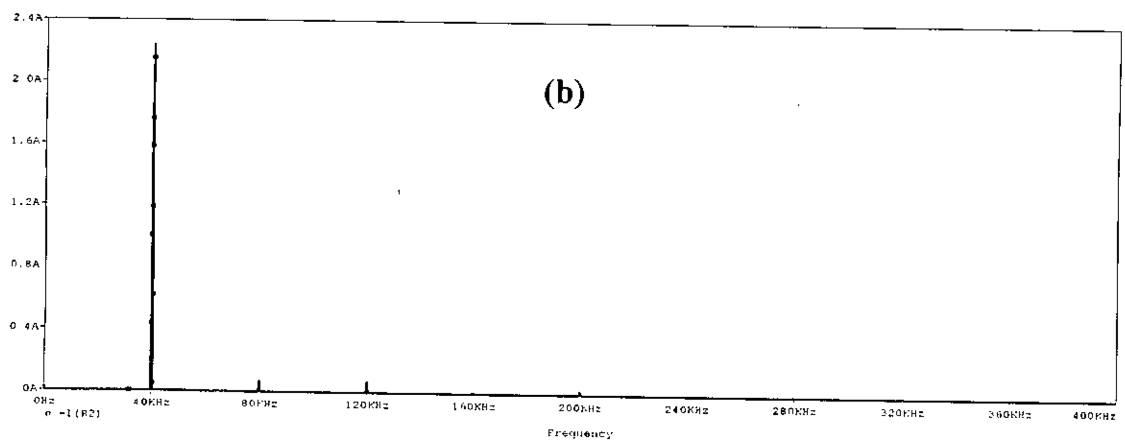


Figure-3.4(b) Resistive load-current harmonics; when V=100v, $\mathbf{T_{on}=6\mu sec}$.

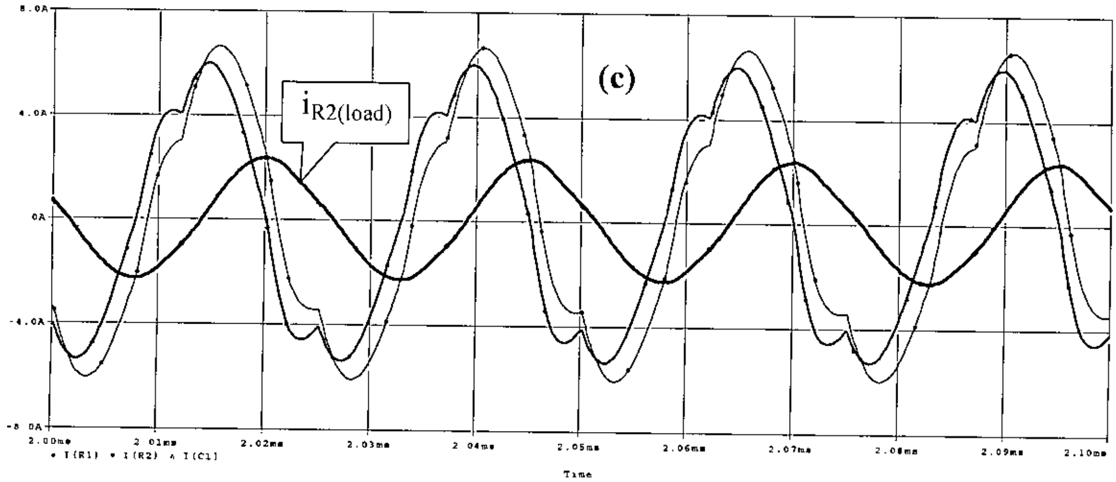


Figure-3.4(c) Waveform of i_{C1}, i_{R1} and i_{R2} as in Fig-3.3; when V=100v, $\mathbf{T_{on}=6\mu sec}$.

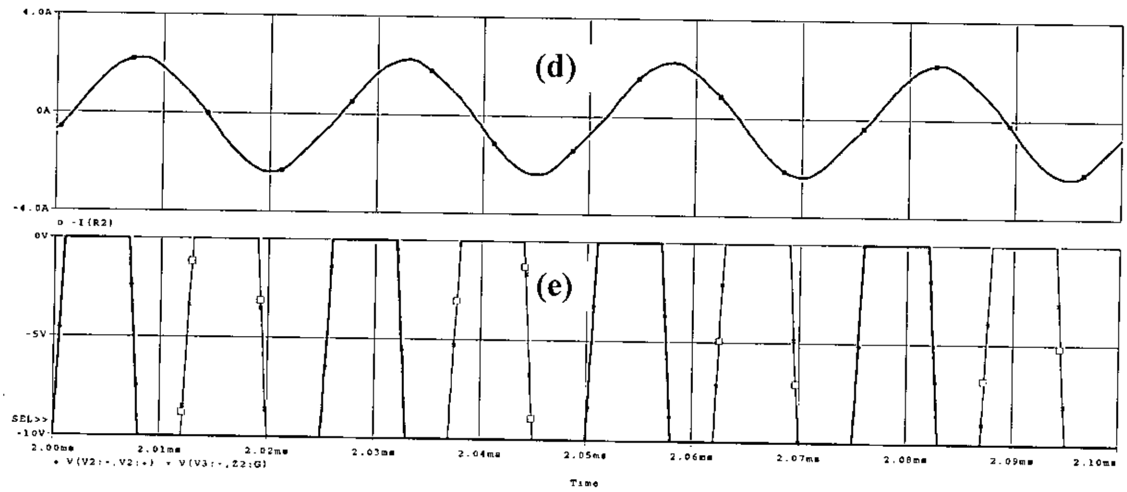


Figure-3.4(d) Load Current and

(e)Alternate Gate pulses; when V=100v, $\mathbf{T_{on}=6\mu sec}$.

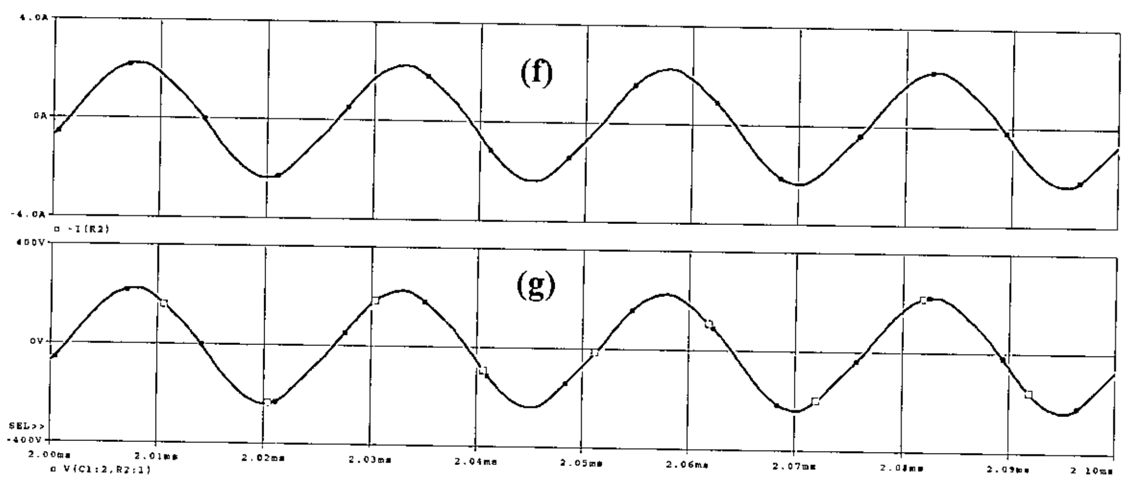


Figure-3.4(f) Load Current and

(g) Voltage (nearly unity PF); when $\mathbf{T_{on}=6\mu sec}$.

