Harmonic Mitigation in Transformers of a Twelve-Pulse Rectifier Using Active Filter

by

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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.

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29.02.08

Mohammad Rubaiyat Tanvir Hossain

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List of Abbreviations of Technical Symbols

C_i, CF	AC input filter capacitance
C_o, Cload	DC output filter capacitance
C_{PWM}	Boost capacitor
D	Duty cycle
D_{PWM}	Boost diode
f_i	Supply frequency
f_r	Ripple frequency
f_{SW}	PWM switching frequency
I_s	12-pulse Rectifier input line current
I_O	12-pulse Rectifier output current
I_{dy}	Delta-wye transformer current (primary) of 12-pulse Rectifier
I_{yy}	Wye-wye transformer current (primary) of 12-pulse Rectifier
L_{dyp}	Delta-wye transformer primary winding inductance
L_{dys}	Delta-wye transformer secondary winding inductance
L_i, LF	AC input filter inductance
L_o, Lload	DC output filter inductance
L_{PWM}	Boost inductor
L_{yy}	Wye-wye transformer winding inductance
M_h	Magnitude of either the voltage or current harmonic component
$M_{fundamental}$	Magnitude of either the fundamental voltage or current
N	Number of turns
$Rload$	12-pulse rectifier resistive load
THD_I_s	Total harmonic distortion of input line current
THD_I_{yy}	Total harmonic distortion of wye-wye transformer current

THD_I_{dy}	Total harmonic distortion of delta-wye transformer current
V_O	12-pulse Rectifier output voltage
V_n	Ripple voltage before filtering
V_{on}	Ripple voltage after filtering
η	Efficiency

List of Abbreviations of Technical Terms

ASD	Adjustable Speed Drives
BESS	Battery Energy Storage Systems
BJT	Bipolar Junction Transistor
DBC	Double Boost Converters
HVDC	High Voltage Direct Current
IEC	International Electrical Commission
IEEE	Institute of Electrical and Electronic Engineers
IGBT	Insulated Gate Bipolar Transistor
PCC	Point of Common Coupling
PWM	Pulse Width Modulation
SBC	Single Boost Converter
SCR	Silicon controlled rectifier
THD	Total Harmonic Distortion
UPS	Uninterruptible Power Supply

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Abstract

In this thesis an active filtering scheme for input current wave shaping of the transformers used in a 12-pulse rectifier system has been proposed, analyzed and compared with passive filtering technique. Both ac and dc filter have been designed and the most appropriate position of the ac filter has been checked and determined in passive filtering scheme. With the active filtering scheme high switching frequency PWM Boost converter has been used at the output of the ac to dc rectifier to shape the input currents by eliminating high frequency harmonic components with small sized filters. The number of Boost stages and its/their position at the output stage have been found out to get a good solution to the problem. With the proposed method the transformers as well as the rectifier draw near sinusoidal currents from the utility. Performance evaluation of the proposed scheme has been carried out and compared with the passive filtering scheme under similar conditions. The outcome is expected to provide a better solution to harmonic mitigation of input current in transformers of a twelve-pulse rectifier.

CHAPTER 1

Introduction

1.1 Background and present state of the problem

Electronic circuits in modern power appliances require stable and regulated dc power supplies. AC to DC conversions done by diode rectifiers followed by filter capacitors are the most common in power converter used for such purposes [1]. Rectifiers are nonlinear circuit element and hence generate harmonic currents. These harmonic currents are injected into the ac power lines /transformers /source [2-3]. The non-sinusoidal shape of the input currents drawn by the rectifiers causes a number of problems for the power distribution network and for other electrical systems in the vicinity of the rectifier including:

1) phase displacement of the current and voltage fundamentals requires that the source and distribution equipment handle reactive power increasing their volt-ampere ratings;
2) high input current harmonics and low input power factor;
3) lower rectifier efficiency because of the large r.m.s. values of the input current;
4) input ac mains voltage distortion because of the associated higher peak currents;
5) high reactive components size;
6) heat loss due to I^2R drop in wire and eddy-current loss and core loss in the transformer core result in lower transformer efficiency;
7) Lower power conversion reliability;
8) Excitation of system resonances;
9) The inefficient use of electric energy, the discontinuous conduction of the bridge rectifier results in a high total harmonic distortion (THD) in the input lines;
10) Malfunctioning of the sensitive electronic equipments.

As a result, development of ac to dc converters/ rectifiers with improved waveforms has gained importance due to stringent power quality regulation and strict limit on total harmonic distortion (THD) of input current placed by standards such as IEC 1000-3-2 and IEEE 519-1992 [4-6]. This has led to constant research in finding various passive and active element based alternative techniques that modify classical diode bridge rectifier followed by a bulk capacitor so that power quality improves due to input current wave shaping [1], [7]-[9]. The most rugged, reliable and cost-effective solution to mitigate these harmonics is to use multi-pulse methods [10], [11]. The essence of these methods is to use multiple converters, which draw currents in a phase-staggered manner, resulting in the cancellation of certain harmonics. A common solution to overcome potential harmonic distortion problems is to specify 12-pulse or 18-pulse rectifiers to comply with distortion limits as specified in e.g. IEEE 519-1992 [4]. Twelve pulse rectifiers are widely used in mid and high-power applications such as heating, ventilating and air conditioning applications, large rated dc drives and ac drives, and in dc large power supplies because of their theoretical ability to achieve low input current harmonics and to reduce the output ripples and to increase the ripple frequencies [9-15]. However, 12 pulse front ends do not meet IEEE 519 harmonic standard without additional filtering. Table 1.1 shows the harmonic component of supply current of a typical 12-pulse rectifier. An 18-pulse rectifier front end is the minimum pulse number required to meet IEEE 519 standard without any additional harmonic filtering [10]. Harmonic filtering is thus needed for 12-pulse rectifier-utility interface to meet IEEE-519 harmonic current limits [12-14].

Table 1.1: Harmonic content of a typical 12 pulse rectifier

	12 pulse load	**IEEE-519 Std.**
5^{th}	3% - 6%	5.6%
7^{th}	2% - 6%	5.6%
11^{th}	5% - 9%	2.8%
13^{th}	3% - 8%	2.8%
THD	**7.5% - 14.2%**	**7.0%**

Several approaches have been proposed in the literature to improve the performance of twelve-pulse-rectifiers.

Most of the active filtering schemes proposed previously require high bandwidth PWM converters to perform the desired harmonic filtering function [16]-[18]. Such implementations are not viable and cost effective for higher power applications (10MW and above).

Therefore, 12 pulse front-end nonlinear loads usually adopt conventional passive filter system, e.g. L-C tuned filters at 5^{th}, 7^{th}, 11^{th}, and 13^{th} harmonic frequencies. Although 12 pulse nonlinear loads do not produce significant 5th and 7th harmonic current, one cannot install 11^{th} and 13^{th} harmonics L-C tuned filters directly, because severe series and parallel resonance of passive filter and line impedance are likely to occur close to 5^{th} and 7^{th} harmonic frequencies. The 5^{th} and 7^{th} L-C tuned filters are required to force the resonance frequency away from 5^{th} and 7^{th} harmonic frequencies respectively. Therefore, 5^{th}, 7^{th}, 11^{th}, and 13^{th} L-C tuned filters are all required for passive filtering of 12 pulse front-end nonlinear load.

Dominant Harmonic Active Filter (DHAF) based on square-wave inverters is another method proposed to cost-effectively meet IEEE 519 harmonic current limits for 12 pulse rectifier loads [12]. The proposed DHAF system employs square-wave inverters switching at 5^{th} and 7^{th} harmonic frequencies, which are transformer coupled in series with 11^{th} and 13^{th} passive filters respectively. The square-wave inverters are controlled to provide 'harmonic isolation' between the supply and load at 5^{th} and 7^{th} harmonic frequencies. The square-wave inverters are rated 1% - 2% of the load KVA rating. The proposed DHAF system eliminates the need for large KVAR rated and bulky 5^{th} and 7^{th} passive filters, delivers superior harmonic filtering performance, and provides cost-effective harmonic filtering solution.

S. Miyairi et *al.* [19] have proposed a sophisticated thyristor converter system for reducing the supply current harmonics by means of an interphase reactor equipped with multiple switched taps. Although the proposed system has similar characteristics to a 36-pulse converter, it requires an interphase reactor with multiple taps switched by additional thyristors. Choi *et al.* [20] have proposed a parallel connected diode rectifier with an active interphase reactor.

Reference [21] proposes a novel interphase reactor design, indispensable for the parallel-connected 12-pulse thyristor converter. In this design, only one interphase reactor with a much small inductance value than the conventional values is utilized, and no additional switching devices or passive components are required. As the inductance value is decreased, the supply current of the 12-pulse thyristor converter with the interphase reactor approaches a sinusoidal waveform which is more sinusoidal than that of a 36-pulse thyristor converter.

In scheme of [22], a low KVA [0.02 P_o (PU)] active current source injects a triangular current into an interphase reactor of a twelve-pulse diode rectifier. This modification results in near sinusoidal utility line currents with less than 1% THD. It is further shown that a low KVA, 12-pulse system with an autotransformer arrangement [KVA rating of 0.18 P_o (PU)] can be implemented with the proposed active interphase reactor. The resulting system draws clean power from the utility and is suitable for powering larger KVA ac motor drive systems. The methods of [19]-[22] require the use of an interphase reactor, which is generally bulky and difficult to design.

Reference [14] presents a new method to eliminate harmonics drawn by a twelve-pulse rectifier through modulation of the dc bus. A PWM converter with low ratings is inserted in the dc link and controlled in a fashion that results in sinusoidal currents at the input. The bulk of the power transfer is handled by the diode bridges, while the additional PWM converter deals only with a ripple voltage. In addition to the increased component count, disadvantages of the proposed method include higher ripple current in the bridges and requirement of a controller for the modulator.

Reference [23] has presented a quasi 12- and 18-pulse rectifier scheme for standard 6-pulse diode rectifiers and it is shown that a significant harmonic current reduction can be obtained by the use of this topology. However, practical aspects such as the resulting voltage distortion and behavior at pre-distorted grid were not discussed.

Steffan *et al.* [24] has reported a quassi 12-pulse rectifier for harmonic reduction. An analysis of the standard diode rectifier shows that the harmonic currents to some degree are independent of the load. As a result, near true 12-pulse rectifier line currents for a wide load range can be achieved with the quasi 12-pulse scheme. Furthermore, it is shown that the harmonic performance of the quasi 12-pulse scheme actually is superior to the true 12-pulse rectifier if the supply voltage is pre-distorted. But here the THD of the ac mains current at full load is 10.5% and at 40% load, it is around 20%.

Autotransformer-based 12-pulse ac-dc converters have been reported [25] for reducing the total harmonic distortion (THD) of the ac mains current, but in this case, the dc-link voltage is high. To ensure equal power sharing between the diode bridges and to achieve good harmonic cancellation, this topology needs interphase transformers and impedance-matching inductors, resulting in increased complexity and cost. To achieve similar performance with reduced magnetic, dc ripple reinjection has been used [26], [27] for harmonic current reduction. One such configuration has been reported [28], but the dc-link voltage is higher than that of a six-pulse diode bridge rectifier, thus making the scheme nonapplicable for retrofit applications. To overcome this problem of higher dc-link voltage, Hammond [29] has proposed a new topology, but the transformer design is very complex. To simplify the transformer design, Paice [30] has reported a new topology for 12-pulse ac-dc converters. But this topology requires higher ratings magnetic, resulting in increase of capital cost. Kamath *et al.* [31] have also reported a 12-pulse converter, but the THD of the ac mains current is high even at full load (10.1%) and as load decreases, the THD increases further (17% THD at 50% load).

In reference [32], a novel autotransformer-based 12-pulse ac-dc converter with reduced kilovolt-ampere (KVA) rating is proposed to feed the vector-controlled induction motor drives (VCIMDs). The presented technique for the design of the autotransformer provides flexibility in design to vary the output voltages to make it suitable for retrofit applications without much alteration in the system layout.

1.2 Objective of the thesis

The objective of this work is to investigate a scheme to reduce the total harmonic distortion (THD) of input currents drawn by the transformers of a twelve-pulse rectifier. The twelve-pulse rectifier consists of two six-pulse rectifiers, displaced by 30 electrical degrees, connected in series. A delta-wye and a wye-wye transformer have been used to obtain the necessary phase shift. Both passive and active filtering techniques have been used separately to make the input current almost sinusoidal. Passive filtering techniques employing inductor and/or capacitors to reduce the amplitude of the low frequency harmonics are attractive for their simplicity and reliability, although size and weight of these filters are comparatively large. Active filtering technique of a rectifier current uses high switching frequency PWM Boost converter that shapes the input current by eliminating high frequency with small sized filters. This technique has been used in the single phase and three phase conventional rectifiers so far. No mention has been found in literature about the technique being used in twelve-pulse rectifier. In this investigation, the Boost converter has been incorporated at the output of a twelve-pulse rectifier to shape the input current and also the currents in the windings of transformers used for twelve-pulse rectifier. The number of Boost stages and its/their position at the output stage has been determined to get an improved solution to the problem. Also filter design has been done to eliminate the high frequency components in the current, which appears as a result of high frequency switching of the Boost converter stage. Performance evaluation of the proposed scheme has been carried out and compared with the passive filtering scheme under similar conditions. The outcome is expected to provide a better harmonic reduction of input current in transformers of a twelve-pulse rectifier.

1.3 Thesis Outline

This thesis includes five chapters. Background followed by literature review and objective of the thesis are presented in Chapter 1. In chapter 2 the harmonic problem is addressed and different mitigation techniques are reviewed and discussed. Chapter 3 describes the harmonic phenomena in twelve-pulse rectifier and discusses in detail different filtering schemes to reduce the total harmonic distortion (THD) of input currents drawn by the transformers of a twelve-pulse rectifier. Chapter 4 presents the simulation results obtained and different performance parameters including total harmonic distortion (THD), efficiency etc. for different combinations to evaluate the performance of the proposed scheme with the passive filtering scheme under similar conditions in order to determine a better harmonic mitigation method. Conclusion and suggestions for future research are given in Chapter 5.

CHAPTER 2

Harmonics Phenomena

2.1 Basics of the harmonics phenomena

Harmonics are integral multiples of some fundamental frequency that, when added together, result in a distorted wave form. Harmonic currents and voltages are created by non-linear loads connected on the power distribution system. Harmonic distortion is a form of pollution in the electric system that can cause problems if the harmonics increase above certain limits. All power electronic converters used in different types of electronic systems can increase distortion of voltages and currents by injecting harmonics directly into the utility lines. The principle of how the harmonic components are added to the fundamental current is shown in Figure 2.1, where only the 5^{th} harmonic is shown.

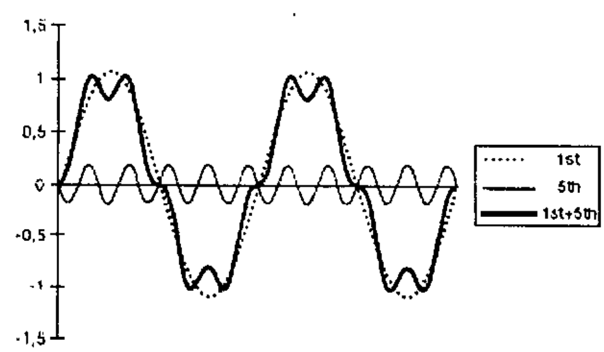


Figure 2.1: The total current as the sum of the fundamental and 5^{th} harmonic

As an example, problem of harmonics in ac drives is discussed. Before a discussion on harmonics, it is necessary to have an understanding of a PWM AC drive, specifically how it draws power from the utility line. Figure 2.2 is a schematic diagram of a typical "voltage source" AC drive.

A modern AC drive consists of three stages. The first stage of the drive converts three-phase AC to DC. The first stage is the converter section. In an AC drive, the converter stage consists of a three phase, full wave diode bridge, though SCRs (Silicon controlled rectifiers) are sometimes used in place of diodes. A "filter" stage is required to smooth out the ripple on the DC bus. This consists of a large capacitor bank. Often an inductor or "link choke" is added. The choke, when used, helps buffer the capacitor bank from the AC line and serves to reduce pulse current due to sudden capacitor changing. The third stage is the inverter section. This section uses high-speed switches to apply a "Pulse Width Modulated" or PWM waveform to the motor.

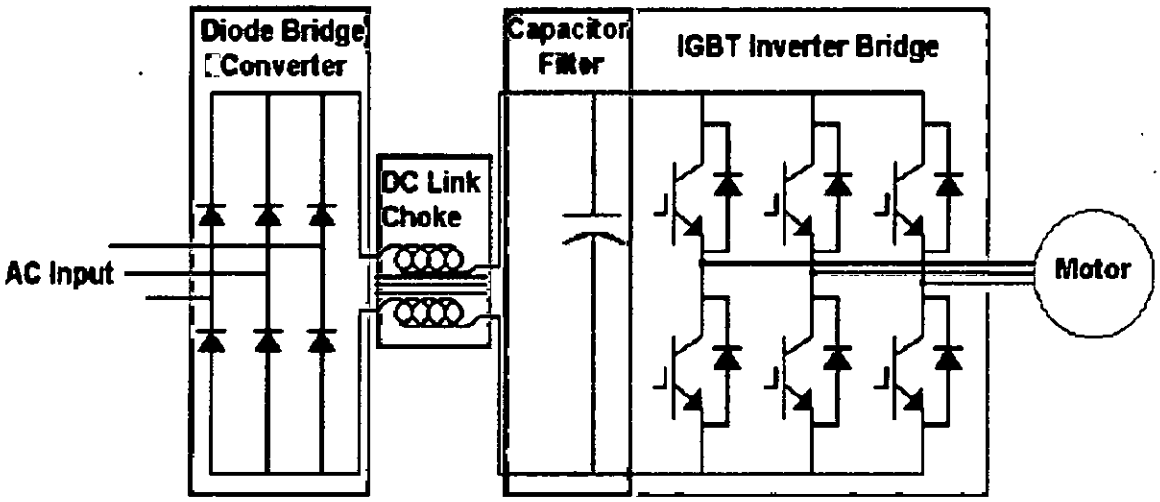


Figure 2.2: Typical AC Drive Power Structure

The rectifier and the filter that have affect on the power line. In figure 2.3 is a single phase diode rectifier circuit with a filter capacitor and load resistor across the DC bus.

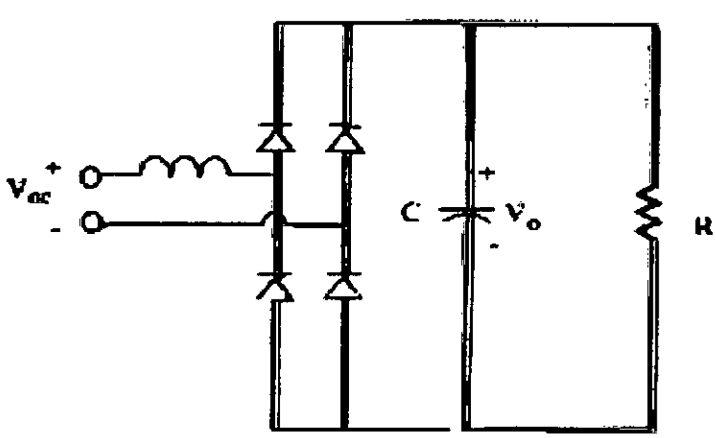


Figure 2.3: Single Phase Converter and Filter.

Upon application of AC power the capacitor will charge up to the peak of the applied line voltage through the diode bridge. When the polarity of the AC input changes, the conducting and blocking diode pairs also change. When a load is applied to the DC bus, the capacitor will begin to discharge. With the passing of the next input line cycle, the capacitor only draws current through the diodes and from the line when the line voltage is greater than the DC bus voltage. This is the only time a given diode is forward biased. This occurs at or near the peak of the applied sine wave resulting in a pulse of current that occurs every input cycle around the +/- peak of the sine wave. As load is applied to the DC bus, the capacitor bank discharges and the DC voltage level drops. A lower DC voltage level means that the peak of the applied sine wave is higher than the capacitor voltage for a longer duration. Thus the width of the pulse of current is determined in part by the load on the DC bus. Figure 2.4 shows input line voltage V_{ac}, Filtered DC bus voltage V_o and the pulsating Input Current *I*.

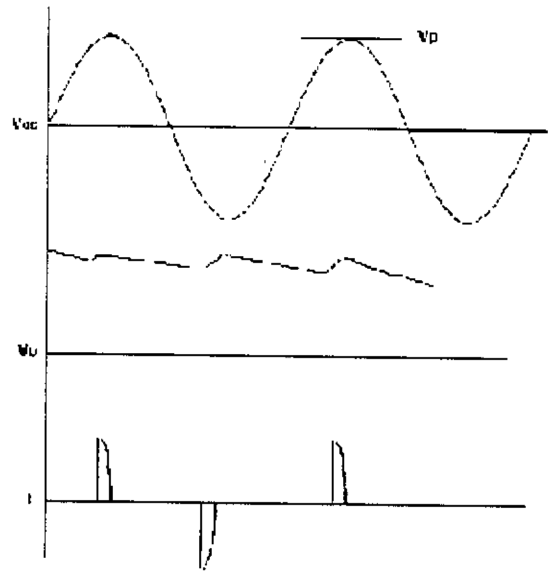


Figure 2.4: Single Phase Converter Measurements.

The aforementioned characteristics hold true for the three phase model with the difference being 6 diodes and 6 pulses per cycle rather than two pulses per cycle as shown in the single phase model. A three phase rectifiers currents is always nonsinusoidal even without the output filter circuit because only two 60^0 pulses conduct in each cycle of a line current of a three phase diode bridge rectifier. It is the pulsating input current shown in figure 2.5 that gives the term "nonlinear load" since the current does not flow in proportion to the applied voltage.

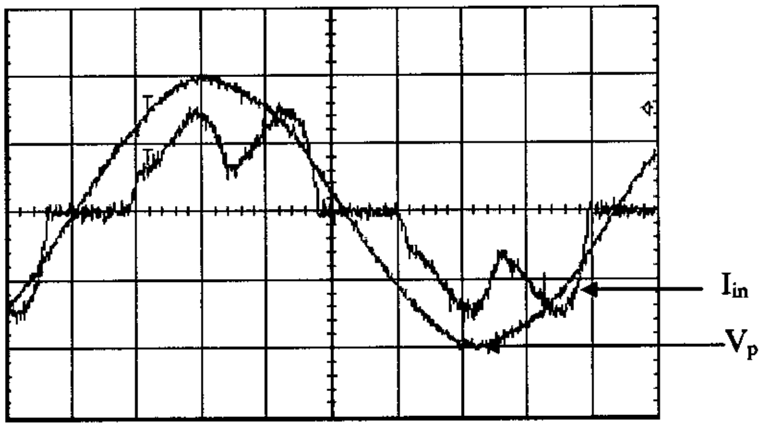


Figure 2.5: Input Line to Neutral Voltage and Input Current on phase A of a 3 phase AC drive.

In a three-phase system, the widest conduction time possible would be 120 degrees (roughly +/-60 degrees from the peak). Outside this 120 degree conduction window, one of the other two phases will have a higher peak voltage and current will flow from that phase.

In figure 2.6 each waveform is close to a perfect sine wave and the current is proportional to voltage (although the current is lagging the voltage). This is a linear load and contains no harmonics. A perfect sine wave by definition has no harmonics but rather one fundamental component at one frequency. The waveforms in figure 2.6 are sine waves at one frequency, 50 Hz. It has already been mentioned that AC to DC 1-φ rectifiers have distorted waveforms.

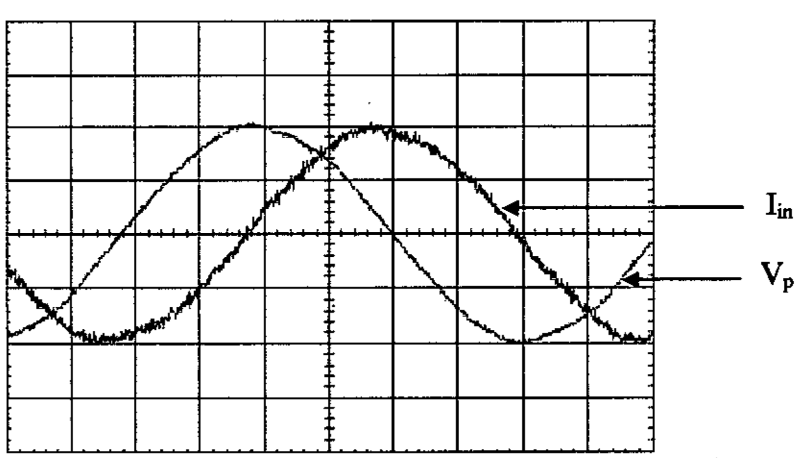


Figure 2.6: 50Hz Input Line to Neutral Voltage and Input Current on phase A of a linear load.

Something about the harmonic content of any waveform can be observed by simply looking at the wave shape. The more it looks like a sine wave, the lower the harmonic content. The sources of most even harmonics are arc furnaces, some florescent lights, welders and any device that draws current in a seemingly random pattern. Another noteworthy fact is that balanced three phase rectifier type loads (such as an AC drive) do not produce a third harmonic component. Nor do they produce any harmonic component with 3 as a multiple (3^{rd}, 9^{th}, 15^{th}, 21^{st} etc). In figure 2.7 no even harmonics or triplens is present. The 11^{th} harmonic and higher is a point where the magnitude diminishes to a very low level.

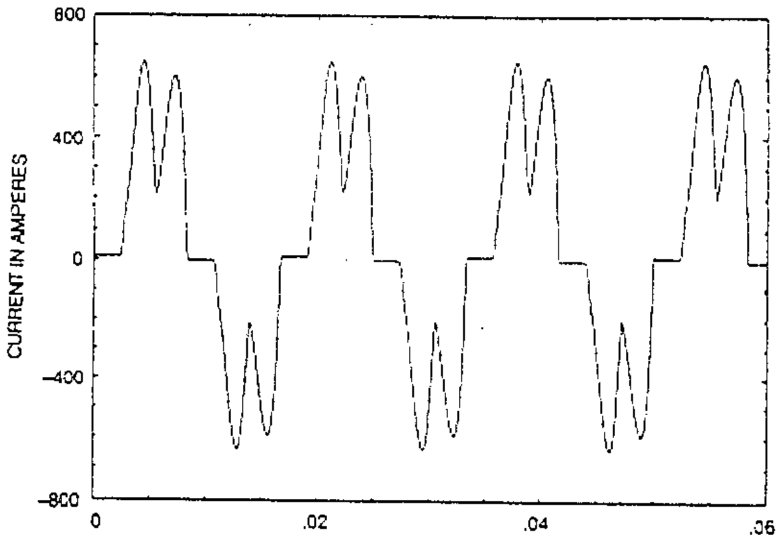


Figure 2.7: Typical input current for an AC drive under load.

2.2 Harmonic Problems

Since harmonic currents flow in an AC drive with a 6 pulse rectifier at the front end, what, if any, problem this may cause. Although noise coupling into phone lines and other equipment is often sited, the main issue is the added cost of the power distribution infrastructure. Power is only transferred through a distribution line when current is in phase with voltage. This is the very reason for concerns about input "power factor".

Neither ***harmonic*** nor ***reactive*** current flowing through a system produces working power. The power infrastructure has to carry these currents causing heat loss due to increased I^2R drop in the wire and higher flux in transformer iron. Transformers and distribution lines in some cases need to be upsized to handle the burden of this additional non power producing current.

Harmonic current distortion can also introduce voltage distortion. Since a typical 6 pulse nonlinear load draws current only near the peak of the sine wave, I^2R voltage drop or loading effect on transformers and power lines only occurs at the peak. A combination of high source impedance and harmonic currents can cause a "flat topping" effect on the line voltage. The distorted line voltage might then introduce harmonic currents in other linear loads in the system. Harmonic current in a motor does not contribute to torque at the shaft, but does add heat and can raise the operating temperature of a motor.

2.3 Harmonic Standards and Recommended Practices

In view of the proliferation of power converter equipment connected to the utility system, various national and international agencies have considered limits on harmonic current injection to maintain good power quality. As a consequence, various standards and guidelines have been established that specify limits on the magnitudes of harmonic currents and harmonic voltages. Harmonic distortion measurements are normally given in "total harmonic distortion" or THD. THD defines the harmonic distortion in terms of the fundamental current drawn by a load:

$$THD\ \% = \frac{\sqrt{\sum_{h=2}^{h=\infty}(M_h)^2}}{M_{fundamental}} \times 100\ \% \qquad \ldots\ldots\ldots (2.1)$$

where M_h is the magnitude of either the voltage or current harmonic component and $M_{fundamental}$ is the magnitude of either the fundamental voltage or current..

The Comite′ Europe′en de Normalisation Electrotechnique (CENELEC), International Electrical Commission (IEC), and West German Standards (VDE) specify the limits on the voltages (as a percentage of the nominal voltage) at various harmonics frequencies of the utility frequency, when the equipment-generated harmonic currents are injected into a network whose impedances are specified. The IEEE-519 document has set limits on the level of "allowable harmonics" and specified these limits at "the point of common coupling" or PCC. The PCC is the point where the customer meets the utility, and is usually the point between the utility transformer and the customer's facility transformer as in figure 2.8.

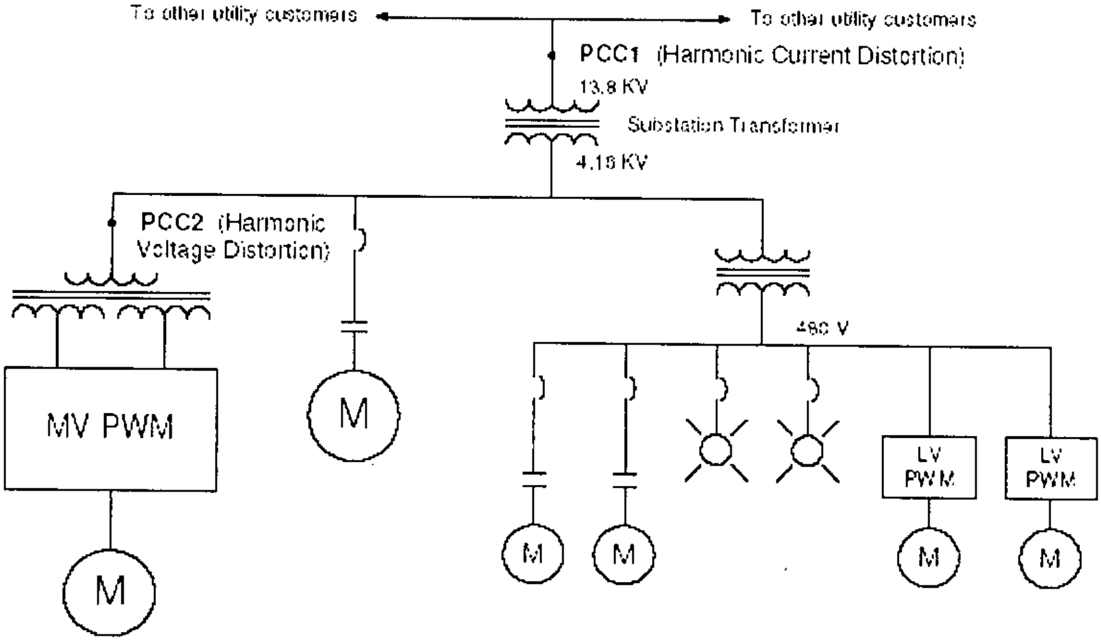


Figure 2.8: Example of the PCC

In accordance with IEEE-519 standards (Institute of Electrical and Electronic Engineers), Table 2.1 lists the limits on the harmonic currents that a user of power electronics equipment and other nonlinear loads is allowed to inject into the utility system. The values are given at the point of connection of nonlinear loads.

Table 2.1: Harmonic current limits in percent of fundamental

Short circuit current [pu]	$h<11$	$11 \le h < 17$	$17 \le h < 23$	$23 \le h < 35$	$h \ge 35$	**THD**
<20	4.0	2.0	1.5	0.6	0.3	5.0
20-50	7.0	3.5	2.5	1.0	0.5	8.0
50-100	10.0	4.5	4.0	1.5	0.7	12.0
100-1000	12.0	5.5	5.0	2.0	1.0	15.0
>1000	15.0	7.0	6.0	2.5	1.4	20.0

The total current harmonic distortion allowed in Table 2.1 increases with the value of short-circuit current. The total harmonic distortion in the voltage can be calculated in a manner similar to that given by eq. (2.1). Table 2.2 specifies the individual harmonics and the THD limits on the voltage that the utility supplies to the user at the connection point.

Table 2.2: Harmonic voltage limits in percent of fundamental

Voltage level	**2.3-69 kV**	**69-138 kV**	**>138 kV**
Maximum for individual harmonic	3.0	1.5	1.0
Total Harmonic Distortion (THD)	5.0	2.5	1.5

2.4 Harmonic Mitigating Techniques

Various techniques of improving the input current waveform are discussed below. The intent of all techniques is to make the input current more sinusoidal so as to reduce the overall current harmonic distortion. The different techniques can be classified into four broad categories:

(a) Introduction of line reactors and/or dc link chokes;

(b) Passive Filters (Series, Shunt, and Low Pass broad band filters);

(c) Phase Multiplication (12-pulse, 18-pulse rectifier systems); and

(d) Active Harmonic Compensation.

Available harmonic mitigation technologies are discussed with their relative advantages and disadvantages in following sections.

2.4.1 Introduction of line reactors and/or dc link chokes

2.4.1.1 Three-Phase Line Reactors

Line reactors offer significant magnitudes of inductance which can alter the way that current is drawn by a non-linear load such as an input rectifier bridge. The reactor makes the current waveform less discontinuous resulting in lower current harmonics. Since the reactor impedance increases with frequency, it offers larger impedance to the flow of higher order harmonic currents. It is thus instrumental in impeding higher frequency current components while allowing the fundamental frequency component to pass through with relative ease.

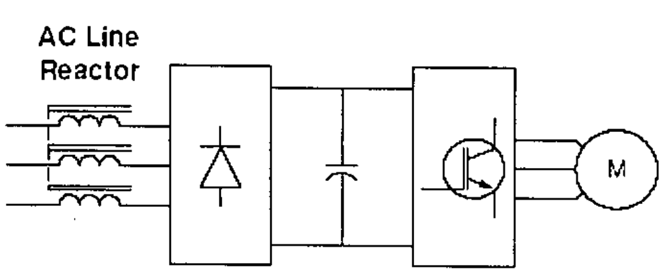


Figure 2.9: Three-phase Line Reactors

2.4.1.2 DC Link Choke

A DC link choke is electrically present after the diode rectifier bridge and before the dc bus capacitor. The dc link choke performs very similar to the three phase line inductance. The ripple frequency that the dc link choke has to handle is six times the input ac frequency for a six-pulse rectifier. The magnitude of the ripple current is small. However, the effective impedance offered by a dc link choke is only half its numerical impedance value when referred to the ac side. DC link chokes are electrically after the diode bridge and they do not offer any significant spike or overvoltage surge protection to the diode bridge rectifiers. It is, thus, a good engineering practice to incorporate both dc link choke and a 3 phase line reactor with a three phase rectifier.

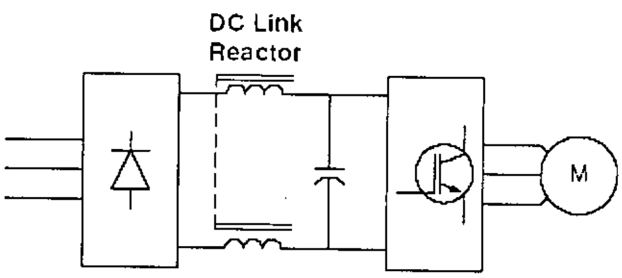


Figure 2.10: DC Link Reactors

2.4.2 Passive Filters

Passive filters consist of passive components like inductors, capacitors, and resistors arranged in a predetermined fashion either to attenuate the flow of harmonic components through them or to shunt the harmonic component into them. Passive filters can be of many types. Some popular ones are: Series Passive filters, Shunt Passive filters, and Low Pass broad band Passive filters. Series and Shunt passive filters are effective only in a narrow proximity of the frequency at which they are tuned.

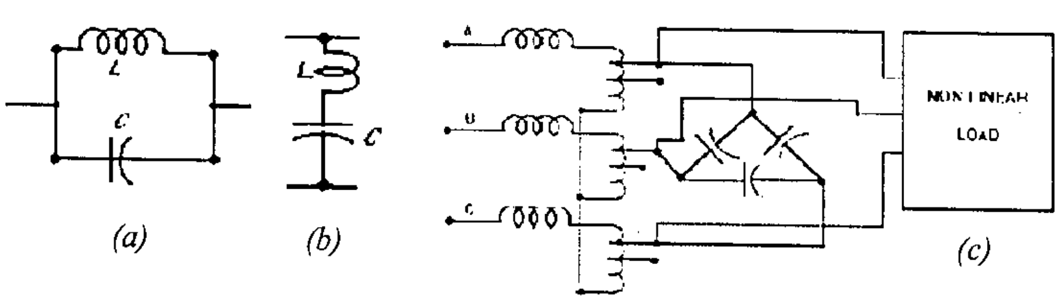


Figure 2.11: (a) Series, (b) Shunt and (c) Low Pass broad band passive filters

Low Pass broad band passive filters have a broader bandwidth and attenuate almost all harmonics above their cutoff frequency. The addition of a passive, tuned filter to a power system always has some risks involved with it. The risks are associated with the change that takes place to the system resonances. This can cause the filter to become the low-impedance sink for all of the harmonics in the power system to which it is tuned, possibly overloading the filter components. It can also cause voltage oscillations within the system leading to component failures.

2.4.3 Phase Multiplication

The characteristic harmonics generated by a semiconductor converter is a function of the pulse number for that converter. A 12-pulse converter will have the lowest harmonic order of 11. In other words, the 5th, and the 7th harmonic orders are theoretically non-existent in a 12-pulse converter. Similarly, an 18-pulse converter will have harmonic spectrum starting from the 17th harmonic and upwards. The lowest harmonic order in a 24-pulse converter will be the 23rd. The size of passive harmonic filter needed to filter out the harmonics reduces as the order of the lowest harmonic in the current spectrum increases. Hence, the size of the filter needed to filter out the harmonics out of a12-pulse converter is much smaller than that needed to filter out the harmonics of a 6-pulse converter. However, a 12-pulse converter needs two 6-pulse bridges and two sets of 30^0 phase shifted ac inputs. The phase shift is either achieved using an isolation transformer with one primary and two phase shifted secondary windings or auto-transformer which provide phase shifted outputs. Many different auto-transformer topologies exist and the choice of a topology over the other involves a compromise between ease of construction, performance, and cost. An 18-pulse converter would need three 6-pulse diode bridges and three sets of 20^0 phase shifted inputs; similarly, a 24-pulse converter would need four 6-pulse diode bridges and four sets of 15^0 phase shifted inputs. The transformers providing the phase shifted outputs for multi-pulse converters have to be properly designed to handle circulating harmonic flux.

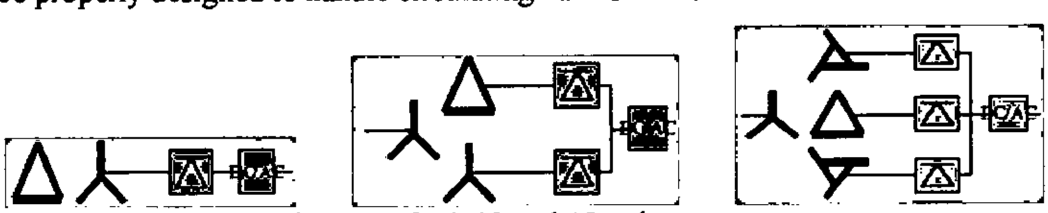


Figure 2.12: 6, 12 and 18 pulse converter

2.4.4 Active Harmonic Compensation

Most passive techniques discussed above aim to cure the harmonic problems once they have been created by non-linear loads. Active harmonic filters/conditioners are suitable for almost all types of application and can be preset to eliminate all the dominant harmonics from 2nd to 50th. There is built-in flexibility to cover for any future change in the load harmonic spectrum. Power flow through a switch becomes bi-directional and can be manipulated to recreate a current waveform which linearly follows the applied voltage waveform.