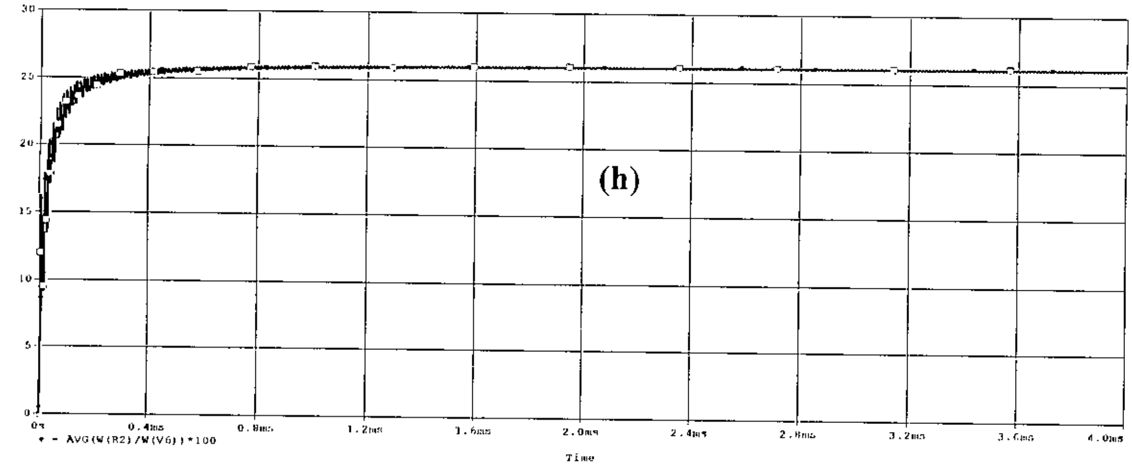


Figure-3.4(h) Resonant Inverter Efficiency (approx. 26.2%); when $\mathbf{T_{on}=6\mu sec}$.

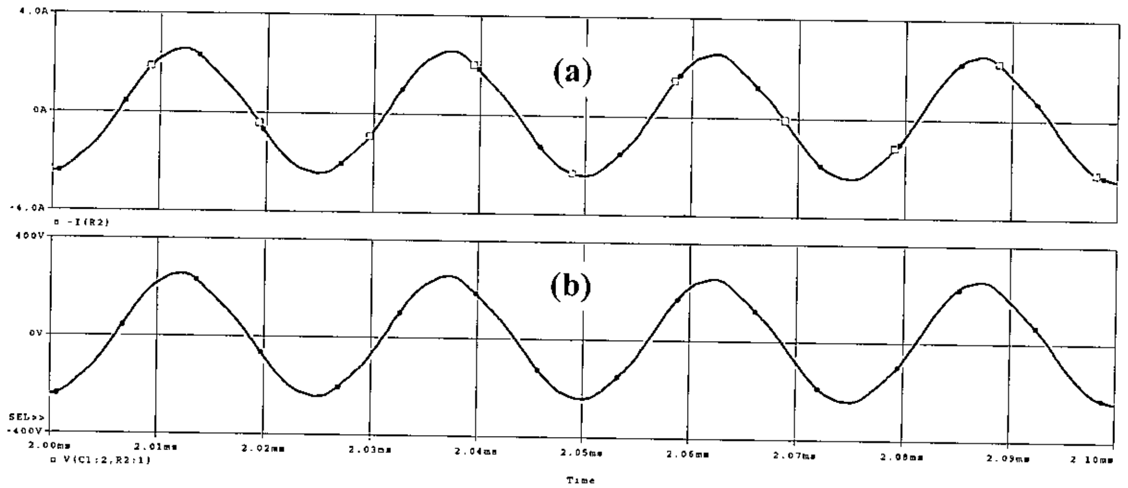


Figure-3.5(a) Load Current and
(b) Voltage (nearly unity PF); when $\mathbf{T_{on}=15\mu sec}$.

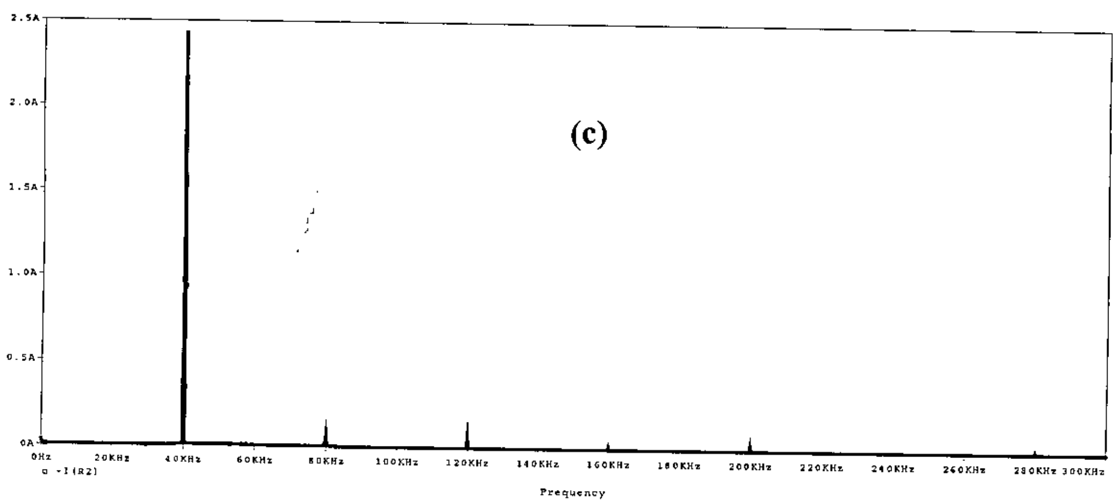


Figure-3.5(c) Load Current harmonics; when $\mathbf{T_{on}=15\mu sec}$.

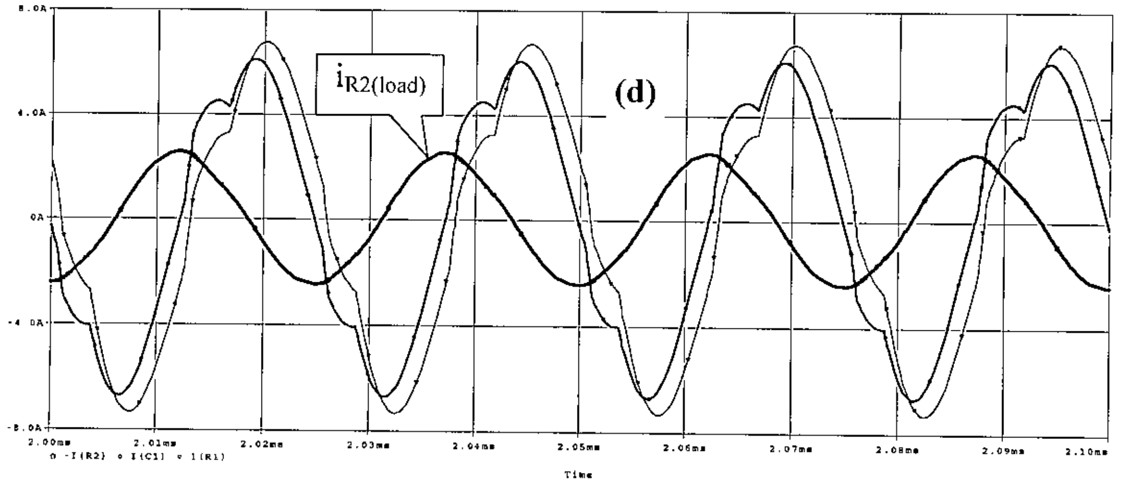


Figure-3.5(d) Waveform of I_{C1}, I_{R1} and I_{R2} as in Fig-3.3; when V=100v, Ton=15μsec.

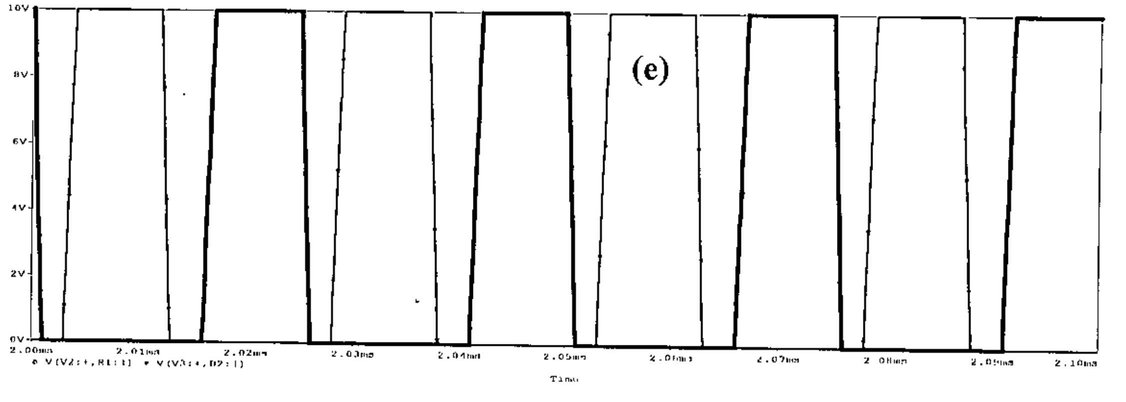


Figure-3.5(e) Alternate Gate pulses; when V=100v, Ton=15μsec.