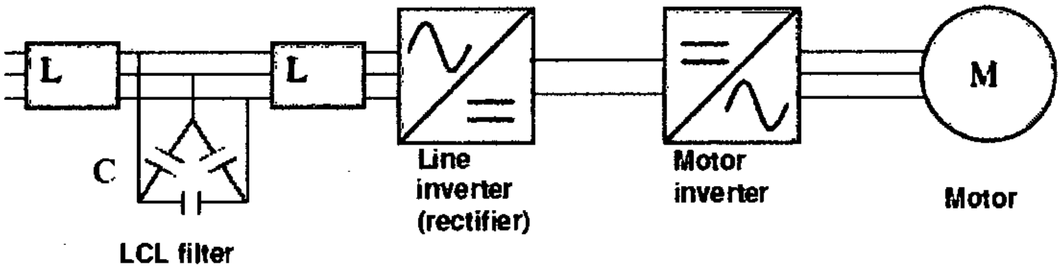


Figure 2.13: Active Filter front end with LCL filter

Apart from the active front ends, there also exists shunt active filters used for actively introducing a current waveform into the ac network which when combined with the harmonic current, results in an almost perfect sinusoidal waveform. One of the common active filter topology for use in retrofit applications is the combination of a series active filter along with shunt tuned passive filters. This combination is also known as the Hybrid Structure. However, selection should be only the shunt type active harmonic filters rather than the series connected ones to prevent risk due to overload or internal malfunction.

Manufacturers of smaller power equipment like computer power supplies, lighting ballast, etc. have successfully employed active circuits. Active filter topologies are complex and require switches and control circuits. The active filter topology also needs current and voltage sensors. The extra hardware increases the cost and component count, reducing the overall reliability and robustness of the design. There is no risk of resonance with this type of unit. In the long run this is a very effective method and it is the solution which meets all of the global stringent standards designed to contain harmonics.

CHAPTER 3

Harmonic Mitigation of Twelve Pulse Rectifier

3.1 Twelve-Pulse Rectifier

High quality low-harmonic rectification is becoming increasingly important, to meet regulations which limit ac line current harmonic content, such as IEEE-519. Twelve pulse rectifiers are widely used for high power applications such as heating, ventilating and air conditioning applications, large rated dc drives and ac drives, and in dc large power supplies because of their theoretical ability to reduce current distortion and to reduce the output ripples. In the mid 1960s when power semiconductors were only available in limited ratings, twelve-pulse drives provided a simpler and more cost effective approach to achieve higher current ratings than direct paralleling of power semiconductors. This technique is still employed today in very large drive applications.

Two 6-pulse bridges can be combined either in series or in parallel, displaced by 30 electrical degrees, to produce an effective 12-pulse output. A typical diagram of a twelve-pulse rectifier is shown in figure 3.1. Three-phase transformer connections can be used to shift the phase of the voltages and currents. This shifted phase can be used to cancel out the low-order harmonics. In figure 3.1 three-phase delta-wye and wye-wye transformers are used, where the delta-wye transformer connection shifts phases by 30°.

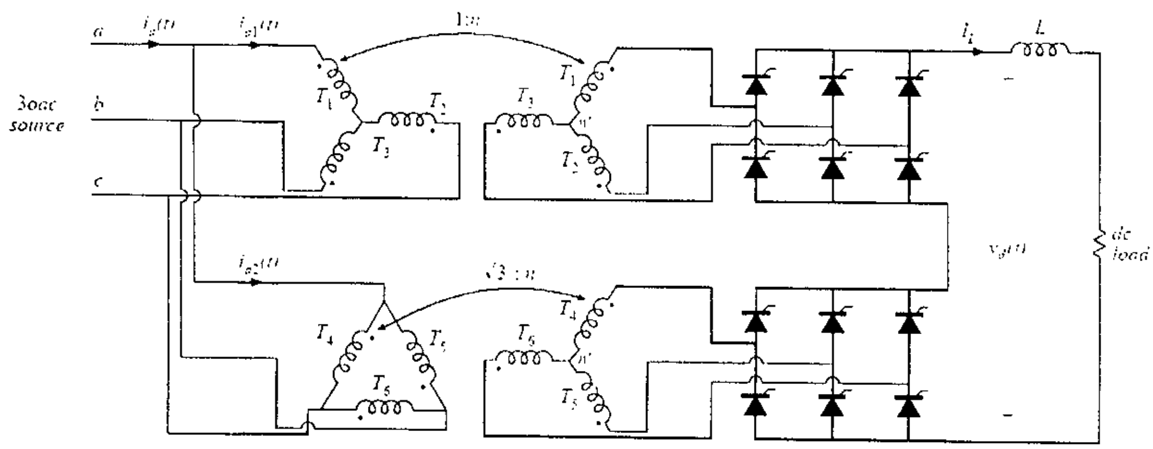


Figure 3.1: Twelve-pulse rectifier

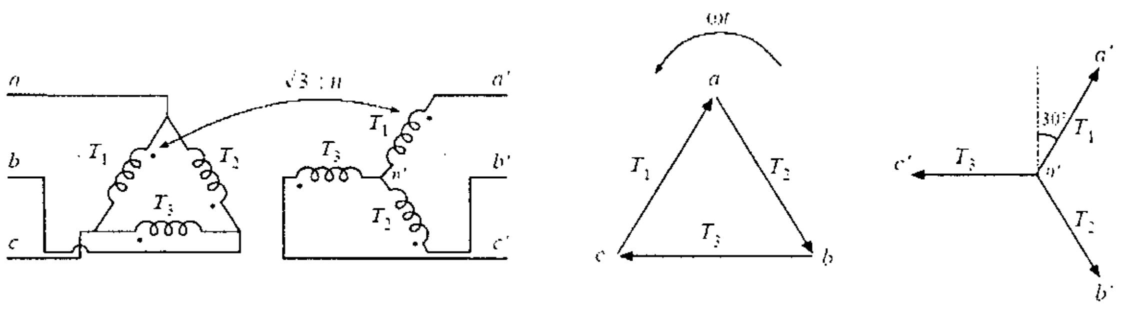


Figure 3.2: Transformer connections

The input current i_{a1} of the wye-wye transformer as shown in figure 3.3(a), is not a sinusoid. For example, the current generated from the primary of the wye-wye transformer has the following harmonic contents,

$$i_{a1} = \frac{2\sqrt{3}}{\pi} I_L (\cos\omega t - \frac{1}{5}\cos 5\omega t + \frac{1}{7}\cos 7\omega t - \frac{1}{11}\cos 11\omega t + \quad \ldots\ldots\ldots (3.1)$$

Some characteristics of the currents, obtained from equation (3.2) are:

i) the absence of triple harmonics;

ii) the presence of harmonics of order $6k \pm 1$ for integer values of k;

iii) harmonics of orders $6k + 1$ are of positive sequence, and

iv) harmonics of orders $6k - 1$ are of negative sequence;

v) the *rms* magnitude of the fundamental frequency is:

$$I_1 = \frac{\sqrt{6}}{\pi} I_L$$

vi) the *rms* magnitude of the *nth* harmonic is:

$$I_n = \frac{I_1}{n}$$

If either, the primary or the secondary three-phase windings of the rectifier transformer are connected in delta, the ac side current waveforms consist of the instantaneous differences between two rectangular secondary currents 120° apart as shown in figure 3.3(b). The resulting Fourier series for the current in phase "a" on the primary side of the delta-wye transformer is:

$$i_{a2} = \frac{2\sqrt{3}}{\pi} I_L (\cos\omega t + \frac{1}{5}\cos 5\omega t - \frac{1}{7}\cos 7\omega t - \frac{1}{11}\cos 11\omega t + \quad \ldots\ldots\ldots (3.2)$$

This series only differs from that of a wye connected transformer by the sequence of rotation of harmonic orders 6k ± 1 for odd values of k, i.e. the 5th, 7th, 17th, 19th, etc.

The resulting ac line current for the twelve-pulse rectifier is shown in figure 3.3(c), which is closer to a sinusoidal waveform. The resultant *ac* current is given by the sum of the two Fourier series of the input currents of the star connection (eq. 3.1) and delta connection transformers (eq. 3.2):

$$i_a = 2\left(\frac{2\sqrt{3}}{\pi}\right)I_L(\cos\omega t - \frac{1}{11}\cos 11\omega t + \frac{1}{13}\cos 13\omega t - \frac{1}{23}\cos 23\omega t + \ldots\ldots \quad (3.3)$$

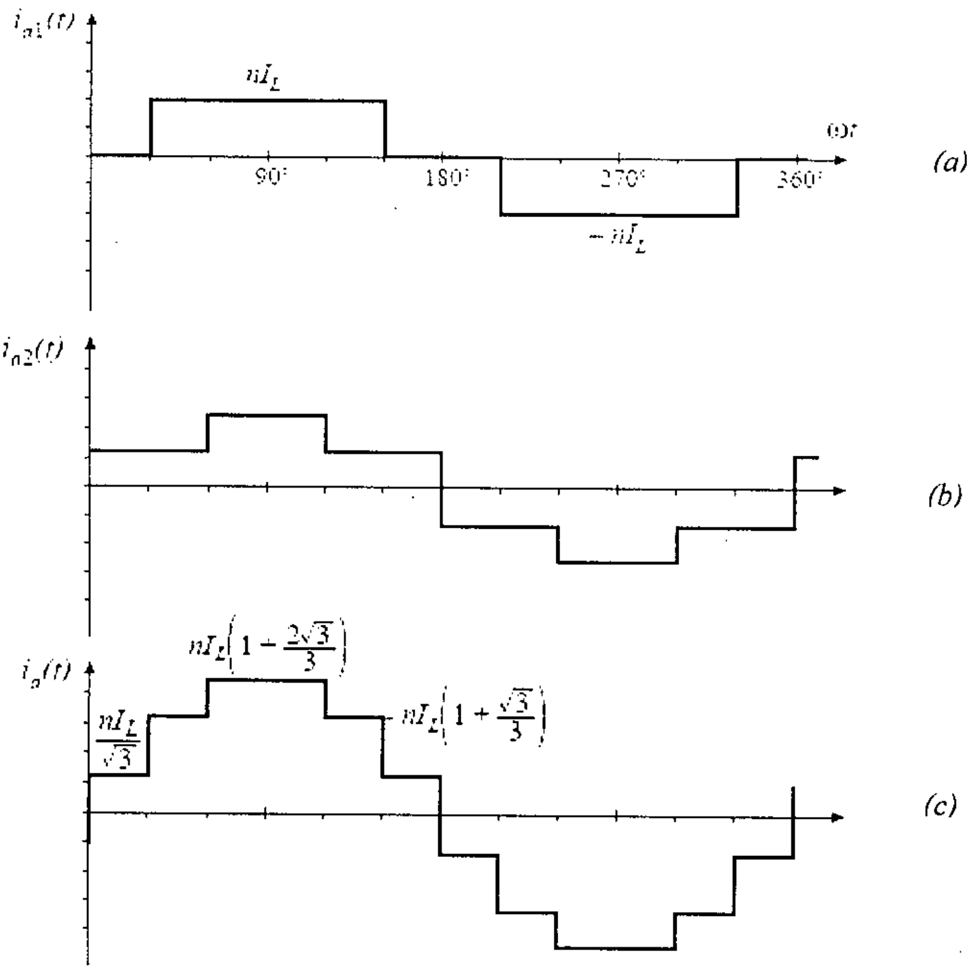


Figure 3.3: Waveforms of 12 pulse rectifier

From eq. (3.1), (3.2) and (3.3), it is noted that the 5th, 7th, 17th, 19th, etc. harmonics are eliminated in the input current of the twelve-pulse system. The ac line current contains 1st, 11th, 13th, 23rd, 25th, etc harmonics. Since these harmonic amplitudes vary as $1/n$ therefore proportional to the reciprocal of the harmonic number, the twelve-pulse system has a lower theoretical harmonic current distortion. However, 12 pulse front ends do not meet IEEE-519 harmonic standard without additional filtering. Also, the individual transformer windings carry nonsinusoidal current containing large low order harmonics. This requires over sizing of these transformers so that transformer windings are not overheated for a certain load. Thus different active and passive filtering schemes have been proposed and discussed here in detail to improve the performance of the twelve-pulse rectifier circuit.

3.2 Analysis of Twelve-pulse Rectifier Circuit

Figure 3.4 shows the schematic diagram using Hierarchical Block of a 12-pulse rectifier with a resistive load of 750 Ω. The rectifier circuit has been modeled using ORCAD simulation software. A three phase balanced supply with peak amplitude of 300 volt with supply frequency, $f_i = 50Hz$ is applied at the input. The 12-pulse rectifier's input circuit consists of two six-pulse rectifiers, displaced by 30 electrical degrees, operating in series. A wye-wye and a delta-wye transformer have been used to give the necessary phase shift to produce the desired twelve pulse output voltage and to cancel out the low-order harmonics. The transformers are designed using mutual inductances such that the trans-ratio $\frac{N1}{N2} = \sqrt{\frac{L1}{L2}}$. The turns-ratio of the wye-wye and delta-wye transformer are purposely chosen 1:1 and √3:1 respectively so that the peak output voltages of each transformer secondary are equal. Simulating the twelve-pulse rectifier circuit the wave shapes of the input line current of the supply (phase A) and the input currents of the transformers, the output voltage and current and their respective frequency spectrums have been found which are presented in figure 3.7, 3.8, 3.9 and 3.10 respectively.

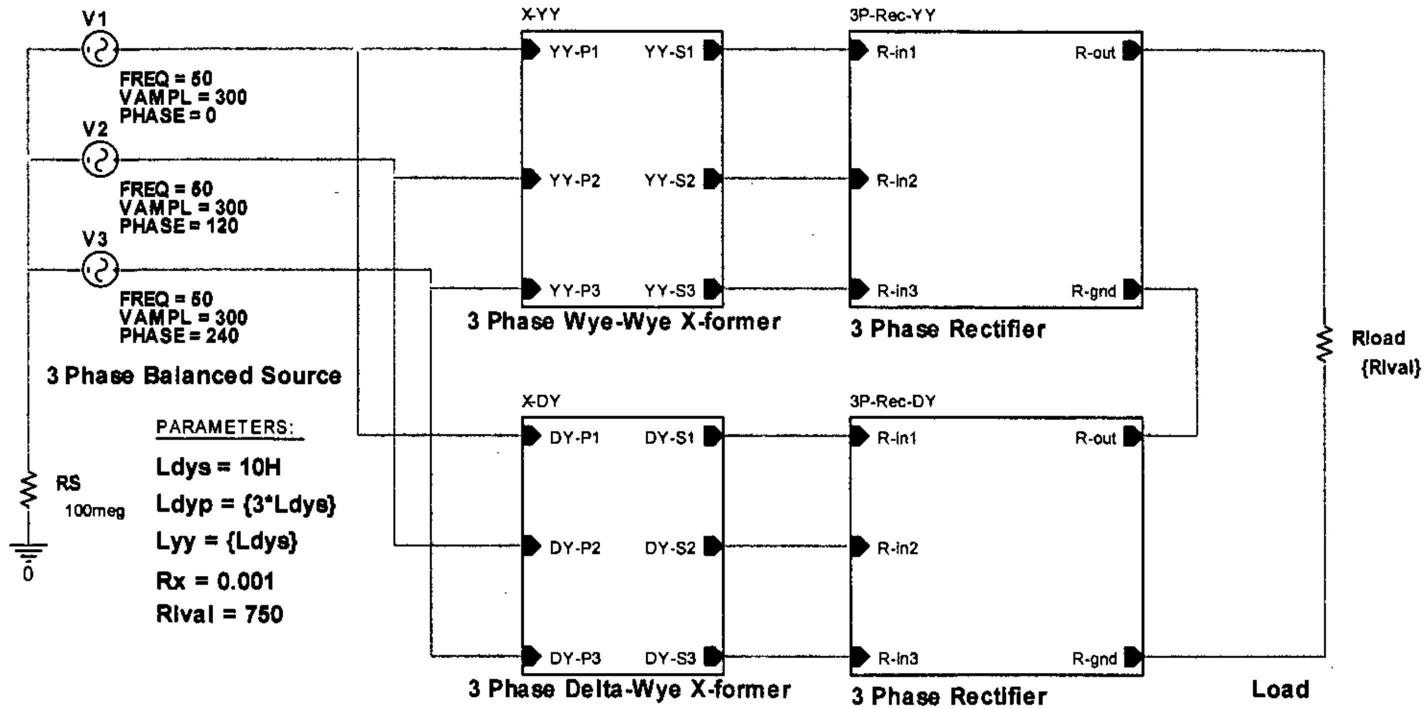


Figure 3.4: Schematic diagram using Hierarchical Block of Twelve Pulse Rectifier.

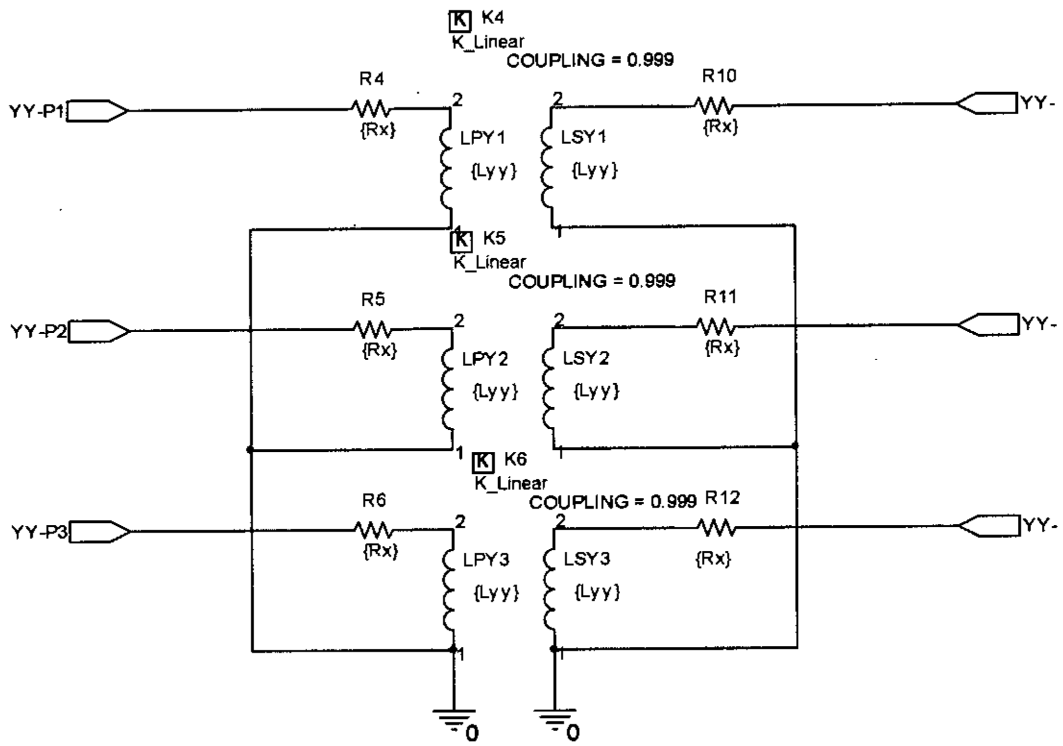


Figure3.5: Schematic diagram of wye-wye transformer of twelve-pulse rectifier.

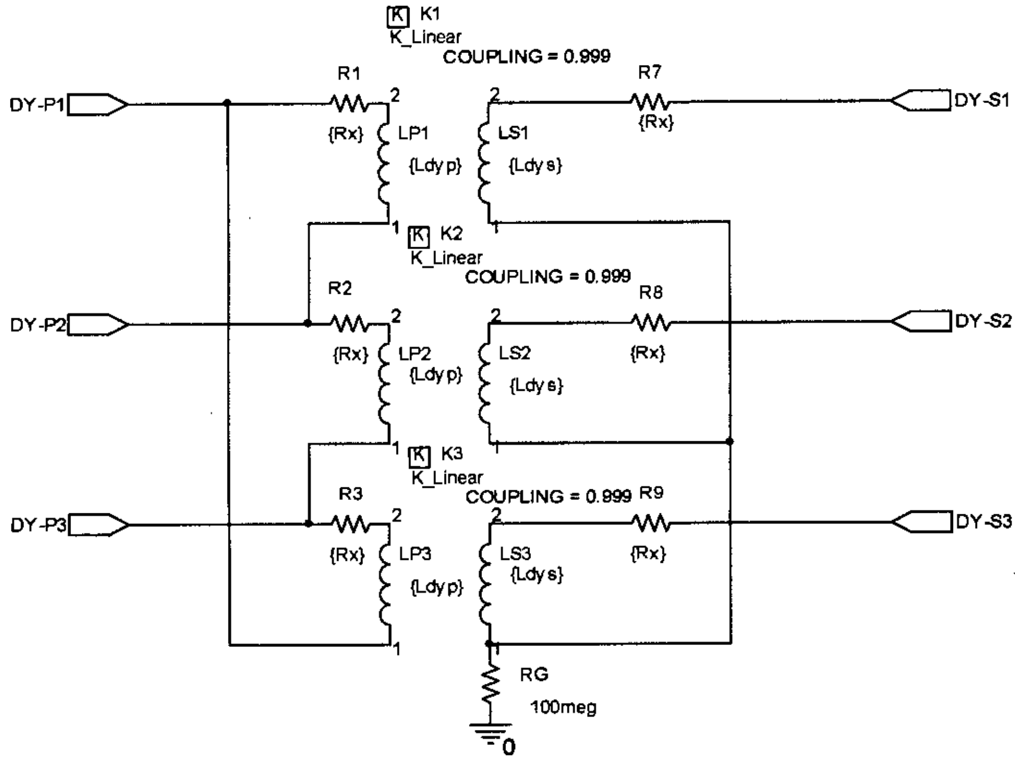


Figure3.6: Schematic diagram of delta-wye transformer of twelve-pulse rectifier.

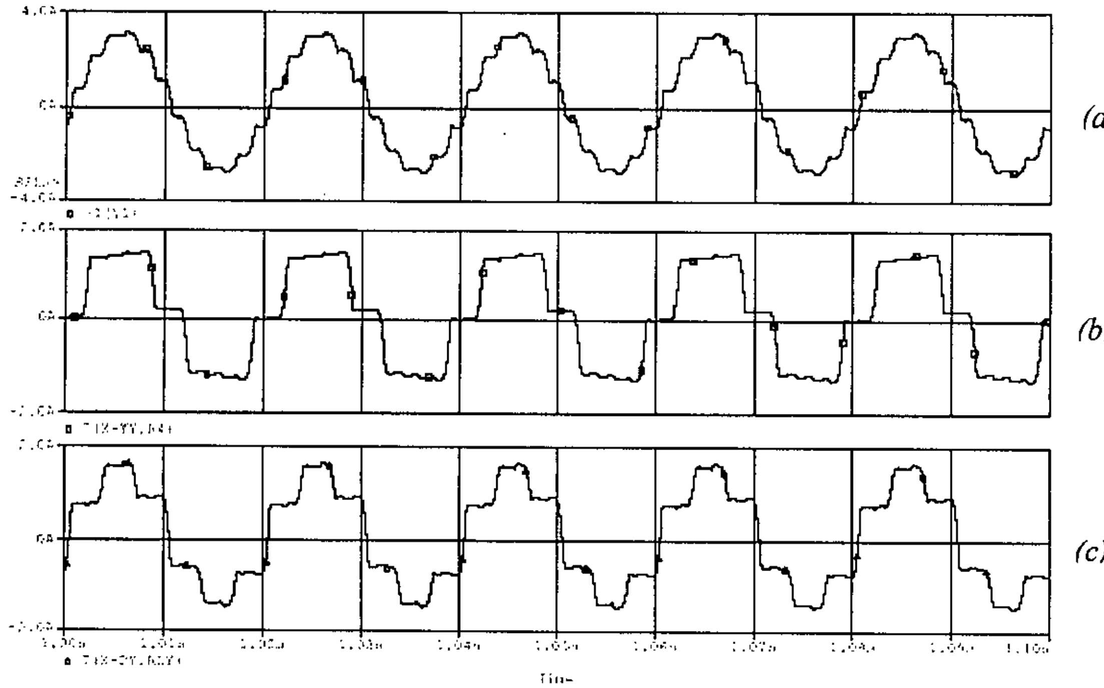


Figure 3.7: Input current wave shapes of (a) supply, (b) wye-wye and (c) delta-wye transformer

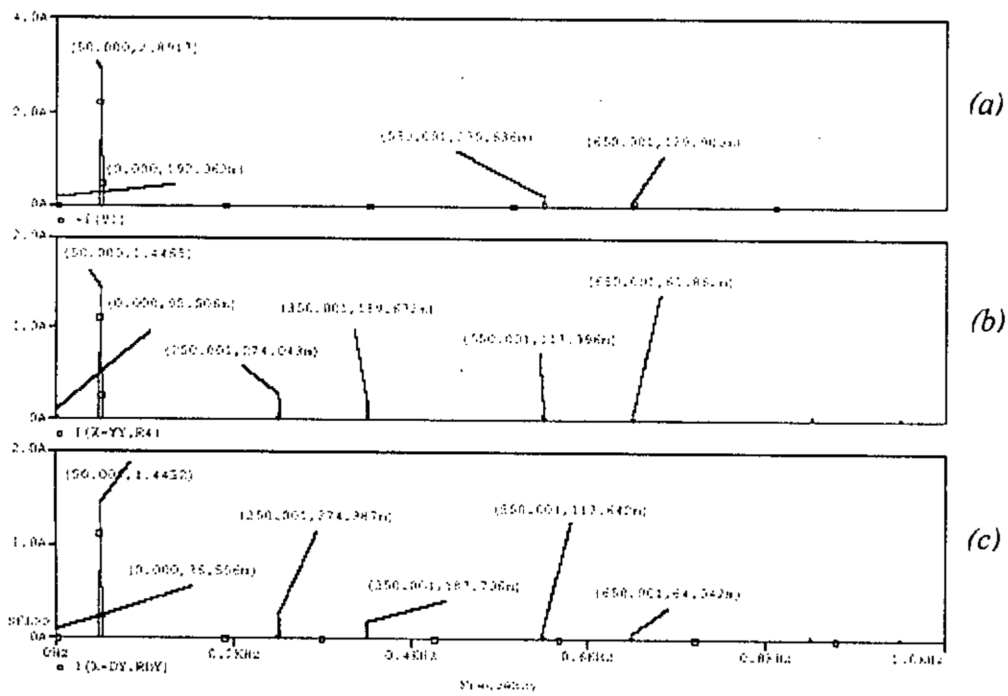


Figure 3.8: Input current frequency spectrums of (a) supply, (b) wye-wye and (c) delta-wye transformer

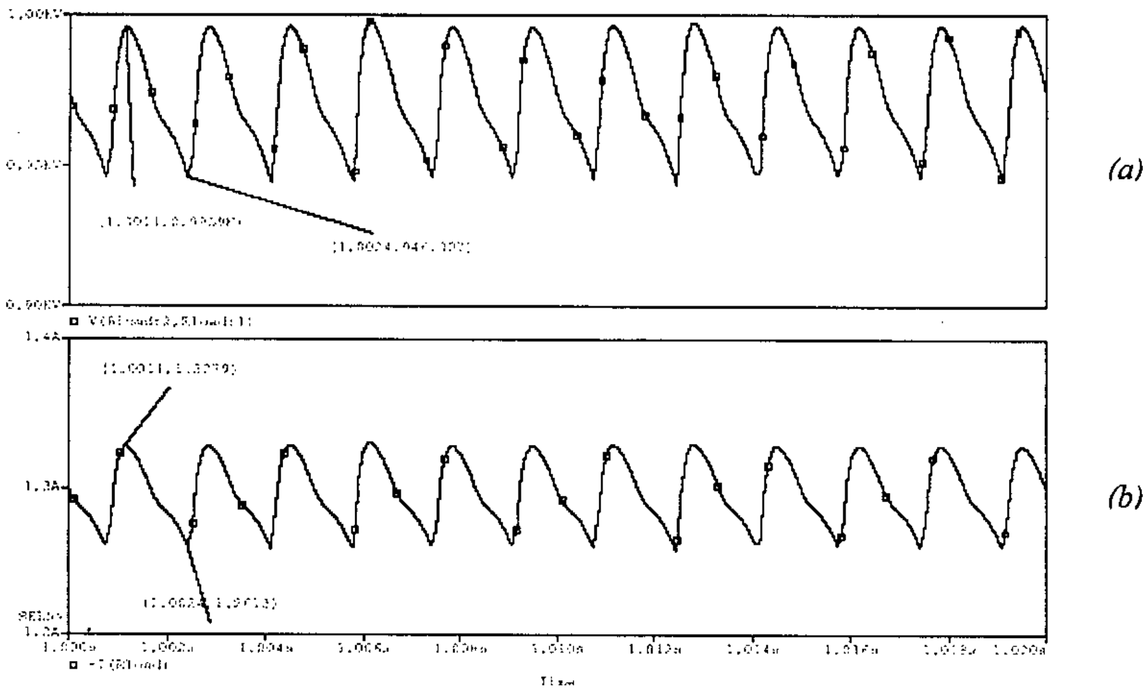


Figure 3.9: Wave shapes of (a) output voltage and (b) current of 12-pulse rectifier

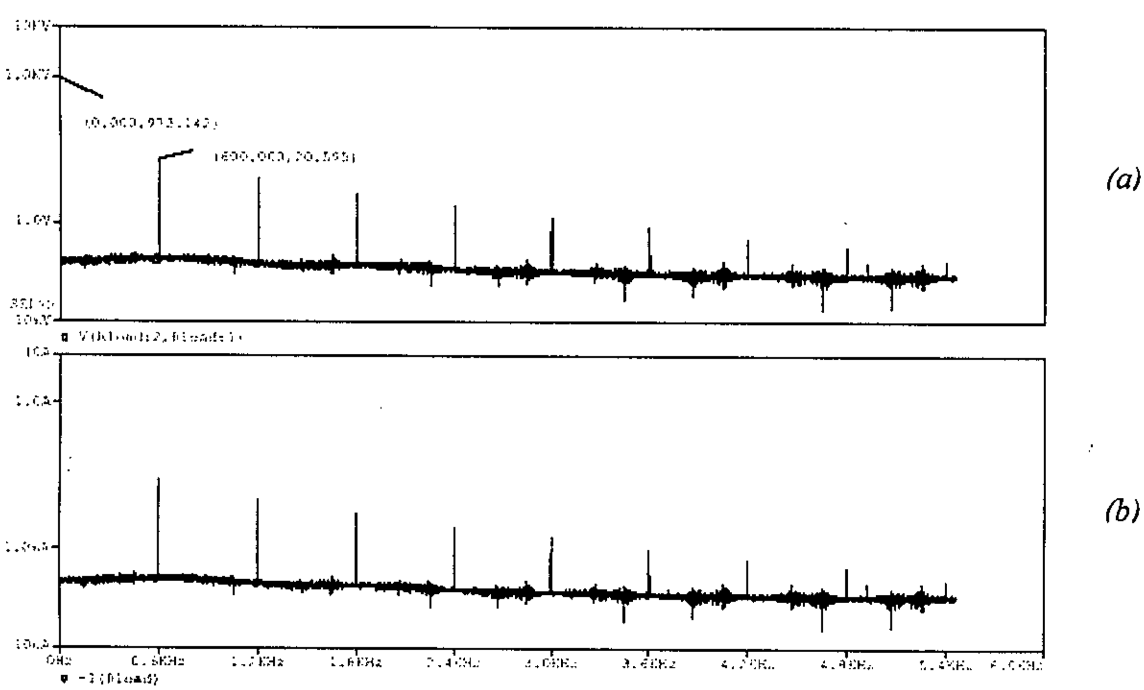


Figure 3.10: Frequency spectrums of (a) output voltage and (b) current of 12-pulse rectifier

From figure 3.7 and 3.8 it has been revealed that the individual transformer windings of the twelve pulse rectifier system carry nonsinusoidal current containing large low order harmonics such as 5th, 7th as discussed earlier. This requires over sizing of these transformers so that transformer windings are not overheated for a certain load. However, in the resultant input *ac* current, which is the sum of the two input currents of the star connected and delta connected transformers, the 5th, 7th, 17th, 19th, etc. harmonics are eliminated. Consequently, the input line current for the twelve-pulse rectifier is close to sinusoidal waveform as shown in figure 3.7(a). Again, from figure 3.9 and 3.10 it is found that the output of the 12-pulse rectifier contains ripples of twelve pulses in 20ms time duration whose frequency is 600Hz, which is twelve times that of the fundamental input frequency. Table 3.1 includes the Fourier components and Total Harmonic Distortion (THD) of input line current and transformers input currents considering upto 50th dominant harmonic components which shows that the 12-pulse front ends do not meet IEEE-519 harmonic standard (refer to Table 1.1 in Chapter 1) without additional filtering.

Table 3.1: Fourier components of transient response of input current of phase-a, transformers input currents

I_s		I_{yy}		I_{dy}	
Harmonic Frequency	Fourier Component (mA)	Harmonic Frequency	Fourier Component (mA)	Harmonic Frequency	Fourier Component (mA)
I_1 (50Hz)	2892	I_1 (50Hz)	1446.00	I_1 (50Hz)	1446.00
I_{11} (550Hz)	235.7	I_5 (250Hz)	273.90	I_5 (250Hz)	274.20
I_{13} (650Hz)	130.3	I_7 (350Hz)	189.10	I_7 (350Hz)	188.90
I_{23} (1150Hz)	49.26	I_{11} (550Hz)	117.90	I_{11} (550Hz)	117.80
I_{25} (1250Hz)	27.94	I_{13} (650Hz)	65.05	I_{13} (650Hz)	65.22
I_{35} (1750Hz)	19.23	I_{17} (850Hz)	45.61	I_{17} (850Hz)	45.20
I_{37} (1850Hz)	10.39	I_{19} (950Hz)	35.60	I_{19} (950Hz)	36.11
I_{47} (2350Hz)	8.95	I_{23} (1150Hz)	24.65	I_{23} (1150Hz)	24.61
I_{49} (2450Hz)	6.55	I_{25} (1250Hz)	13.98	I_{25} (1250Hz)	13.96
		I_{29} (1450Hz)	10.38	I_{29} (1450Hz)	9.83
		I_{31} (1550Hz)	8.91	I_{31} (1550Hz)	9.22
		I_{35} (1750Hz)	9.66	I_{35} (1750Hz)	9.57
		I_{37} (1850Hz)	5.24	I_{37} (1850Hz)	5.15
		I_{41} (2050Hz)	5.54	I_{41} (2050Hz)	5.21
		I_{43} (2150Hz)	4.95	I_{43} (2150Hz)	5.19
		I_{47} (2350Hz)	4.50	I_{47} (2350Hz)	4.46
		I_{49} (2450Hz)	3.32	I_{49} (2450Hz)	3.23
THD = 9.56%		THD = 25.27%		THD = 25.27%	

3.3 Filtering Schemes for Twelve-Pulse Rectifier System

Due to rectification action, the input current of the twelve-pulse rectifier and those of the transformers contain harmonics. Both passive and active filtering techniques can be applied separately to make the input current almost sinusoidal. Passive filtering technique employing inductor and/or capacitors to reduce the amplitude of the low frequency harmonics is attractive for its simplicity and reliability, although size and weight of these filters are comparatively large. Active filtering technique of a rectifier current uses high switching frequency PWM Boost converter that shapes the input current by eliminating high frequency components with the aid of small sized filters. This technique has been used in the single phase and three phase conventional rectifiers so far. No mention has been found in literature about the technique being used in twelve-pulse rectifier. Normally, the filter design requires determining the magnitudes and frequencies of the harmonics.

In addition to nonsionusoidal input current the output of the 12-pulse rectifier also contains ripples. Filters are commonly employed in rectifier circuits for smoothing out the dc output voltage of the load and these are known as dc filters. They are classified as inductor-input dc filters and capacitor-input dc filters. Inductor-input dc filters are preferred in high-power applications because more efficient transformer operation is obtained due to the reduction in the form factor of the rectifier current. Capacitor-input dc filters can provide volumetrically efficient operation, but they demand excessive turn-on and repetitive surge currents. Therefore, capacitor-input dc filters are suitable only for lower-power systems where close regulation is usually achieved by an electronic regulator cascaded with the rectifier. The dc filters of L, C, and LC type are shown in figure 3.4.

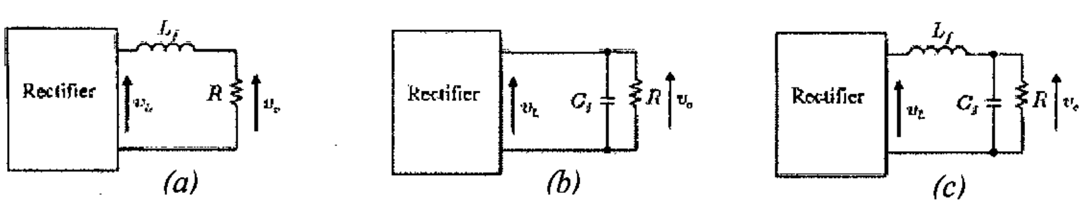


Figure 3.11: DC filters

3.3.1 Filter for smoothing out the dc output voltage

A simple inductive input dc LC filter can be used to reduce the ripple content of the output voltage for 12-pulse rectifier. Considering only the harmonic components, the equivalent circuit of rectifier with dc LC filter can be found as shown in figure 3.5.

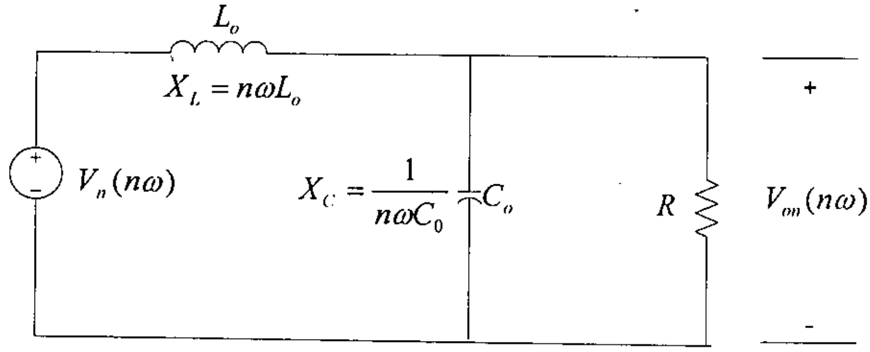


Figure 3.12: Equivalent circuit for harmonics.

The rms value of nth harmonic component appearing on the output can be found by using the voltage-divider rule and is expressed as

$$V_{on} = \left| \frac{-1/(2\pi f_r C_o)}{(2\pi f_r L_o) - 1/(2\pi f_r C_o)} \right| V_n = \left| \frac{1}{1-(2\pi f_r)^2 L_o C_o} \right| V_n$$

where V_n is the ripple voltage before filtering, V_{on} is the ripple voltage after filtering, and f_r is the ripple frequency. The amount of reduction in the ripple voltage can be estimated as

$$\frac{V_{on}}{V_n} = \left| \frac{1}{1-(2\pi f_r)^2 L_o C_o} \right| \qquad \ldots\ldots\ldots (3.4)$$

Considering the ripple voltage to be reduced to 1% after filtering, the product of L_o and C_o, which is generally termed as L-C constant, can be determined from the above equation.

$$\frac{V_{on}}{V_n} = 0.01 = \left| \frac{1}{1-(2\pi f_r)^2 L_o C_o} \right|$$

$$\left| 1-(2\pi f_r)^2 L_o C_o \right| = 100$$

$$\left| -(2\pi f_r)^2 L_o C_o \right| = 99$$

$$L_o C_o = \frac{99}{(2\pi f_r)^2} = \frac{99}{(2\pi \times 600)^2} = 6.97 \times 10^{-6}; \text{ (here } f_r\text{=600Hz)}$$

$$\therefore L_o C_o = 6.97 \times 10^{-6} \qquad \text{......... (3.5)}$$

Again, to make it easier for the nth harmonic ripple current to pass through the filter capacitor, the capacitance value should be so chosen that the load impedance must be much greater than that of the capacitor. That is,

$$R >> \frac{1}{2\pi f_r C_o} \qquad \text{......... (3.6)}$$

$$750 >> \frac{1}{2\pi \times 600 \times C_o}; \text{ (here R=750}\Omega\text{)}$$

Choosing $C_o = 1000\mu F$, the value of L_o is found as $6.97mH \approx 7mH$ from eq. (3.5).