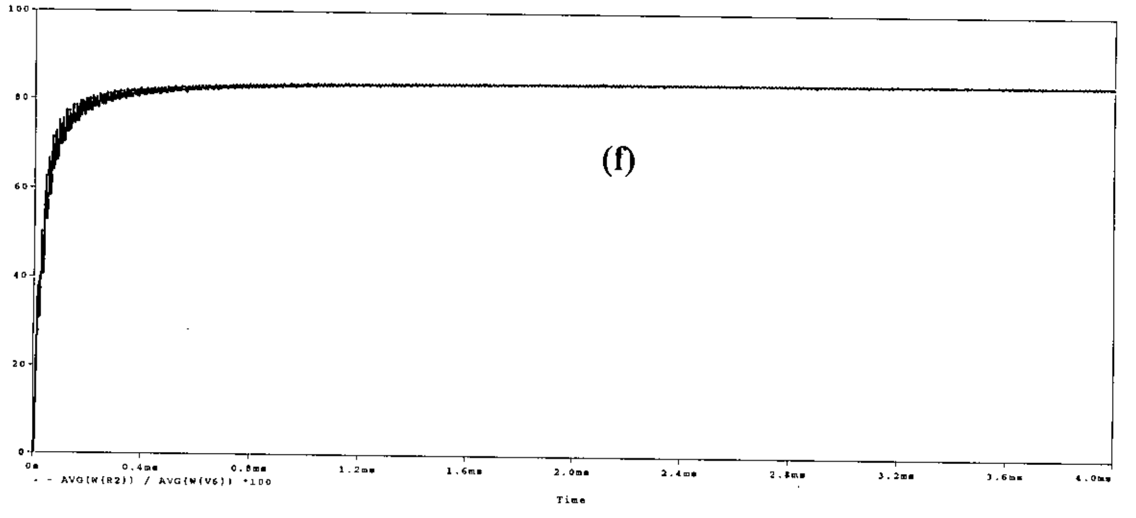


Figure-3.5(f) Resonant Inverter Efficiency (approx. **84%**); when Ton=15μsec.

3.5 Resonant Inverters with Full-bridge Rectifier:

In most cases the dc input of the resonant inverters are fed from output of a full-bridge rectifier along with utility ac input. In this section resonant inverter fed from a full-bridge rectifier with active filtering scheme is studied. From previous chapter we found better performance from Buck-boost rectifier in terms of THD, efficiency, PF and input current wave-shape. Hence, a buck-boost rectifier is added in front of a resonant inverter studied in the previous sections of this chapter.

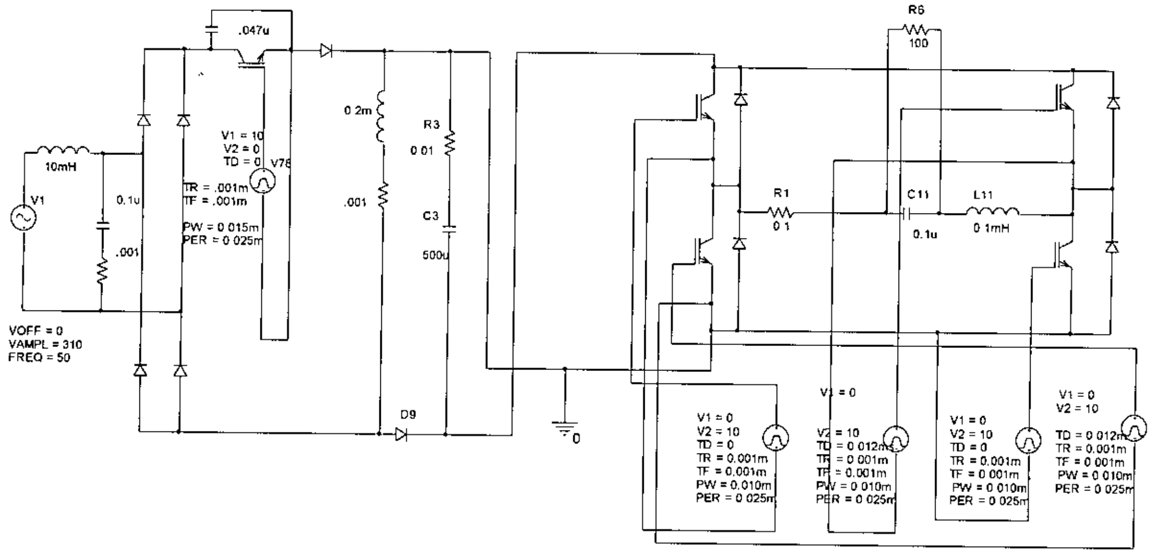


Figure-3.6 Circuit Diagram of a Buck-boost regulated Resonant Inverter.

In this section, various performance parameters like - input current wave shape, %THD, power factor, efficiency etc. is observed graphically from simulations performed. From various switching duty cycle and inductor value combination, component values and duty cycle of the buck-boost regulator have been chosen to provide a trade-off between overall efficiency and input current %THD. It has been found that by changing duty cycle, overall efficiency of the resonant inverter can be achieved above 80% but the input current wave-form gets more distorted. In the simulations we got better overall performance using input inductor value as 10mH, inductor after the buck-boost switch with value of 0.2mH, pulse-width of buck-boost switch as 15μsec and all other component values as shown in Fig-3.6. Typical results of waveforms and their harmonic spectra are shown in Figs-3.6(a) – (n).

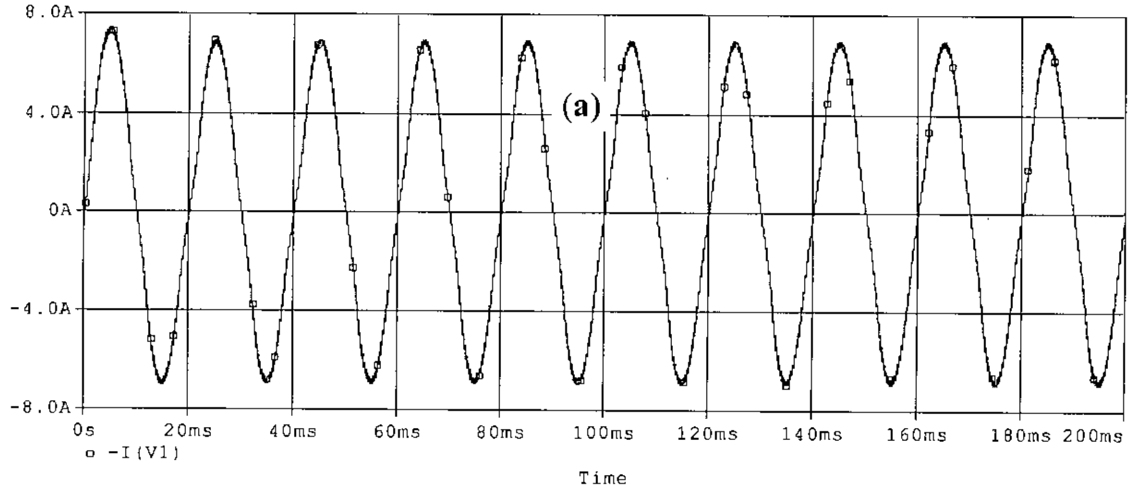


Figure-3.6(a) Input Current Wave-form of the Buck-boost regulated Resonant Inverter as shown in Fig-3.6.

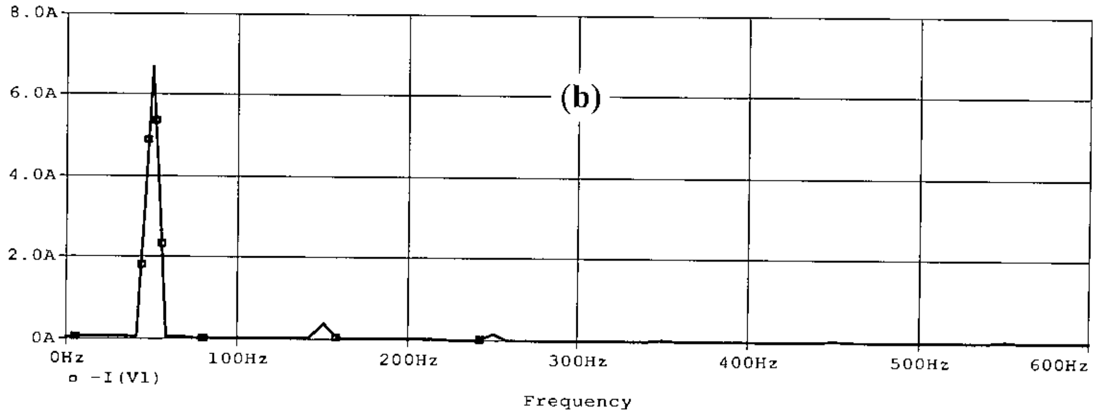


Figure-3.6(b) Input Current Harmonics (THD = 6.27%)

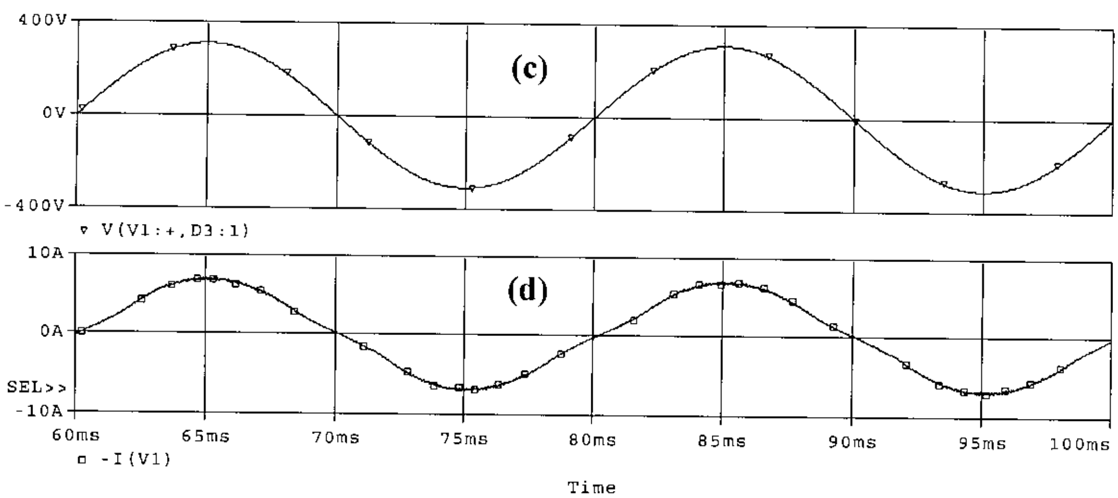


Figure-3.6(c) Input AC Voltage waveform and
(d) Input AC Current waveform (Close-up view shows almost unity Power Factor).

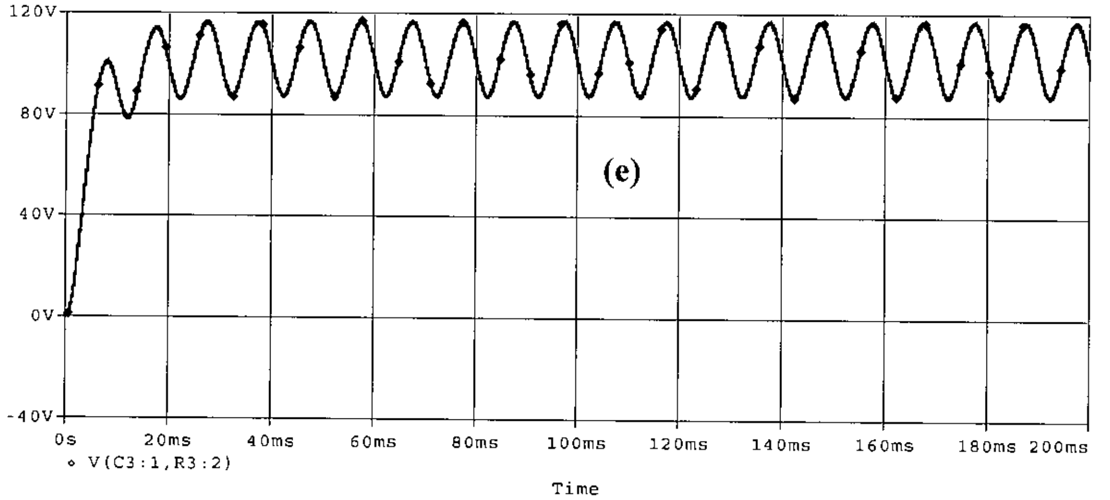


Figure-3.6(e) Rectifier Output Voltage (approx. 102V dc).

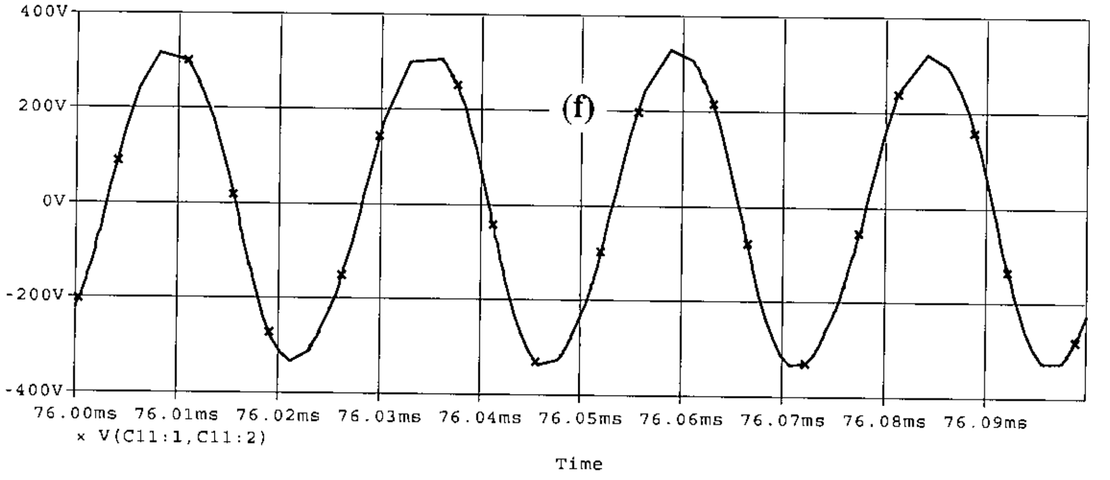


Figure-3.6(f) Resonant Inverter Output Voltage (approx. 226V rms).

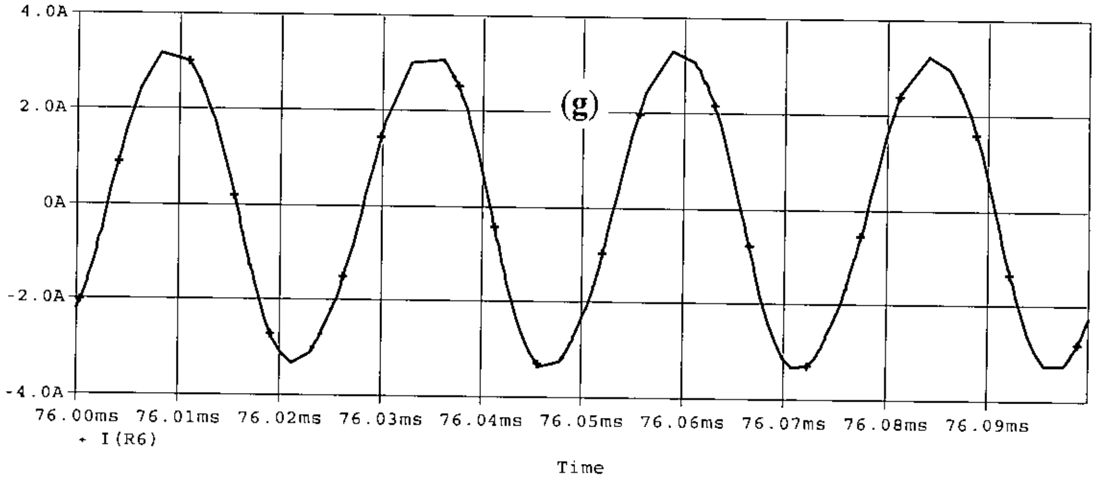


Figure-3.6(g) Resonant Inverter Load Current (approx. 2.26A rms).