3.3.2 Passive Filtering scheme for 12-pulse rectifier

The Passive filter constituted of three phase *L-C* filter (Figure 3.13) has been used for reducing the harmonics content of the input current of the twelve-pulse rectifier.

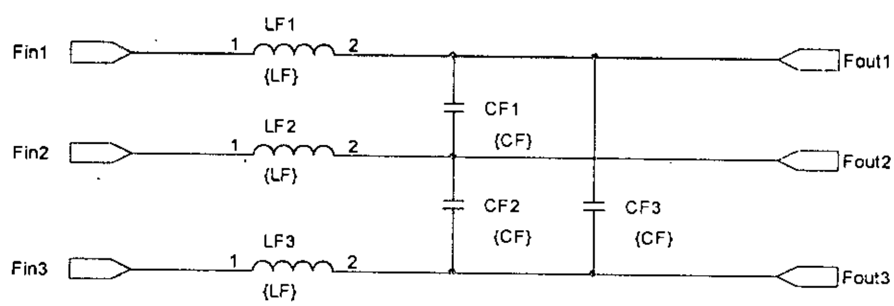


Figure 3.13: Three phase *L-C* input ac filter

To find the values of an *LC* input filter to limit the amount of input ripple current, considering only the harmonic components, the equivalent circuit per phase for the nth harmonic component of the rectifier system is given in figure 3.6.

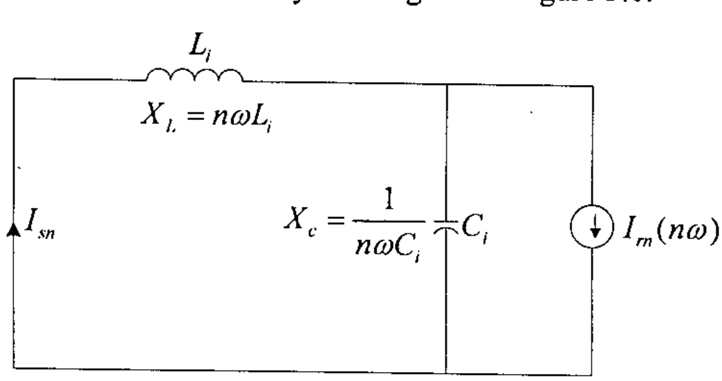


Figure 3.14: Equivalent circuit for harmonic current.

From figure 3.6, the rms value of the *n*th harmonic current appearing in the supply can then be obtained using the current-division rule, for parallel circuit,

$$I_{sn} = \left| \frac{1/(n\omega C_i)}{(n\omega L_i) + 1/(n\omega C_i)} \right| I_{rn} = \left| \frac{1}{(n\omega)^2 L_i C_i + 1} \right| I_{rn} \qquad \dots\dots\dots (3.7)$$

where I_{rn} is the rms value of the nth harmonic current of the rectifier. The total amount of harmonic current in the supply line is

$$I_h = \left(\sum_{n=2,3,\dots}^{\infty} I_{sn}^2 \right)^{1/2} \qquad \dots\dots\dots (3.8)$$

The harmonic factor or the total harmonic distortion (THD), which is a measure of the distortion of a waveform, is defined as

$$THD = \frac{I_h}{I_{s1}} = \sqrt{\sum_{n=2,3,\dots}^{\infty} \left(\frac{I_{sn}}{I_{s1}} \right)^2} \qquad \dots\dots\dots (3.9)$$

Applying eq. (3.6) and eq. (3.8) and knowing $\frac{I_{rn}}{I_{r1}}$, the THD of the rectifier with input filter can be found as

$$Filtered\,THD = \sqrt{\sum_{n=2,3,\dots}^{\infty} \left(\frac{I_{rn}}{I_{r1}} \right)^2 \left| \frac{(\omega^2 L_i C_i + 1)^2}{[(n\omega)^2 L_i C_i + 1]^2} \right|} \qquad \dots\dots\dots (3.10)$$

As previously mentioned the Fourier series for the current in phase "a" on the primary side of the delta-wye transformer only differs from that of the wye connected transformer by the sequence of rotation of harmonic orders 6k ± 1 for odd values of k, i.e. the 5th, 7th, 17th, 19th, etc. Therefore the 5th, 7th, 17th, 19th, etc. harmonics are eliminated in the resultant input *ac* current, which is the sum of the two input currents of the star connected and delta connected transformers. The ac line current contains 1st, 11th, 13th, 23rd, 25th, etc harmonics. Since these harmonic amplitudes vary as $1/n$ therefore proportional to the reciprocal of the harmonic number, to simplify the calculations, only the dominant 11th order harmonic is considered so that the total harmonic harmonic distortion (THD) of the input line current is reduced to 1% and thereby reducing the THDs of transformer currents.

Thus $\frac{I_{rn}}{I_{r1}} = \frac{I_{r11}}{I_{r1}}$.

Although eq. (3.3) gives $\frac{I_{r11}}{I_{r1}} = \frac{1}{11}$, from the frequency spectrum of the input current of the supply (Figure 3.8 (a)) the peak values of I_{r1} and I_{r11} are found as 2.8917 A and 235.636 mA. Thus from eq. (3.9), considering 1% of total harmonic distortion, the value of L_iC_i can be found as-

$$0.01 = \left| \frac{\left[(2\pi \times 50)^2 L_i C_i + 1\right]}{[(2\pi \times 11 \times 50)^2 L_i C_i + 1]} \right| \times \frac{235.636 \times 10^{-3} \times \sqrt{2}}{\sqrt{2} \times 2.8917}$$

$$[(2\pi \times 11 \times 50)^2 L_i C_i + 1] = 8.15 \times \left|(2\pi \times 50)^2 L_i C_i + 1\right|$$

$$L_i C_i \times [(2\pi \times 11 \times 50)^2 - (2\pi \times 50)^2] = 7.15$$

$$L_i C_i = \frac{7.15}{[(2\pi \times 11 \times 50)^2 - (2\pi \times 50)^2]}$$

$$\therefore L_i C_i = 6.42 \times 10^{-7} \qquad \text{... ... ... (3.11)}$$

Simulation has been performed for different combinations L_i and C_i to get lower total harmonic distortion (THD) of input currents and maximum efficiency of the rectifier circuit.

3.3.3 Active Filtering scheme for 12-pulse rectifier

The active filtering scheme for the 12-pulse rectifier uses high switching frequency PWM Boost converter at the output of the ac to dc rectifier that shape the input current and also the currents in the windings of transformers used for twelve-pulse rectifier by eliminating high frequency harmonic components with small size filter.

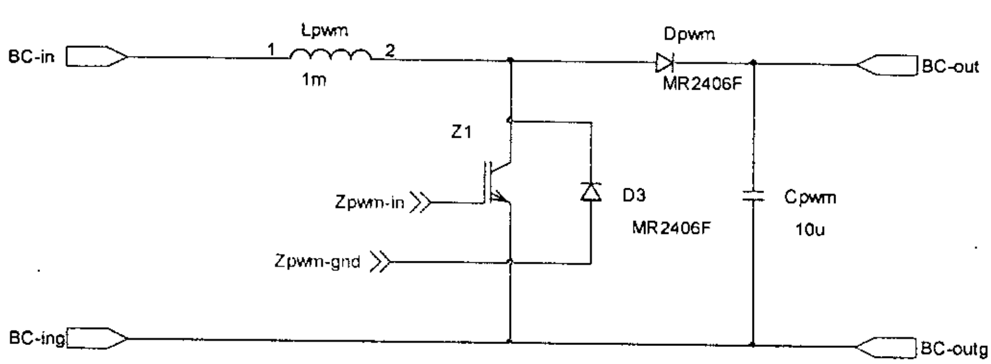


Figure 3.15: PWM Boost converter

The boost switch is turned on at constant frequency. The duty cycle of the switch is varied for load variation only. During the period when the boost switch is turned on, the equivalent single-phase circuit becomes as shown in figure 3.16 (a).

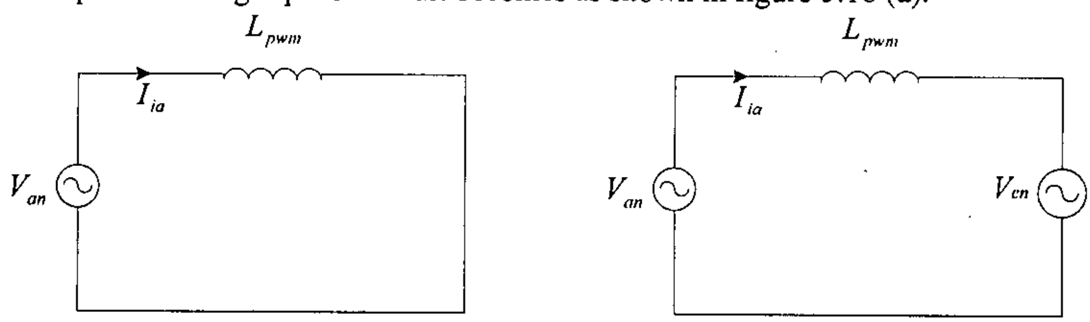


Figure 3.16 (a): Equivalent single-phase circuit when the boost switch is on.
(b) Equivalent single-phase circuit when the boost switch is off.

When the switch IGBT is turned on, a symmetrical short circuit occurs at the rectifier input through the boost inductor, the six rectifier diodes and the boost switch. Consequently the phase currents build up linearly at a rate determined by the input source voltages and the boost inductor, independently of each other, and the magnitude is proportional to the respective phase voltage amplitude. This means that the positive phase voltages cause positive currents through the upper diodes, which return as negative currents through the lower diodes that are caused by the negative phase voltages.

During the period when the boost switch IGBT turns off, the phase currents through the boost inductor flow to the output capacitor decreases linearly at a rate determined by the input voltage, output dc voltage and the inductor. The single phase equivalent circuit under this condition is shown in figure 3.16(b). Consequently all three input ac currents consist of the fundamental (50 Hz) component and a band of high frequency unwanted components centered around the PWM switching frequency of the boost switch. The discontinuous phase current pulses at high PWM frequency and the sinusoidal locus of the peak values can be filtered with a small *LC* filter to ideally obtain a sinusoidal average current with unity power factor.

3.3.3.1The switching scheme using PWM module

The objective of the switching scheme is to enhance the continuity of the input current by providing it an alternate path through closing of an electronic switch. An IGBT has been used as the switch. The gate pulse to the IGBT has been generated by a PWM module. The schematic diagram of the PWM module is shown in figure 3.17.

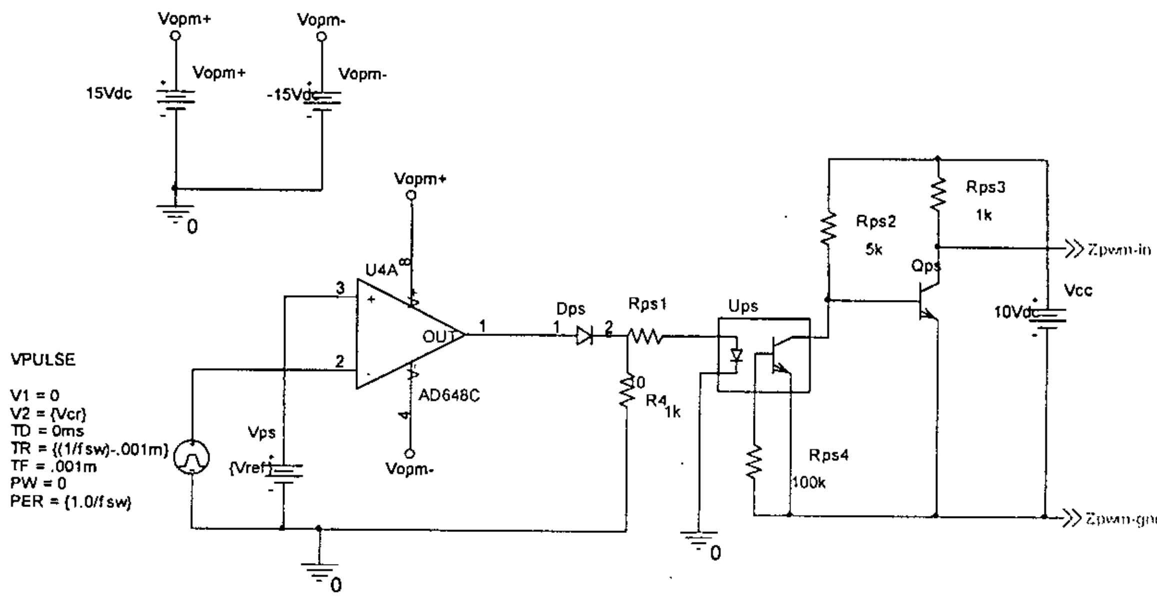


Figure 3.17: PWM Module

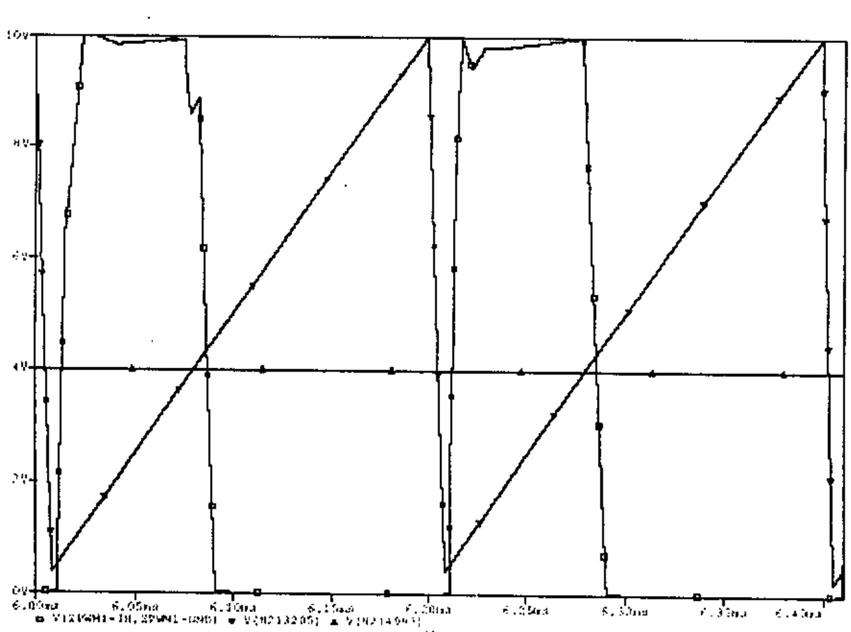


Figure 3.18 (a): Gate pulse generation for duty cycle, D=0.4

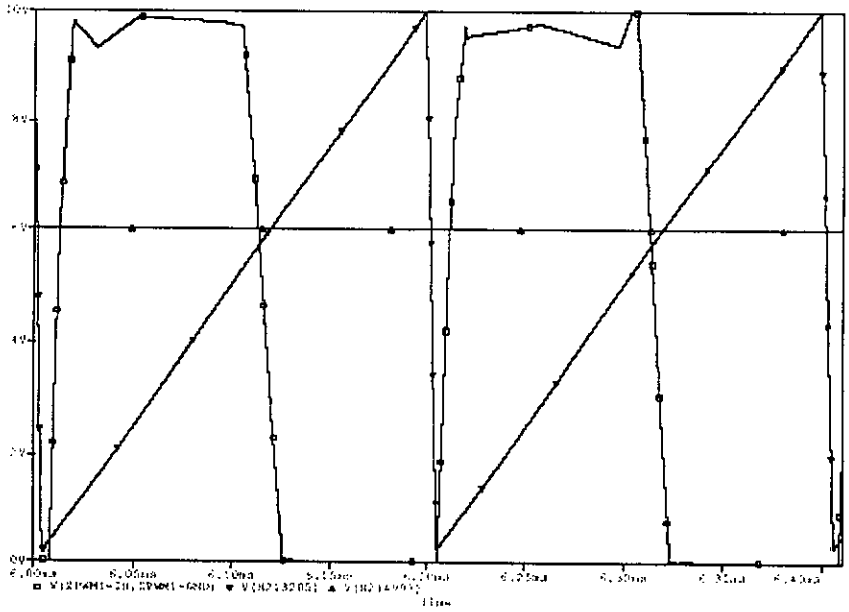


Figure 3.18 (b): Gate pulse generation for duty cycle, D=0.6

The PWM module mainly consists of an opamp (AD648C), an opto-coupler (A4N25A) and BJT (PN2222). The gate pulses are generated by comparing a saw-tooth wave with a reference dc voltage. The saw-tooth wave signal and the reference dc signal are connected to the inverting and non inverting terminals respectively of the op amp. For PWM, changing the reference voltage will change the duty cycle. Figure 3.9 shows how change in reference voltage changes the duty cycle. The opto-coupler has been used to provide necessary ground isolation between the PWM module and the switch while producing the pulses. The voltage at the output of the opto-coupler is in the range of 600 to 800 milivolts. To drive the IGBT the BJT amplifier is connected which increases the voltage level at about 10 volts.

CHAPTER 4

Study of Filtering Schemes

In this chapter the performance of different filtering schemes has been studied through simulation. The simulation results obtained and different performance parameters including total harmonic distortion (THD), efficiency etc. for different combinations have been presented to compare the proposed active filtering scheme with the passive filtering scheme under similar conditions in order to determine a better harmonic mitigation method.

4.1 Analysis of Passive Filtering scheme

4.1.1 Passive filter at the input side

Figure 4.1 shows the schematic diagram of the implementation of passive filtering technique using Hierarchical Block for the twelve-pulse rectifier configuration. Here the three phase *L-C* input ac filter has been used at the input side of the twelve-pulse rectifier circuit for reducing the total harmonic distortion of the input current and transformer currents. The value of the *L-C* constant for the passive filtering scheme has been determined $L_iC_i = 6.42\times10^{-7}$ in chapter 3. An inductive input dc *L-C* filter has been added at the output side in order to reduce the ripple content of the output voltage for 12-pulse rectifier. The value of the L-C constant for the inductive input dc *L-C* filter has been determined $L_oC_o = 6.97\times10^{-6}$ in chapter 3. The dc inductor value L_o has been chosen 7mH and the capacitance $C_o = 1000\mu F$. Simulation has been performed for different combinations of L_i and C_i to get lower total harmonic distortion (THD) of input currents and maximum efficiency of the rectifier circuit. Following the schematic diagram of the passive filtering scheme the simulation outputs of input current, transformer currents, output voltage and output current have been presented for different combinations of L_i and C_i along with a table that has summarized the simulation results obtained.