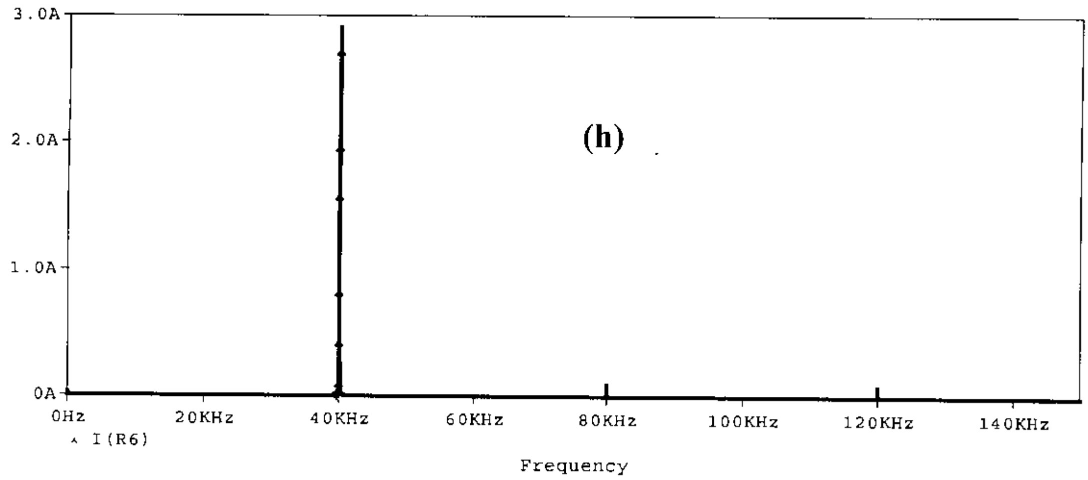


Figure-3.6(h) Output Current Harmonics.

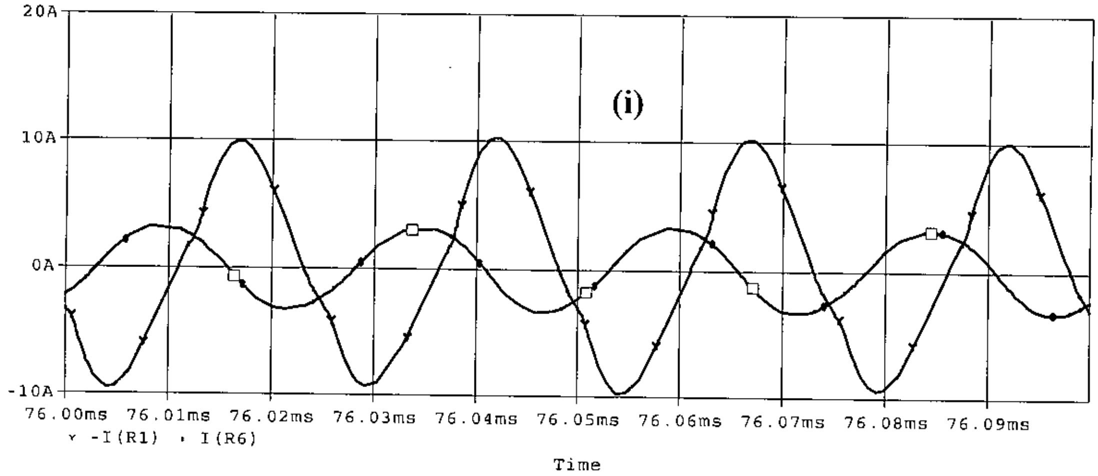


Figure-3.6(i) Output Current through Resistive load and Resonating branch.

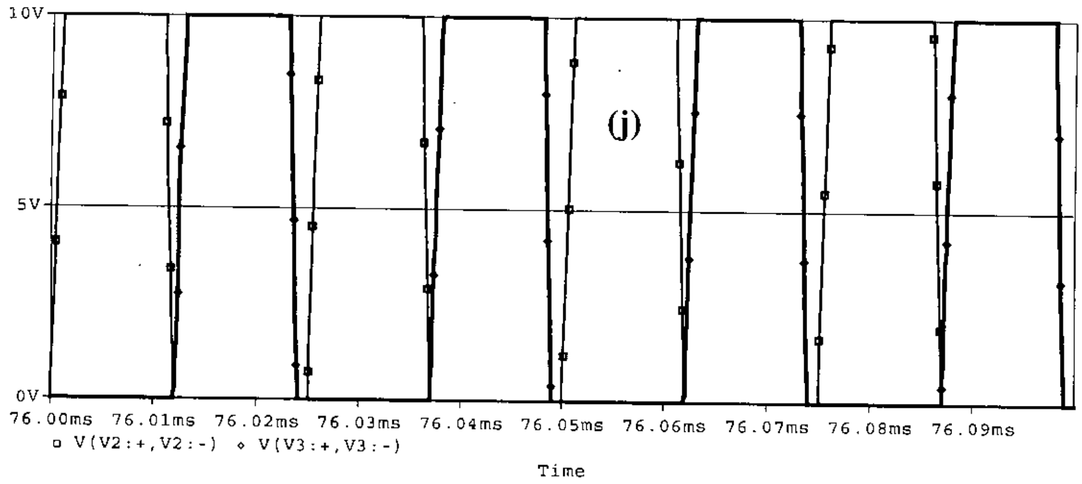


Figure-3.6(j) Alternate Gate-pulses for switches at Resonant Inverter Stage.

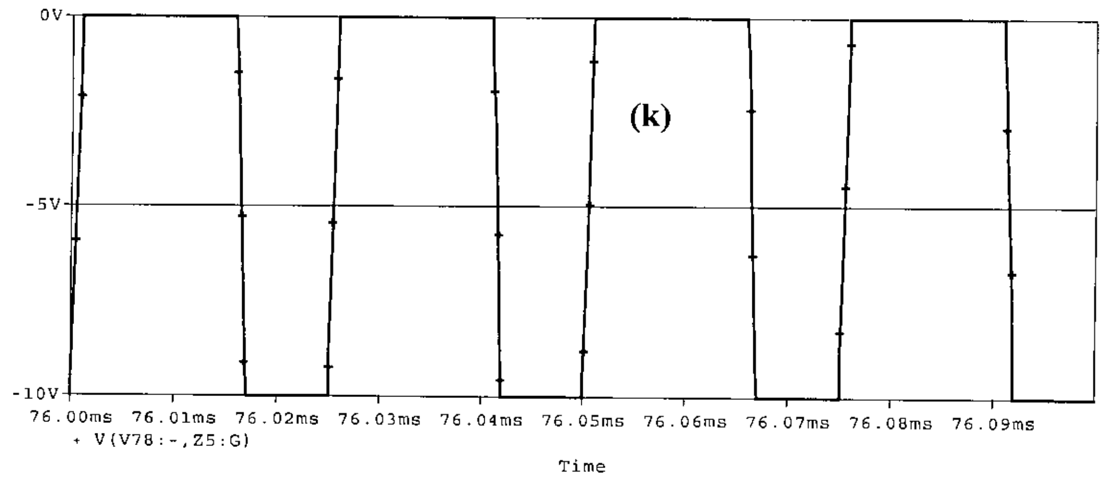


Figure-3.6(k) Gate-pulse for Buck-boost Switch.

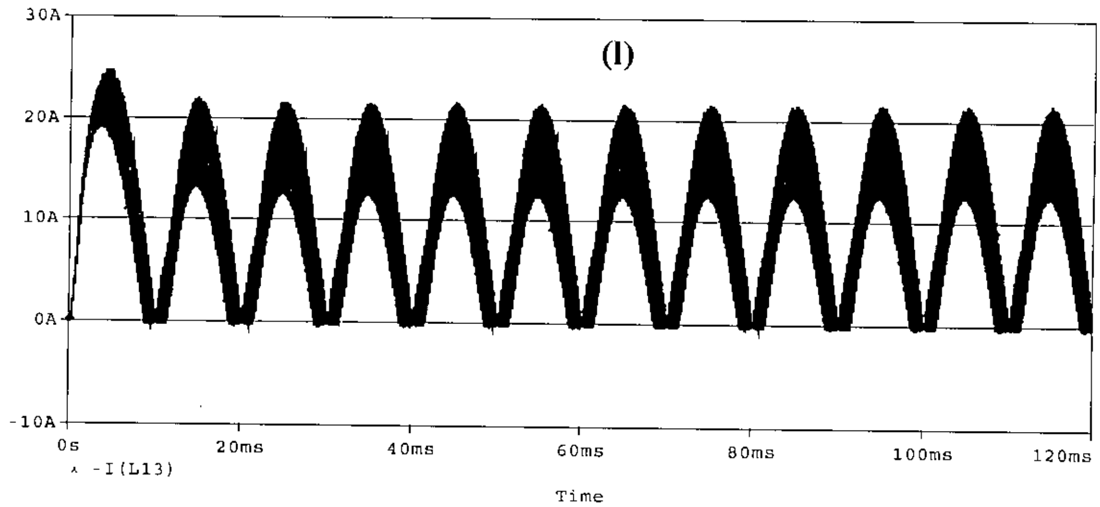


Figure-3.6(l) Current through the inductor associated with Buck-boost switch.