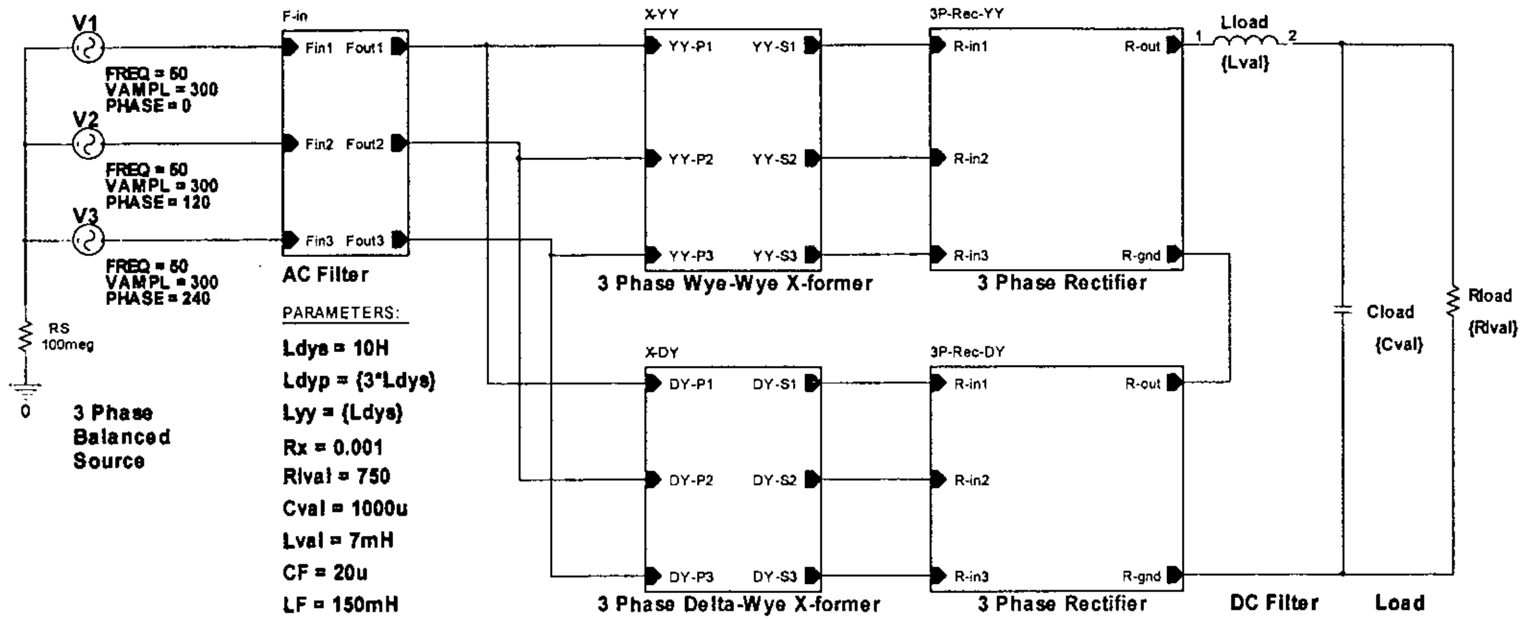
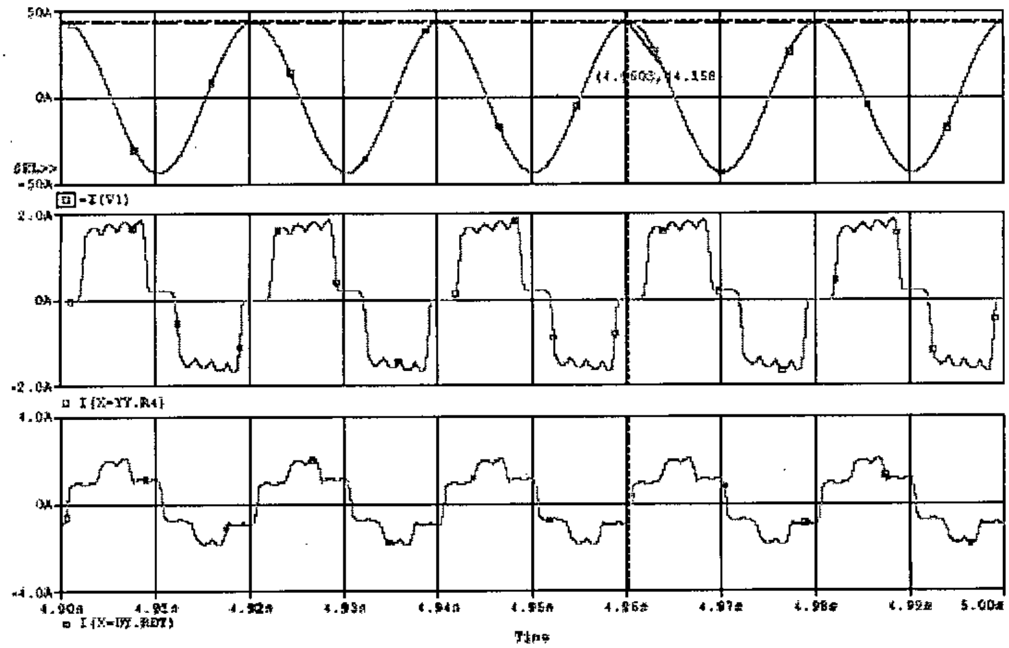


Figure 4.1: Schematic diagram using Hierarchical Block of Passive Filtering Scheme of Twelve Pulse Rectifier with AC Filter at input side

4.1.1.1 Simulation outputs of the passive filtering scheme with ac filter at input

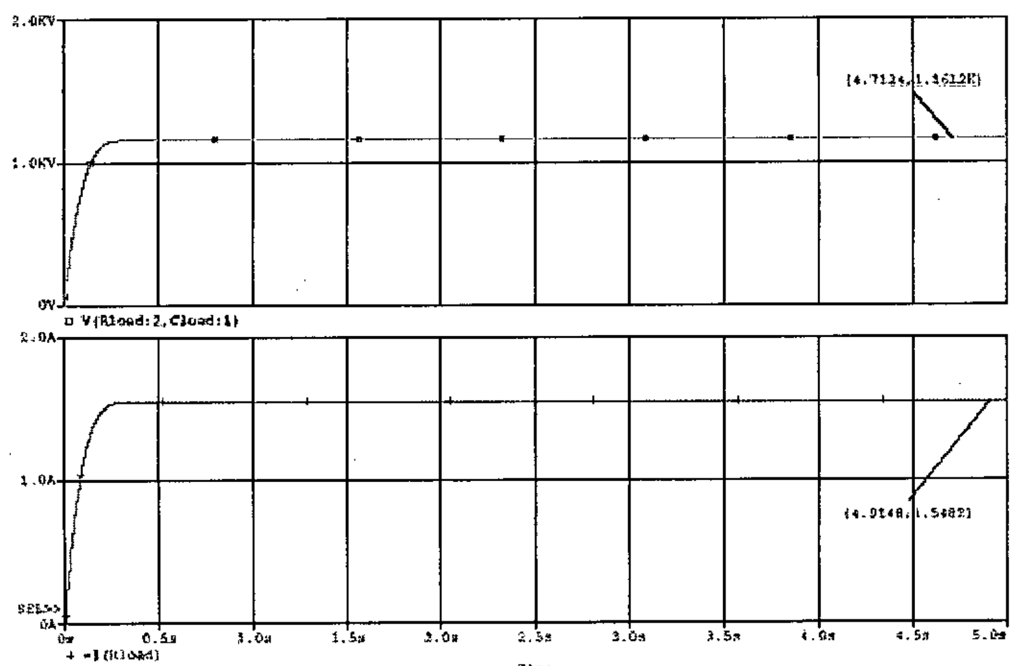


(a)

(b)

(c)

Figure 4.2: Input current wave shapes of (a) supply, (b) wye-wye and (c) delta-wye transformer for $L_iC_i = 6.42\times10^{-7}$, L_i=5mH.



(a)

(b)

Figure 4.3: Wave shapes of (a) output voltage and (b) current for $L_iC_i = 6.42\times10^{-7}$, L_i=5mH.

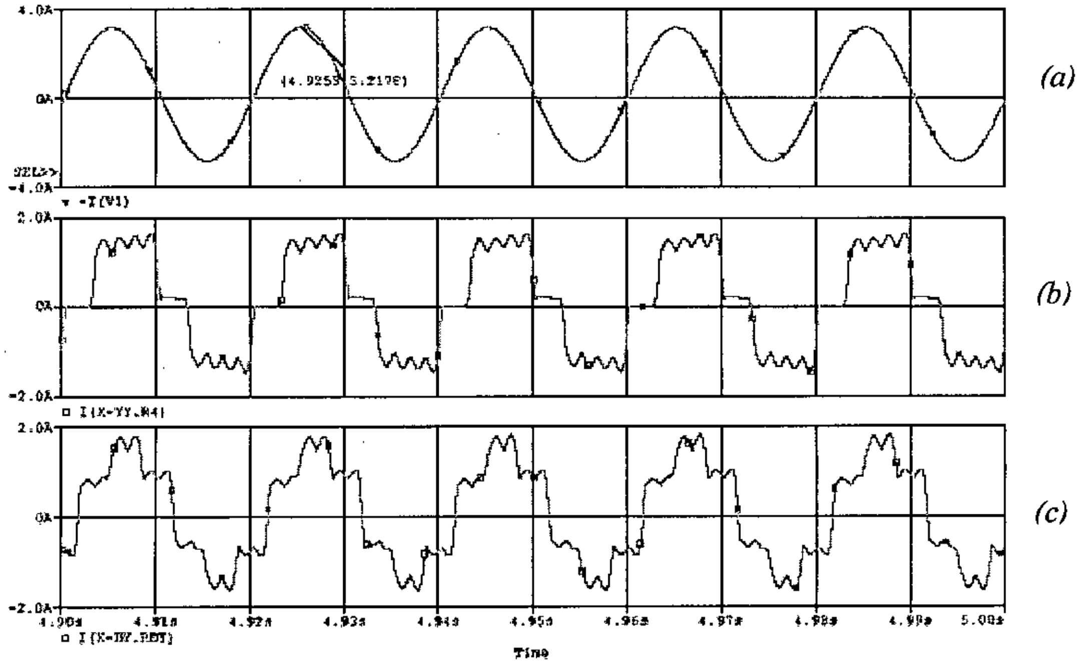


Figure 4.4: Input current wave shapes of (a) supply, (b) wye-wye and (c) delta-wye transformer for $L_iC_i = 6.42 \times 10^{-7}$, L_i=125mH.

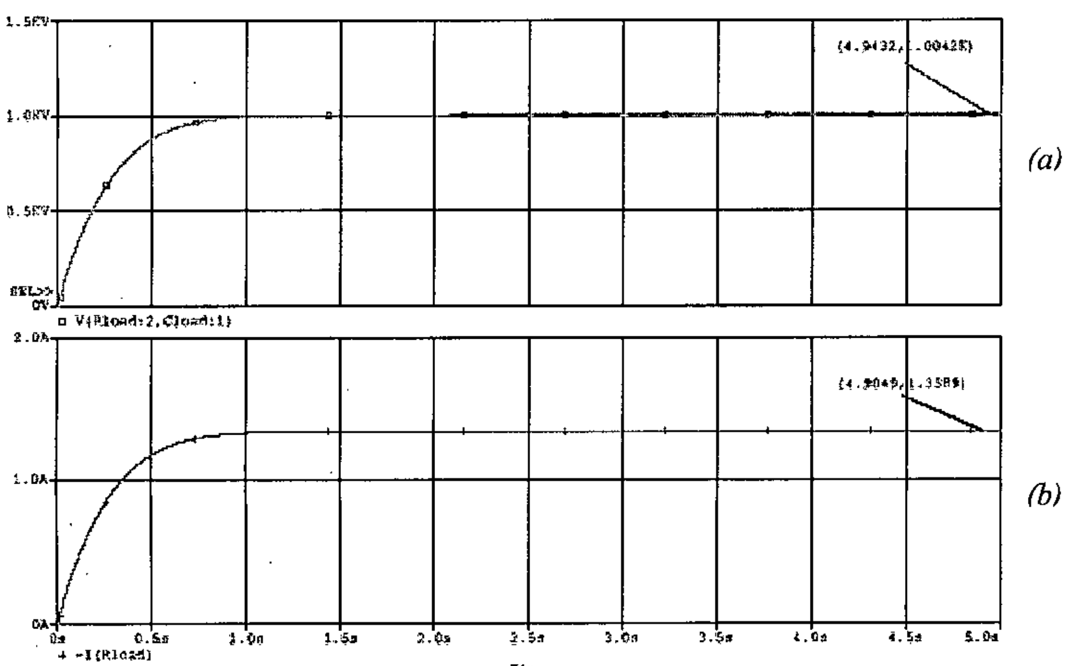


Figure 4.5: Wave shapes of (a) output voltage and (b) current for $L_iC_i = 6.42 \times 10^{-7}$, L_i=125mH.

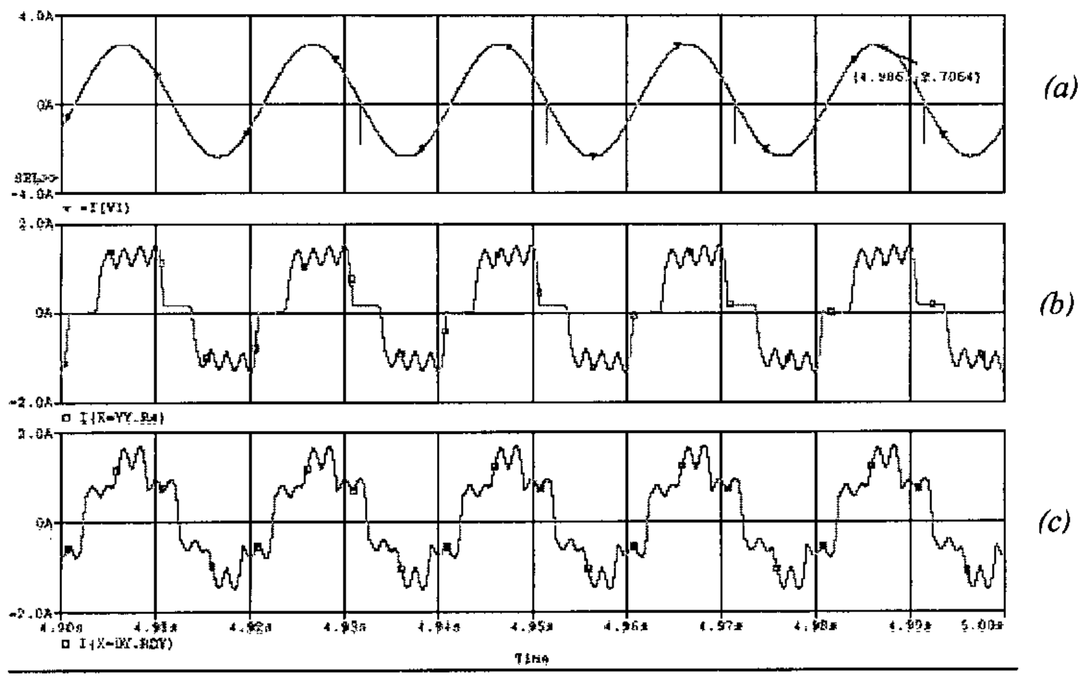


Figure 4.6: Input current wave shapes of (a) supply, (b) wye-wye and (c) delta-wye transformer for $L_iC_i = 6.42\times10^{-7}$, L_i=200mH.

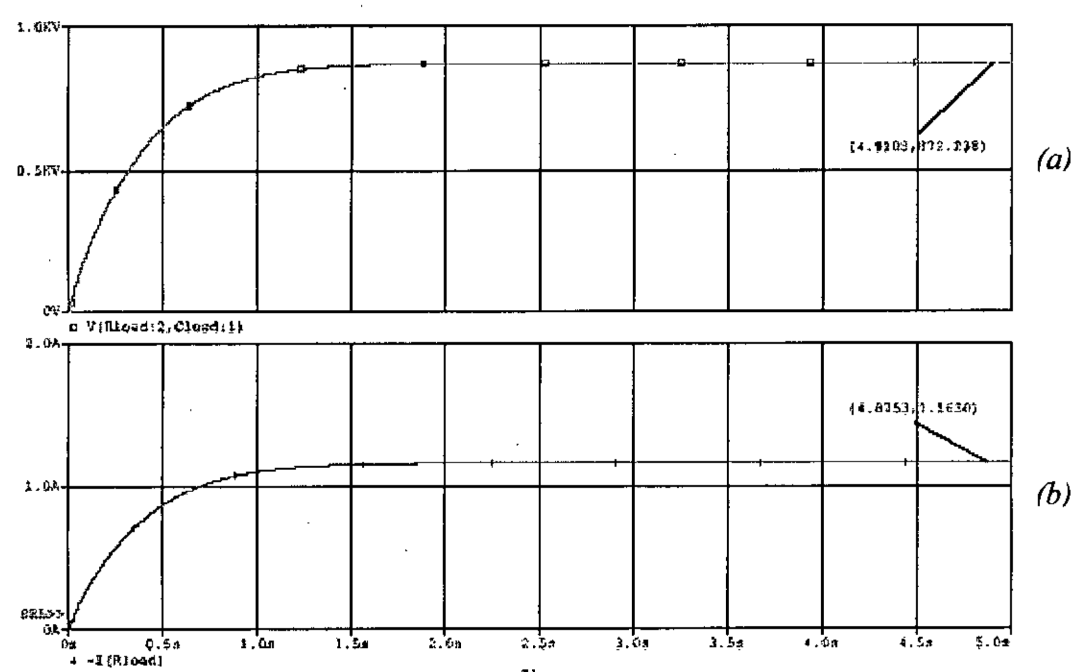


Figure 4.7: Wave shapes of (a) output voltage and (b) current for $L_iC_i = 6.42\times10^{-7}$, L_i=200mH.

Table 4.1: Summary of the simulation results for passive filter at input

AC Input Filter		DC Output Filter		*Efficiency* η (%)	THD_I_s (%)	THD_I_{w} (%)	THD_I_{Δ} (%)
L_iC_i *const*	L_i (mH)	L_o (mH)	C_o (μF)				
6.42E-07	5	7	1000	9.65	0.041	25.7	25.79
6.42E-07	125	7	1000	93.46	0.53	27.45	27.05
6.42E-07	200	7	1000	88.87	0.72	30.05	30.05

Table 4.1 summarizes the results for the passive filtering scheme used at the input side of the twelve-pulse rectifier for different combinations of L_i and C_i. From the table and the simulation outputs of input current, transformer currents, output voltage and output current it is found that incorporating passive filter at the input of the twelve pulse rectifier significantly reduces the harmonic distortion of the input current. But the total harmonic distortion of the wye-wye and delta-wye transformer currents increases. The minimum value ac filter inductance for which the maximum efficiency of the rectifier circuit and lower total harmonic distortion (THD) of input and transformer currents has been found is $L_i = 125mH$ for fixed $L_iC_i = 6.42\times10^{-7}$. At this point the rectifier efficiency is 93.46% and the total harmonic distortion of the supply current and wye-wye and delta-wye transformer currents are 0.53%, 27.45% and 27.05% respectively.

4.1.2 Passive filter at the rectifier input

As the total harmonic distortion of transformer currents had not been reduced by using the input *L-C* ac filter at the input side of the twelve-pulse rectifier the filter position has to be changed. Therefore two *L-C* filters have been incorporated at the rectifier inputs of the twelve-pulse rectifier. Figure 4.8 shows the schematic diagram using Hierarchical Block of Passive Filtering Scheme of Twelve Pulse Rectifier with AC Filters at Rectifier inputs. Following the schematic diagram of the passive filtering scheme the simulation outputs of input current, transformer currents, output voltage and output current have been presented for different combinations of L_i and C_i along with a table that has summarized the simulation results obtained.

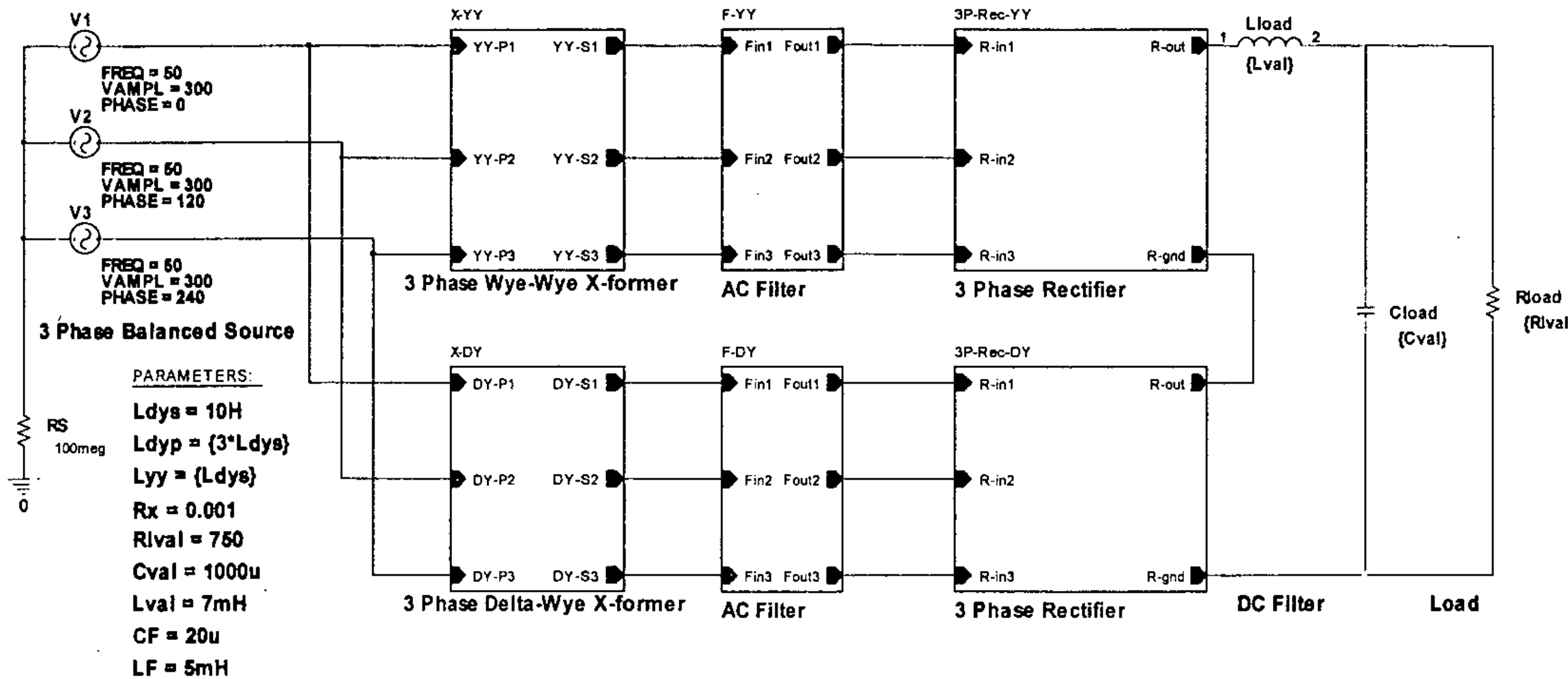


Figure 4.8: Schematic diagram using Hierarchical Block of Passive Filtering Scheme of Twelve Pulse Rectifier with AC Filters at Rectifier inputs

4.1.2.1 Simulation of the passive filtering scheme with ac filter at rectifier input

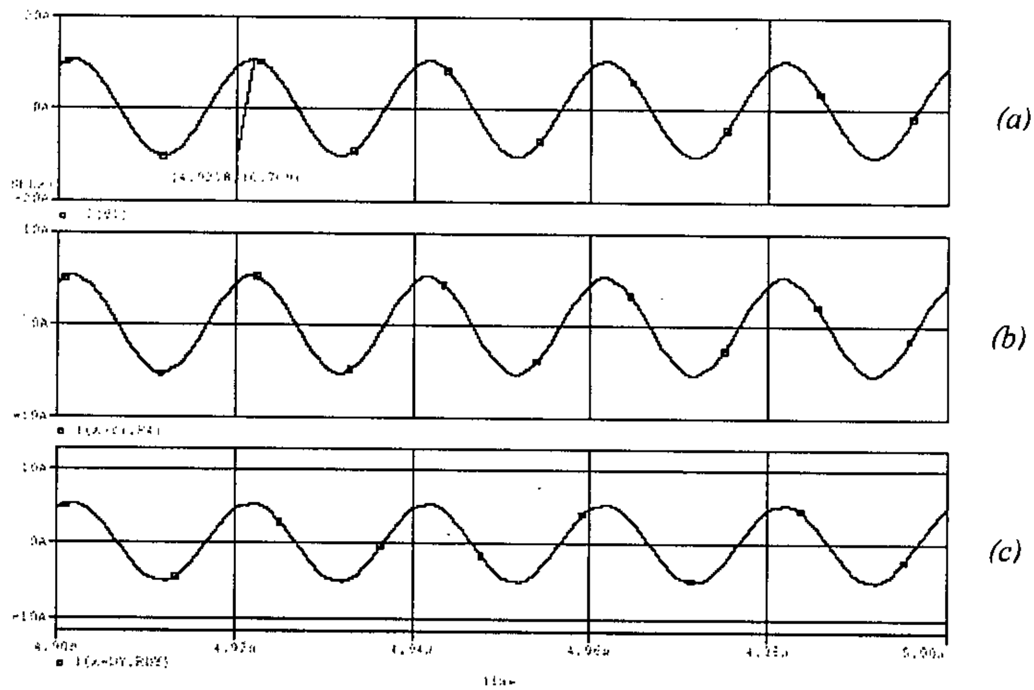


Figure 4.9: Input current wave shapes of (a) supply, (b) wye-wye and (c) delta-wye transformer for $L_i C_i = 6.42\times10^{-7}$, L_i=50mH.

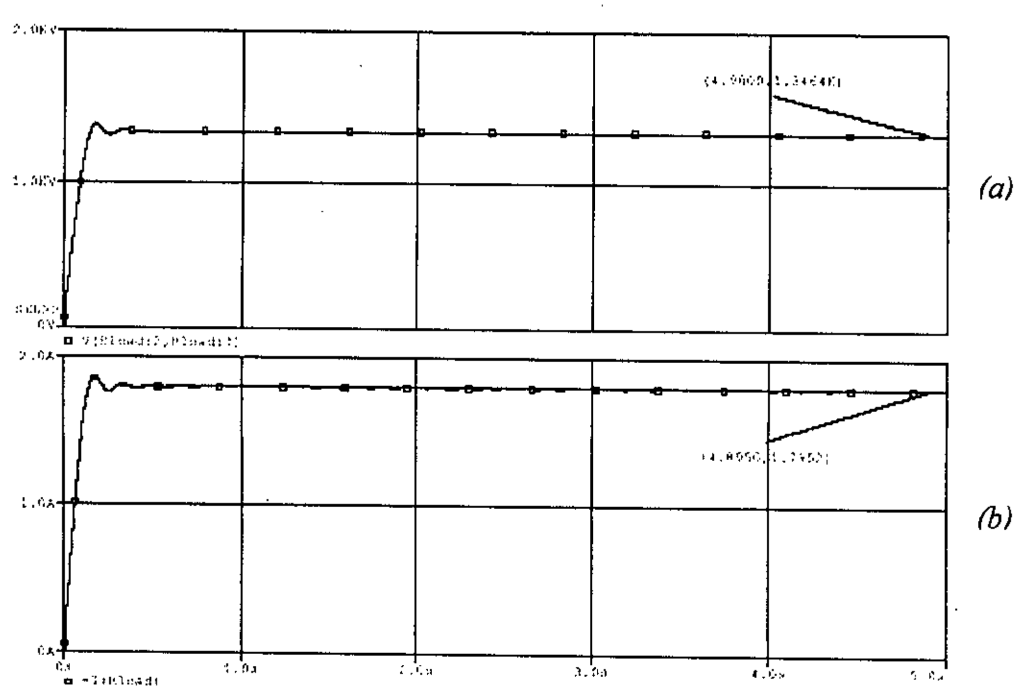


Figure 4.10: Wave shapes of (a) output voltage and (b) current for $L_i C_i = 6.42\times10^{-7}$, L_i=50mH.

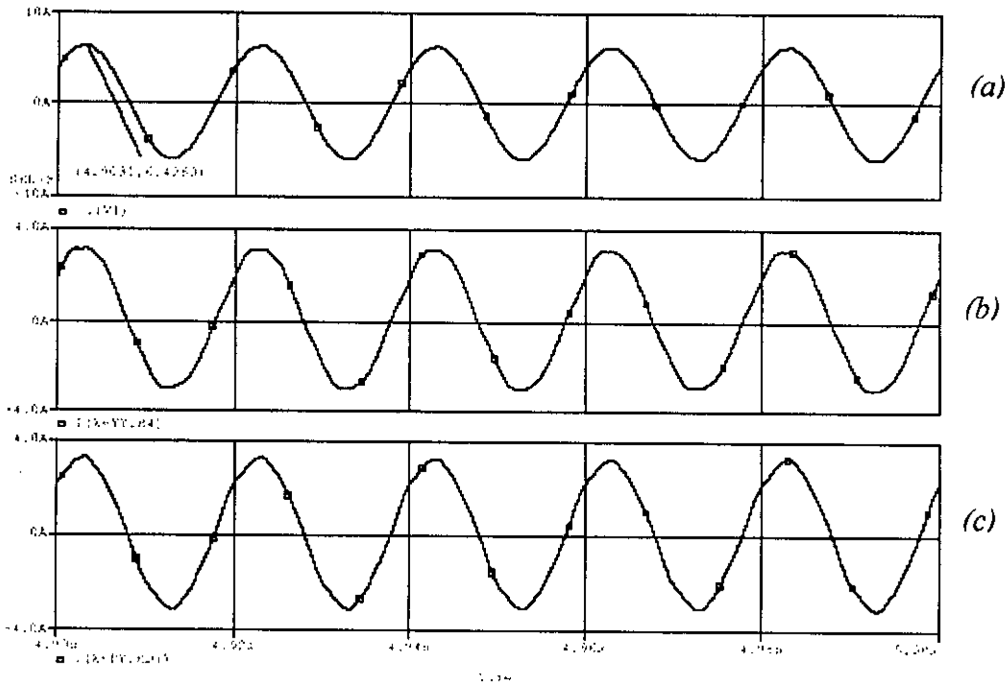


Figure 4.11: Input current wave shapes of (a) supply, (b) wye-wye and (c) delta-wye transformer for $L_iC_i = 6.42\times10^{-7}$, L_i=100mH.

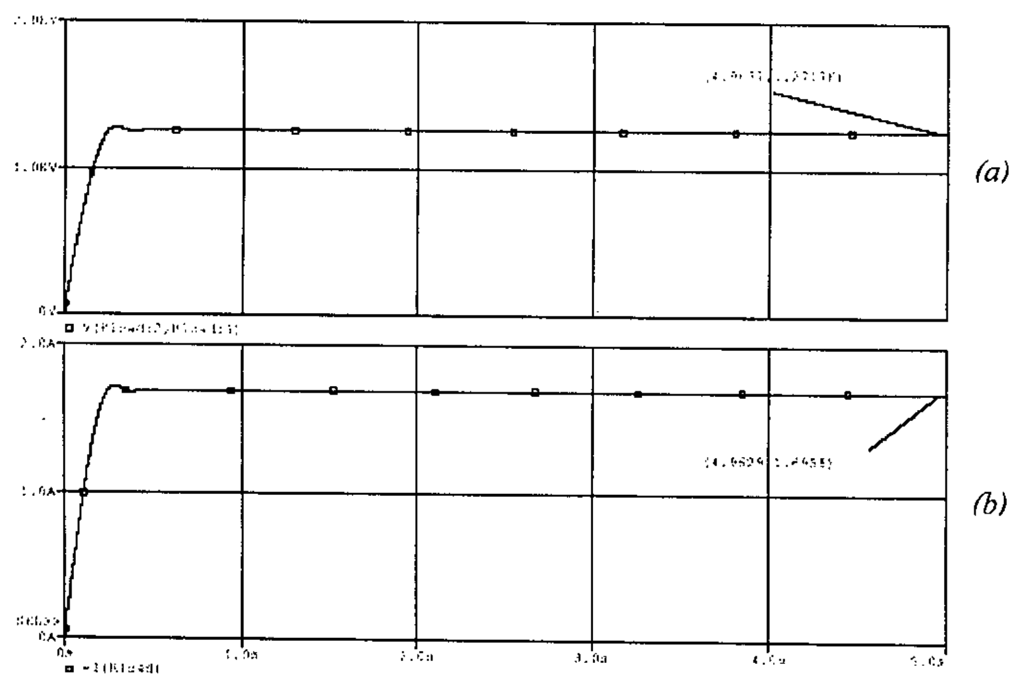


Figure 4.12: Wave shapes of (a) output voltage and (b) current for $L_iC_i = 6.42\times10^{-7}$, L_i=100mH.

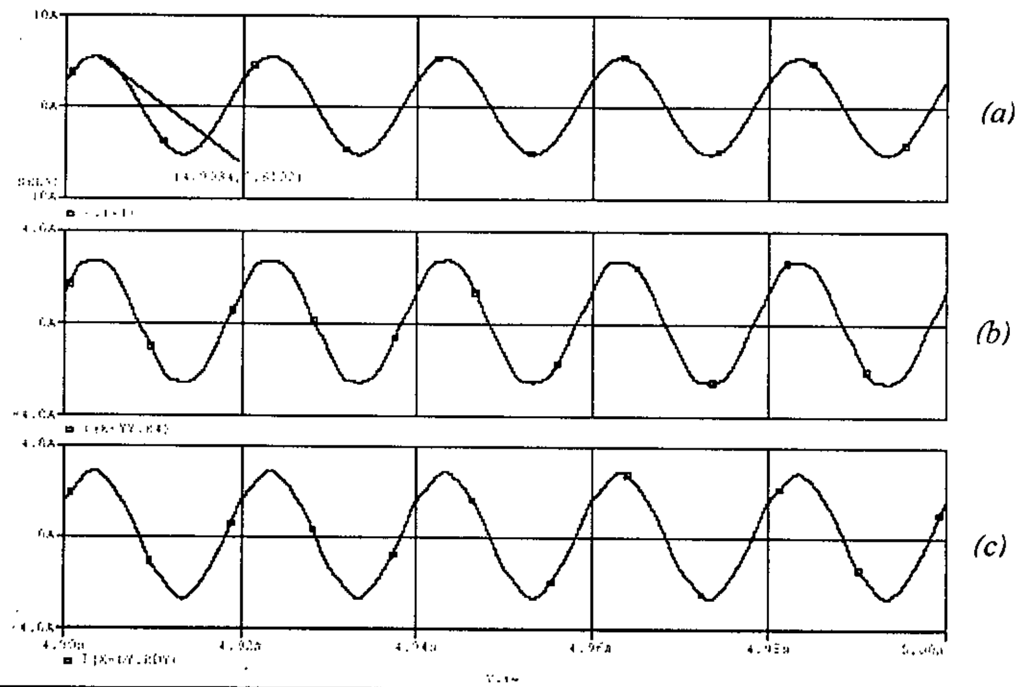


Figure 4.13: Input current wave shapes of (a) supply, (b) wye-wye and (c) delta-wye transformer for $L_iC_i = 6.42\times10^{-7}$, L_i=125mH.

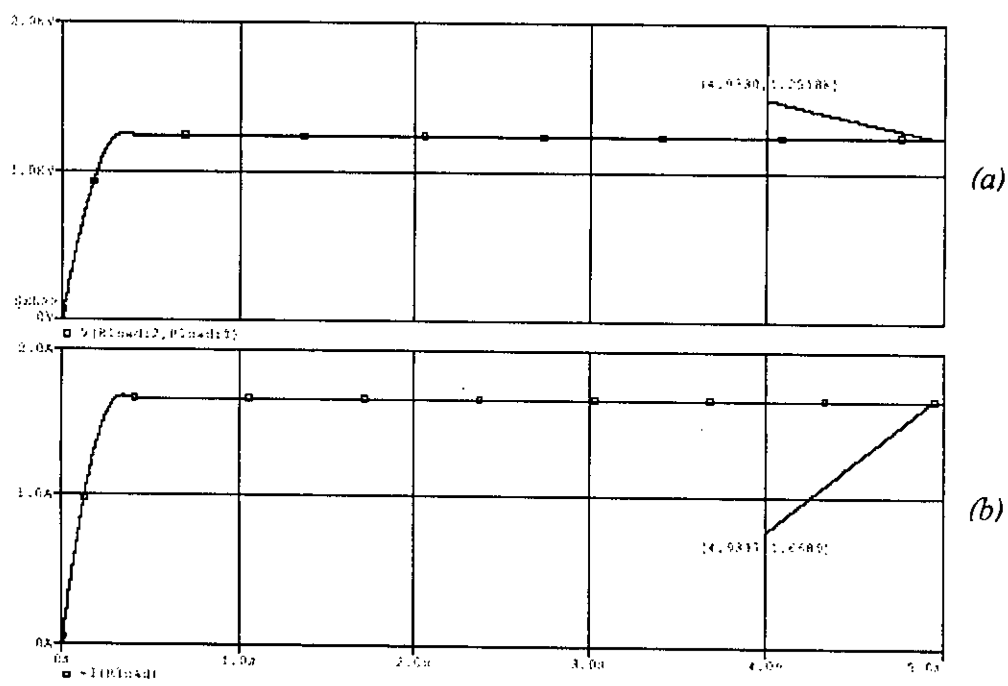


Figure 4.14: Wave shapes of (a) output voltage and (b) current for $L_iC_i = 6.42\times10^{-7}$, L_i=125mH.

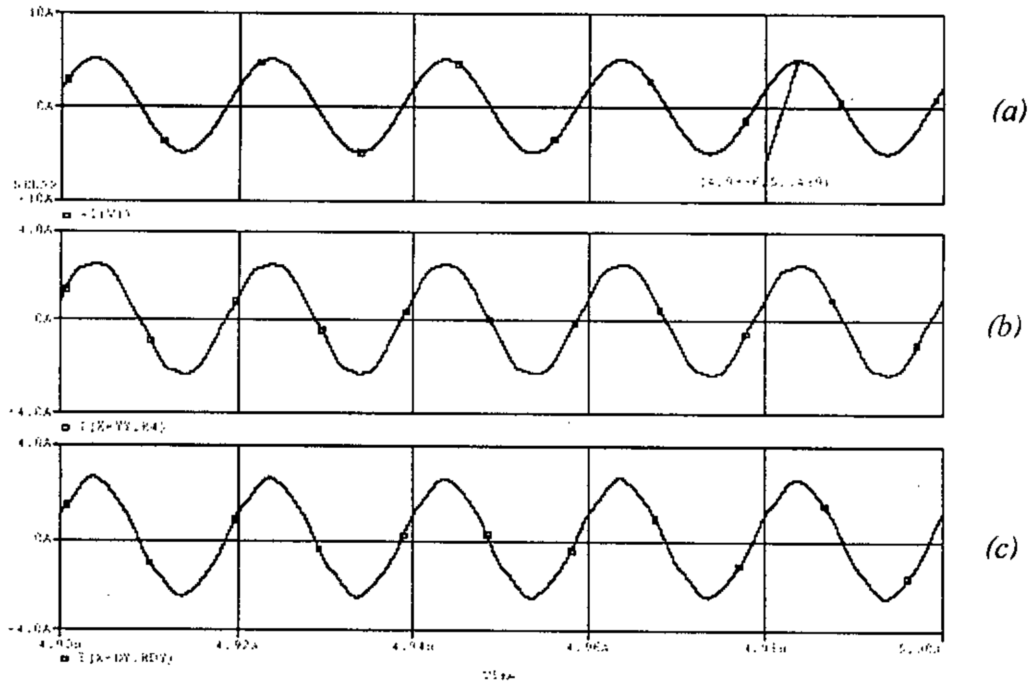


Figure 4.15: Input current wave shapes of (a) supply, (b) wye-wye and (c) delta-wye transformer for $L_iC_i = 6.42\times10^{-7}$, L_i=150mH.

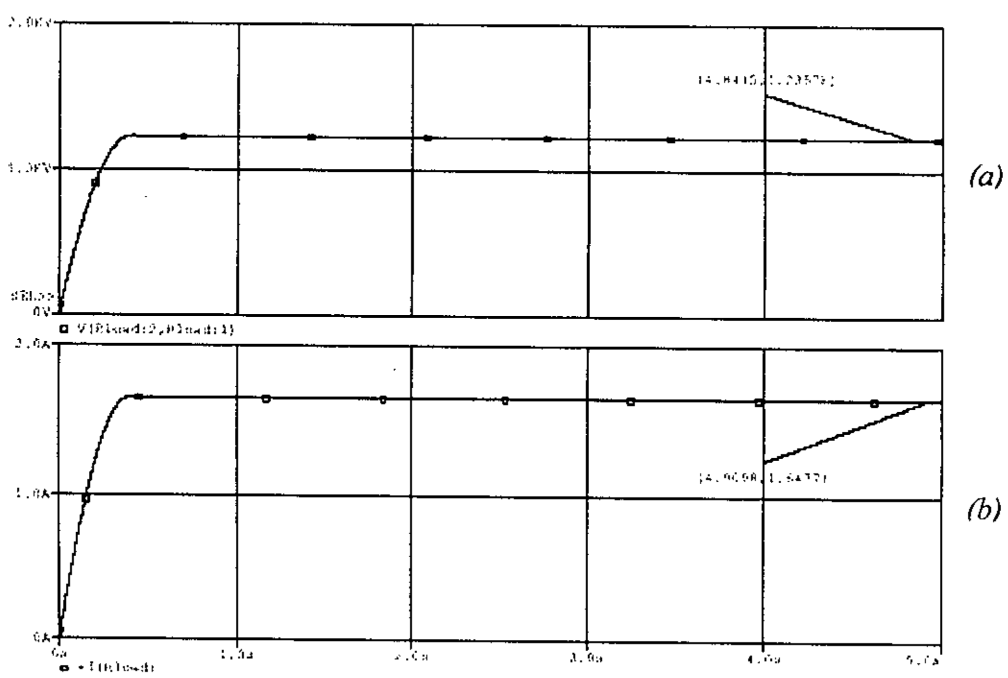


Figure 4.16: Wave shapes of (a) output voltage and (b) current for $L_iC_i = 6.42\times10^{-7}$, L_i=150mH.