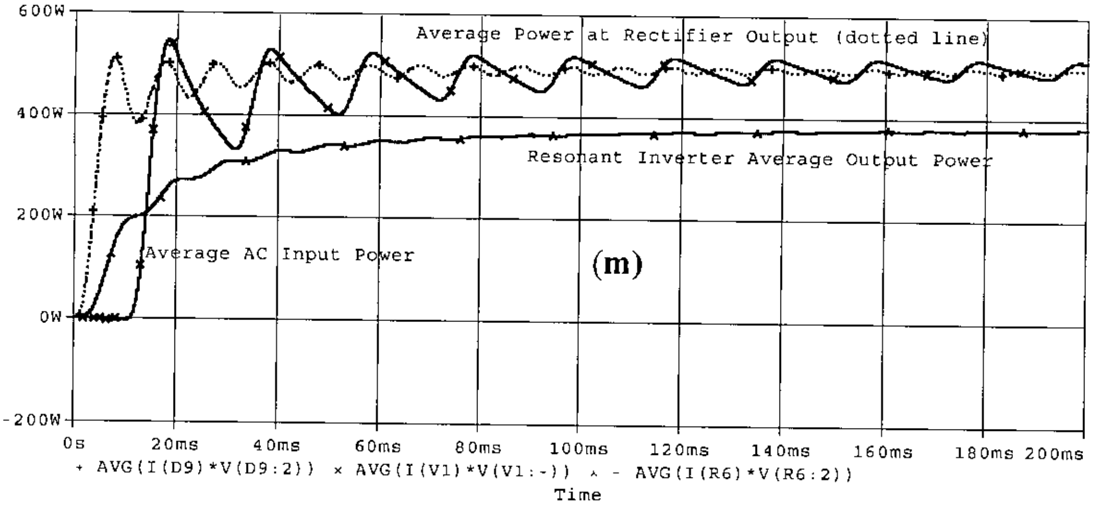


Figure-3.6(m) Average Input power, Output power at Rectifier and Inverter Stage.

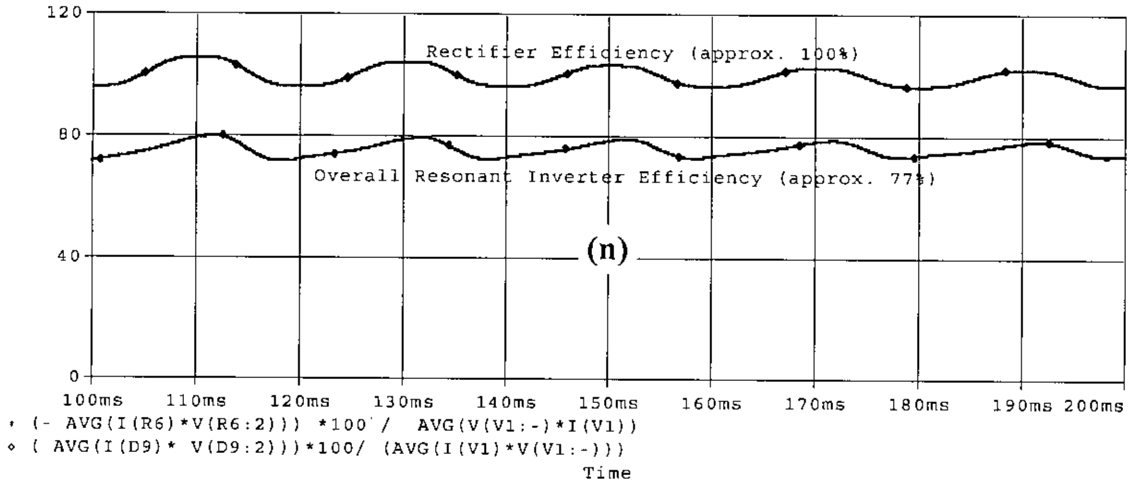


Figure-3.6(n) Efficiency at Rectifier stage (98%) and Overall (76%).

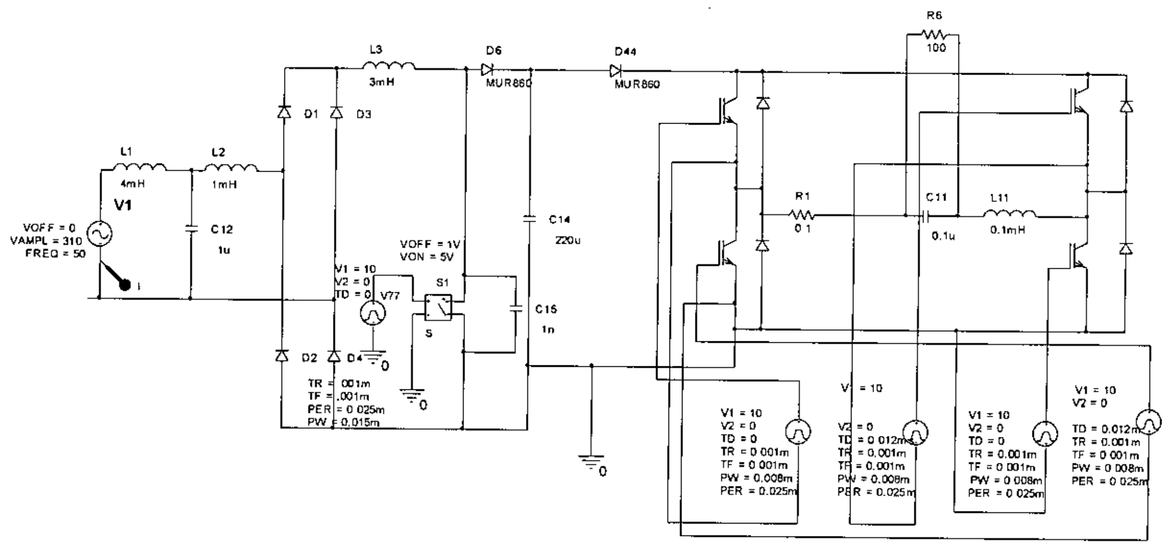


Figure-3.7 Circuit Diagram of a **Boost** regulated Resonant Inverter.

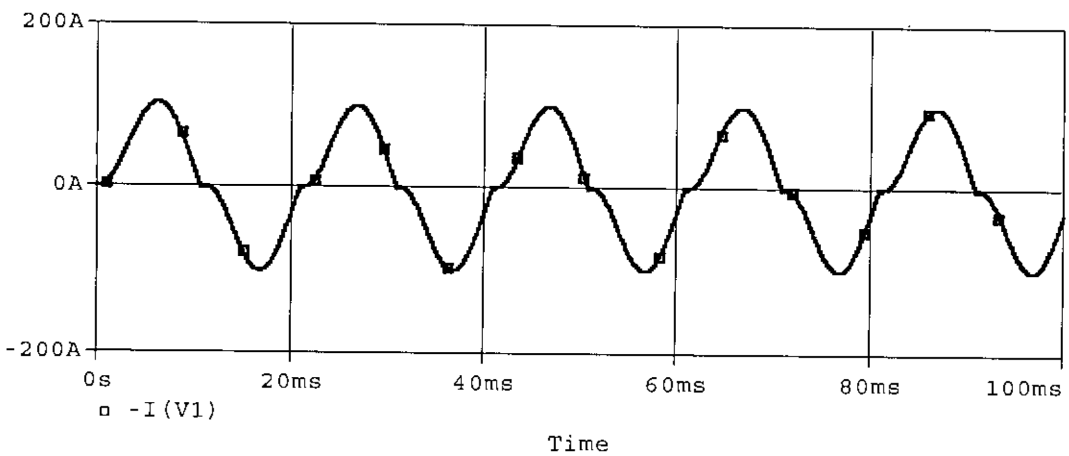


Figure-3.7(a) Input Current Wave-form of the Boost regulated Resonant Inverter as shown in Fig-3.7 (70A rms).

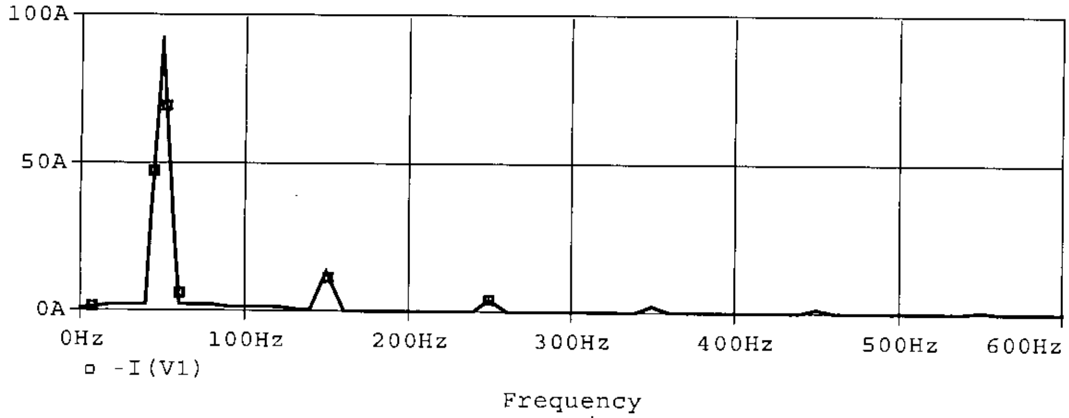


Figure-3.7(b) Input Current Harmonics (THD = 15.92%)

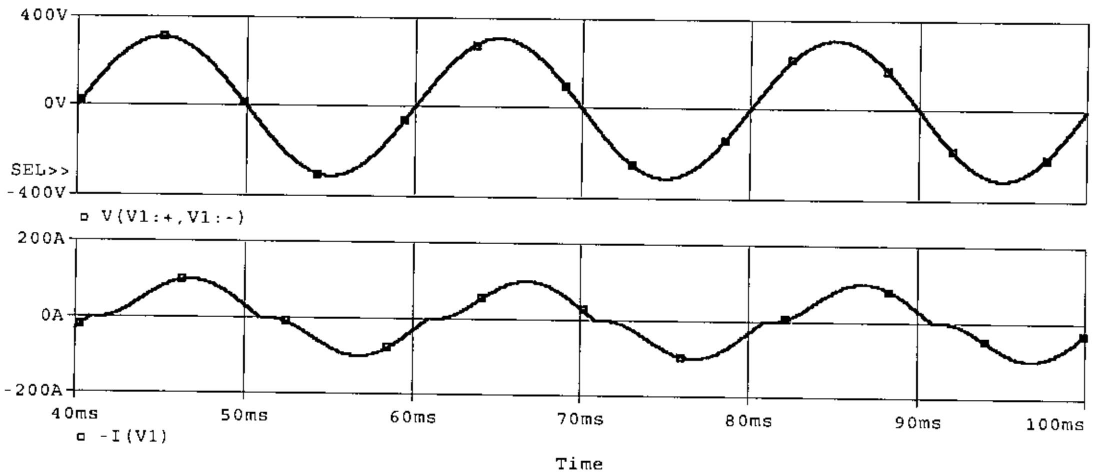


Figure-3.7(c) Input AC Voltage waveform and
(d) Input AC Current waveform; Power Factor = 0.99 (Close-up view shows almost unity Power Factor).

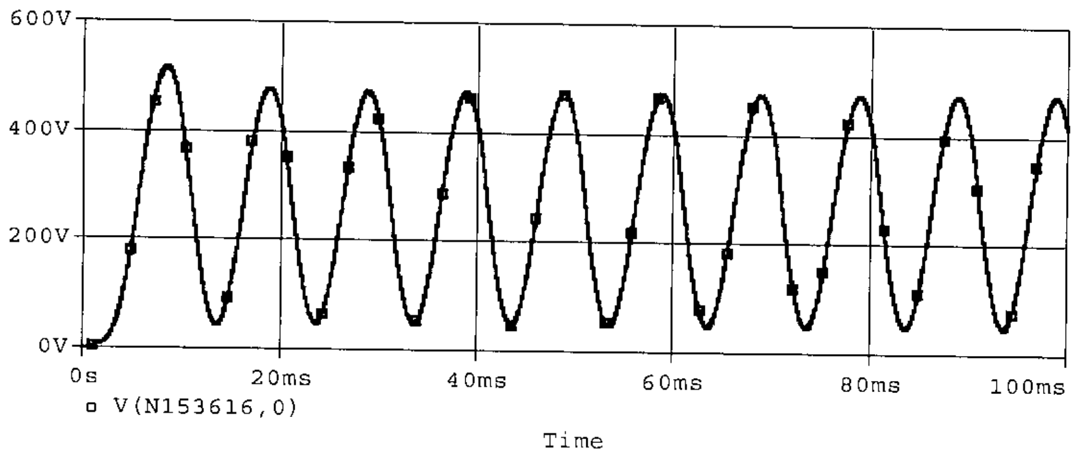


Figure-3.7(e) Rectifier stage Output Voltage.

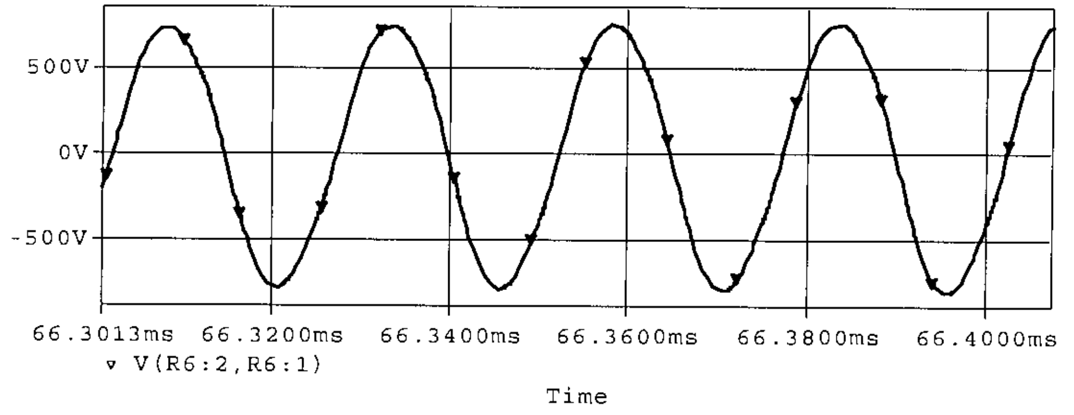


Figure-3.7(f) Resonant Inverter Output Voltage.

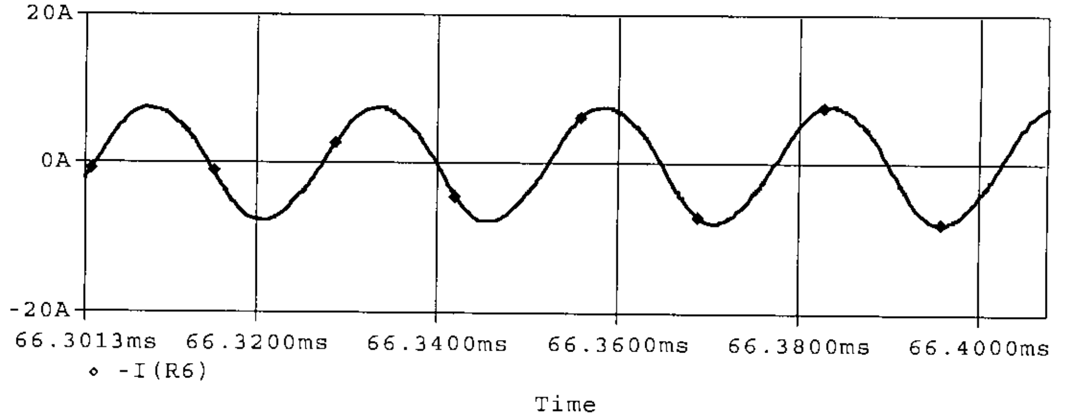


Figure-3.7(g) Resonant Inverter Load Current.

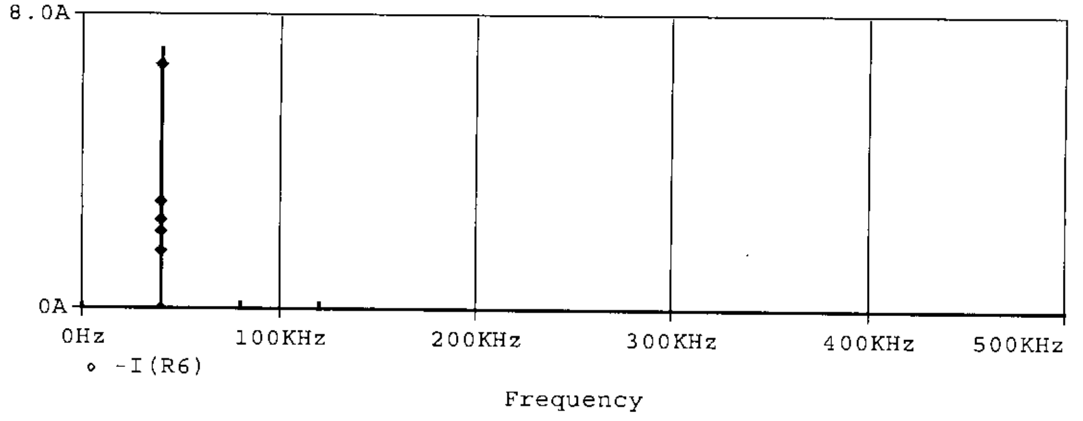


Figure-3.7(h) Output Current Harmonics.

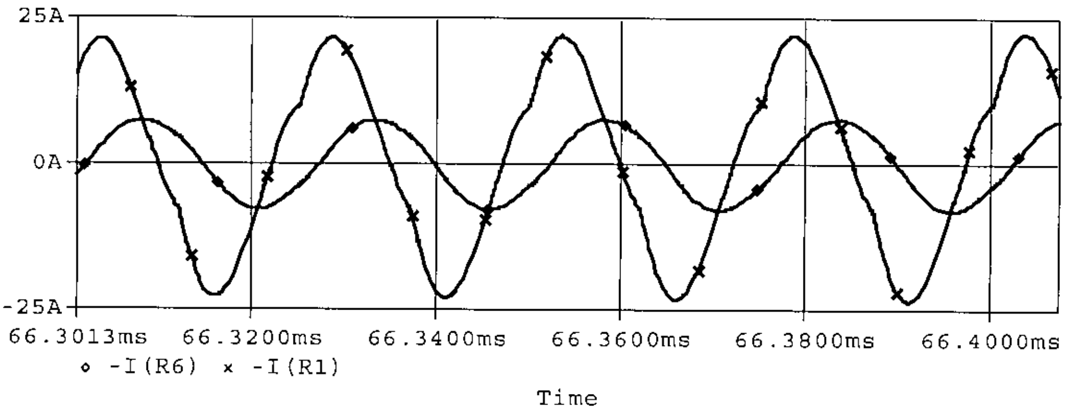


Figure-3.7(i) Output Current through Resistive load and Resonating branch.

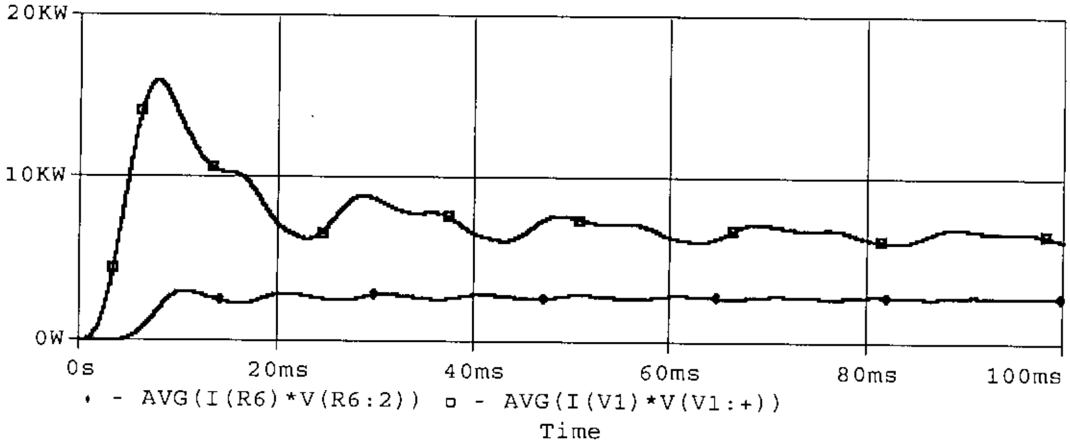


Figure-3.6(j) Average Input power, Output power of the rectifier-inverter circuit (efficiency = **48%** approx.).

Our observations and findings obtained from above figures (from fig-3.6 to fig-3.7) are tabulated in *Table-3.1* in following page.

Table-3.1: Comparison of a Boost and a Buck-boost rectifier fed Resonant Inverter configuration:

	Buck-boost	**Boost**
Buck-boost switch Duty-cycle	0.6	0.6
Input Current Total Harmonic Distortion	6.27%	15.92%
Input Power Factor	Almost Unity	0.99
Utility Input ac frequency	50 Hz	50 Hz
Input Current	4.95 A (rms)	70 A (rms)
Input Voltage	220 V (rms)	220 V (rms)
Average AC Input Power	510 watt	6kW
Inverter Output Current (resistive load)	2.26 A (rms)	8 A (rms)
Inverter Output Voltage (resistive load)	226 V (rms)	800 V (rms)
Resonant Inverter output frequency	40 kHz	40 kHz
Average Inverter Output Power	390 watt	3 kW
Overall Resonant Inverter Efficiency	Approx. 76%	Approx. 48%

From the above table it is found that the buck-boost circuit provides less total harmonic distortion than that of boost circuit. The boost configuration draws higher input current from the utility than the buck-boost one. In terms of efficiency the buck-boost circuit provides better result.

Chapter 4

Conclusion and Suggestion

4.1 Conclusion:

Objective of this thesis has been to design and study of an active filter based sinusoidal input current resonant inverter. The investigation started from a single-phase full-wave diode rectifier with no input-output filter. Then it has been continued to rectifiers with active filtering schemes (i.e. Boost, Buck-boost) having necessary input-output passive filters. From the rectifier circuit configurations studied at the beginning it has been observed that the input current gets highly distorted after addition of the bulk capacitor across bridge rectifier output needed for pure dc output. This distortion is measured in terms of %THD which causes the input current wave-shape to be changed from its sinusoidal wave-form. High frequency harmonic components associated to the fundamental current component exist. Though the thesis title says more about the resonant inverter, the main objective of shaping the input current to nearly sinusoidal, needs attention at the rectifier stage.

From observations listed in *Table-2.3* it has been found that boost rectifiers without input filter provides high efficiency but very poor THD of 44.1%. And boost rectifiers with input-output filter gives low THD of 4.9% but have very low efficiency. Moreover in some circuit configurations it was found that the input current waveform is not stable and symmetrical in boost rectifier scheme. In *Table-2.4* we observed that buck-boost rectifiers provide THD like 4.28% as well as very good efficiency like 95%.

So we choose buck-boost rectifier to cascade with resonant inverter stage. In *Chapter-3* a resonant inverter with buck-boost rectifier has been studied. The findings and observations are listed in *Table-3.1*. This configuration provides input current THD as 6.27% and overall efficiency as 76%. In our simulation study we found that increase in efficiency simultaneously increases THD of input current, thus distorting the utility current wave form to a great extent. This is why, we just chosen buck-boost configuration and passive filter components as to make a trade-off between tolerable THD and better efficiency. In this configuration, power factor has been obtained as good as unity.

4.2 Suggestion for Future Work:

In this thesis, study has been done by simulation only. A practical implementation of Boost and Buck-boost regulator based resonant inverter can be a future work. The practical circuit would require implementing the following items:

1. Capacitor and Inductor selection for input-output filter;
2. IGBT design for maximum current stress and gate delay;
3. Control logic for the total regulator system;
4. Base drive with proper isolation;
5. Switching logic with almost zero delay.

Favorable outcomes from the above points can lead towards a successful single phase active filter base rectifier fed resonant inverter with nearly sinusoidal input current having high efficiency and good power factor.

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