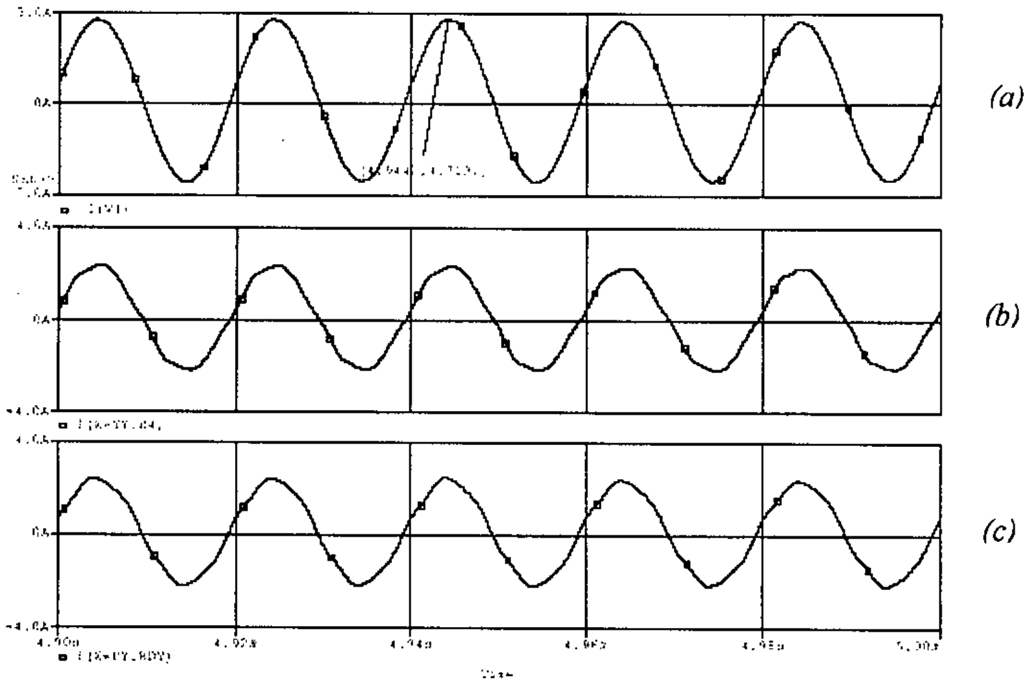


Figure 4.17: Input current wave shapes of (a) supply, (b) wye-wye and (c) delta-wye transformer for $L_iC_i = 6.42\times10^{-7}$, L_i=200mH.

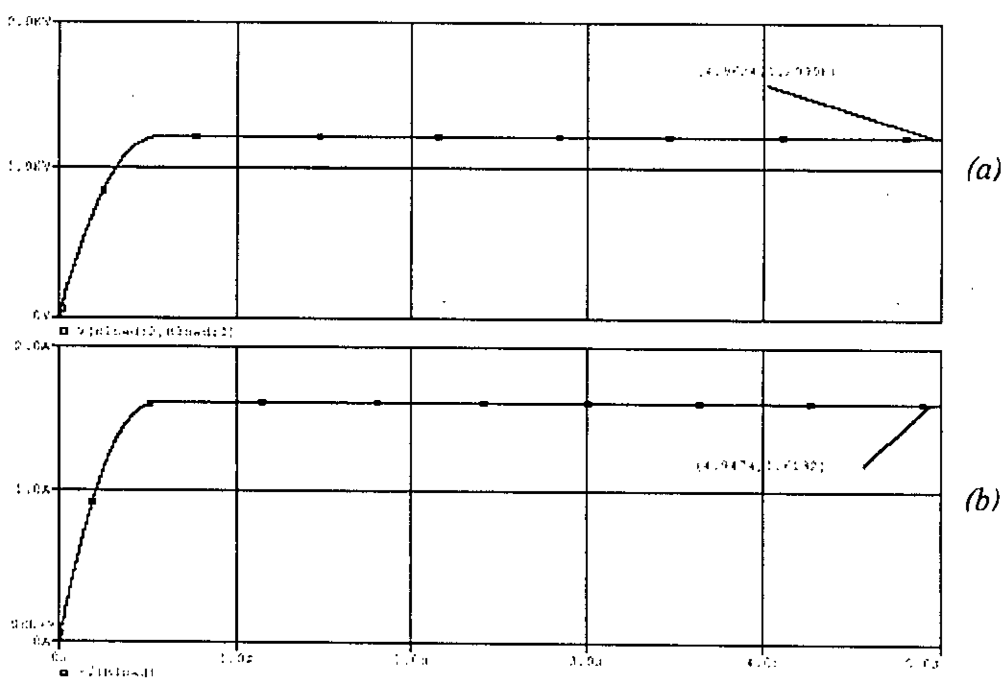


Figure 4.18: Wave shapes of (a) output voltage and (b) current for $L_iC_i = 6.42\times10^{-7}$, L_i=200mH.

Table 4.2: Summary of the simulation results for passive filters at rectifier inputs

AC Input Filter		DC Output Filter		$Efficiency$ η (%)	THD_I_s (%)	THD_I_{yy} (%)	THD_I_{dy} (%)
L_iC_i $const$	L_i (mH)	L_o (mH)	C_o (μF)				
6.42E-07	5	7	1000	63.26	0.04	0.05	0.06
6.42E-07	50	7	1000	51.45	0.89	2	2.04
6.42E-07	100	7	1000	77.21	0.66	2.77	2.87
6.42E-07	125	7	1000	86.78	0.66	3.28	3.18
6.42E-07	150	7	1000	92	0.88	3.48	3.88
6.42E-07	175	7	1000	95.38	0.62	3.96	3.88
6.42E-07	200	7	1000	99.06	0.73	4.136	4.02
6.42E-07	225	7	1000	98.81	0.61	4.25	4.25
6.42E-07	250	7	1000	99.46	0.48	4.09	4.09

Table 4.2 summarizes the results for the passive filtering scheme of Twelve-Pulse Rectifier with AC Filters used at Rectifier inputs for different combinations of L_i and C_i. From the table and the simulation outputs of input current, transformer currents, output voltage and output current it is found that incorporating passive filter at the rectifier input significantly reduces the total harmonic distortion of the input current and the wye-wye and delta-wye transformer currents. The minimum value ac filter inductance for which the maximum efficiency of the rectifier circuit and lower total harmonic distortion (THD) of input and transformer currents has been obtained is $L_i = 200mH$ for fixed $L_iC_i = 6.42\times10^{-7}$. At this point the rectifier efficiency is 99.06% and the total harmonic distortion of the supply current and wye-wye and delta-wye transformer currents are 0.73%, 4.136% and 4.02% respectively.

4.2 Analysis of Active Filtering scheme

The active filtering scheme for the 12-pulse rectifier has incorporated high switching frequency of 5 KHz PWM Boost converter at the output of the ac to dc rectifier that shape the input current and also the currents in the windings of transformers used for twelve-pulse rectifier by eliminating high frequency harmonic components with the aid of very small sized filters. Due to active filtering action all three input ac currents consist of the fundamental (50 Hz) component and a band of high frequency unwanted components centered around the PWM 5 KHz switching frequency of the boost switch. The discontinuous phase current pulses at high PWM frequency and the sinusoidal locus of the peak values can be filtered with a small *LC* filter to ideally obtain a sinusoidal average current with unity power factor. Figure 4.19, 4.20 and 4.21 shows the frequency spectrum of the input line current and wye-wye transformer and delta-wye transformer input currents of twelve-pulse rectifier with active filtering scheme without any input ac filter.

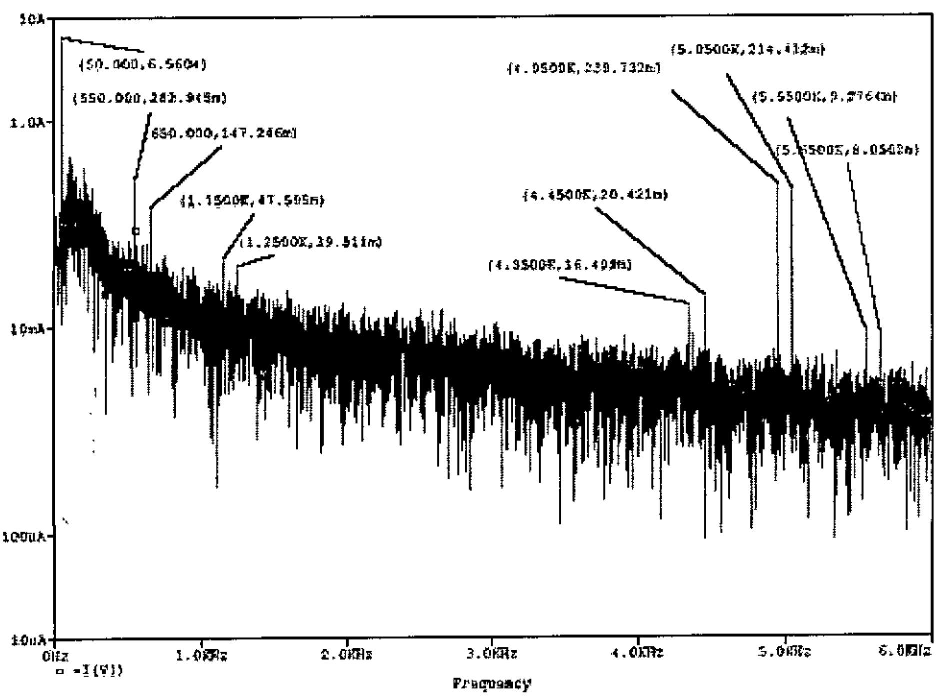


Figure 4.19: Frequency spectrum of the input line current, I_s

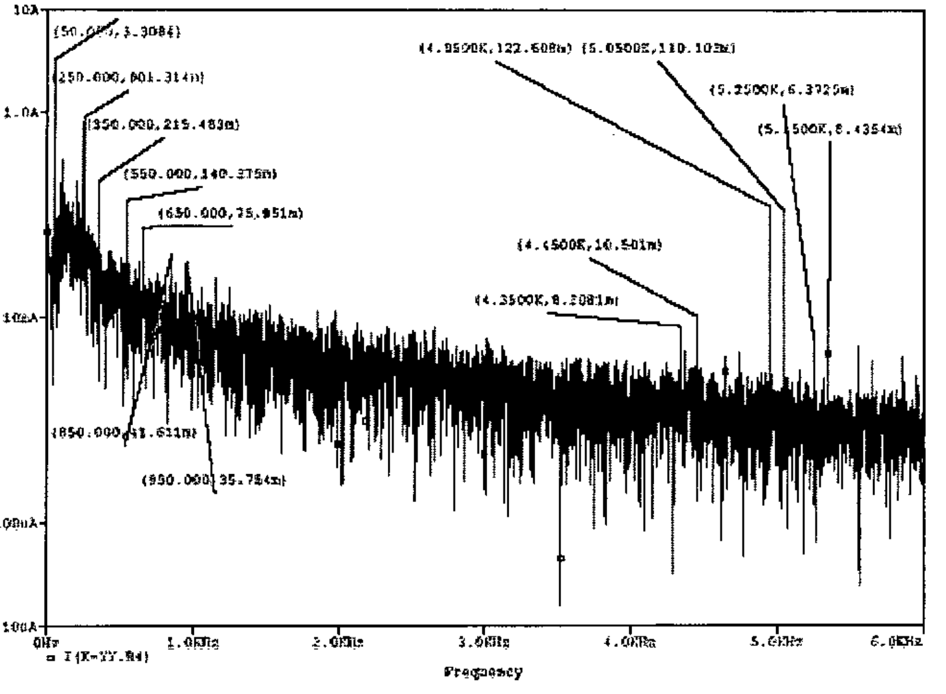


Figure 4.20: Frequency spectrum of the wye-wye transformer current, I_{yy}

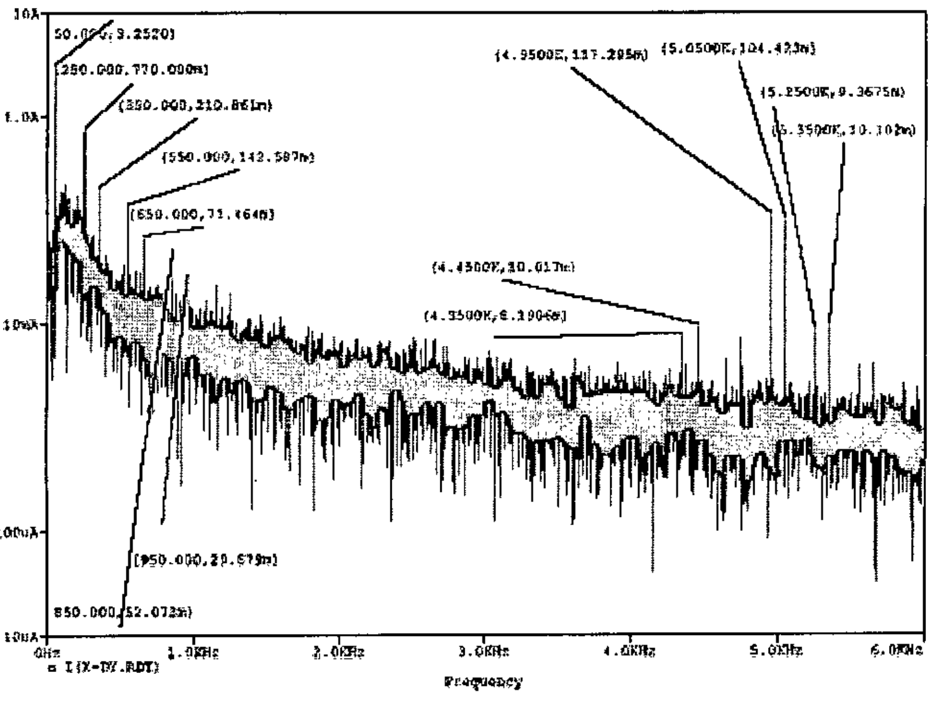


Figure 4.21: Frequency spectrum of the delta-wye transformer current, I_{dy}

The frequency spectrums of the current wave shapes depicts that there is a band of high frequency components at $f_{sw} - f_i = 4.95KHz$ and $f_{sw} + f_i = 5.05KHz$ centered around the PWM switching frequency, $f_{sw} = 5KHz$, where $f_i = 50Hz$ is the supply frequency. To reduce this high frequency unwanted components to 1% at the supply and transformer to get the sinusoidal average currents, small sized *L-C* input filters have to be designed. The value of L_iC_i filter constant is found as-

$$L_iC_i = \frac{1}{(n\omega)^2}\left[\frac{I_{rn}}{I_{sn}} - 1\right] = \frac{1}{(2\pi \times 4.95 \times 10^3)^2}\left[\frac{100}{1} - 1\right] = 102.34 \times 10^{-9}$$

Simulations have been performed for different combinations of L_i and C_i at different duty cycles to get lower total harmonic distortion (THD) of input currents and maximum efficiency of the rectifier circuit. Two models have been studied under active filtering scheme – (1) Active filtering scheme using Double Boost Converters (DBC) at the rectifier outputs with ac filters at rectifier inputs, and (2) Active filtering scheme using Single Boost Converter (SBC) at the rectifier output with ac filters at Rectifier inputs.

4.2.1 Active filter with Double Boost converter at the rectifier output

Figure 4.22 shows the schematic diagram of the active filtering scheme using Hierarchical Block for the twelve-pulse rectifier configuration with PWM module. Here two PWM Boost Converters have been used at the output of the two six pulse rectifiers with ac filters at the rectifier inputs for reducing the total harmonic distortion of the input current and transformer currents. The boost inductor and the boost filter capacitor have been taken 1mH and 10μF respectively. Following the schematic diagram of the active filtering scheme the simulation outputs of input current, transformer currents, output voltage and output current have been presented at different duty cycles with ac input filter inductance value, $L_i = 5mH$ and capacitance value, $C_i = 20\mu F$ along with a table and a graph that have summarized the simulation results obtained.

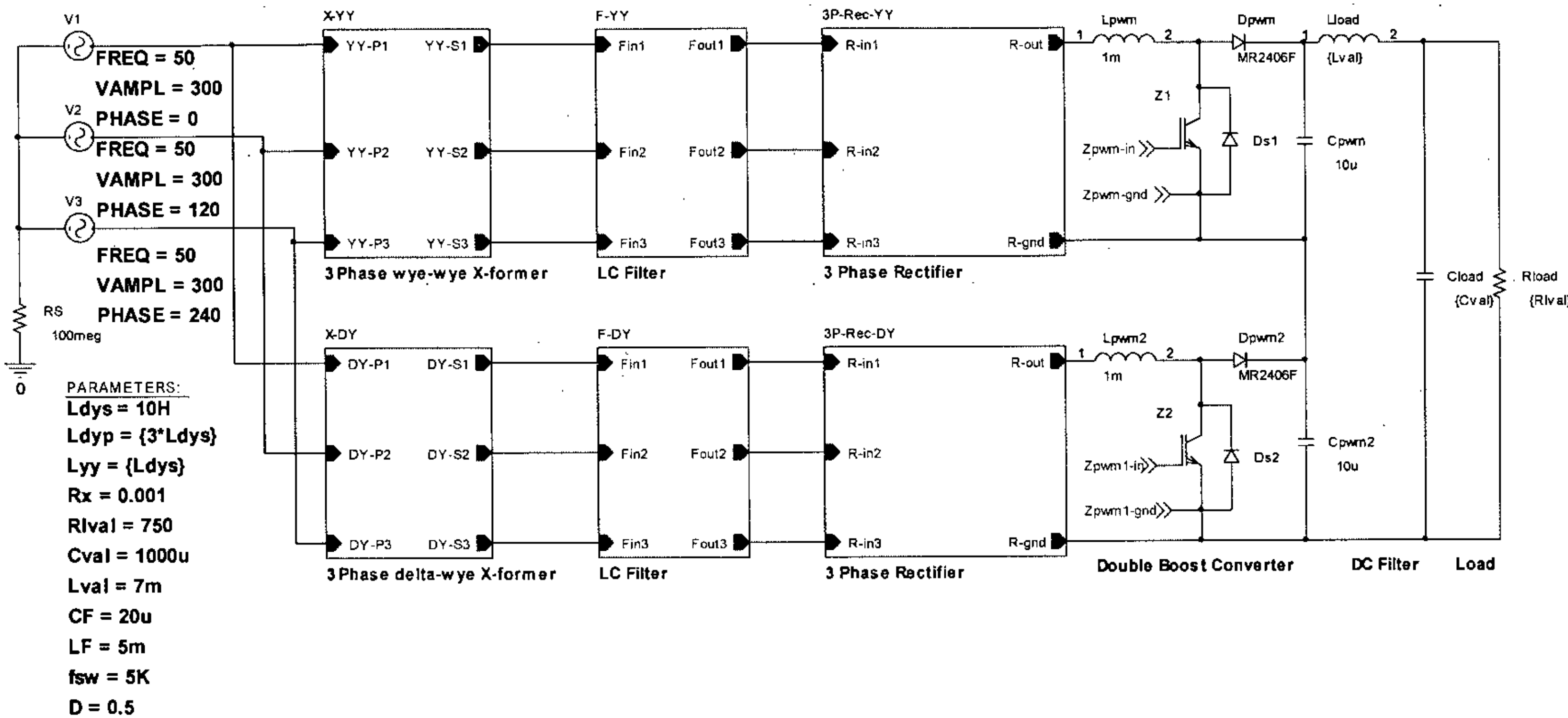


Figure 4.46 (a): Schematic diagram using Hierarchical Block of Active Filtering Scheme of Twelve Pulse Rectifier using Double Boost Converter with AC Filter at rectifier input.

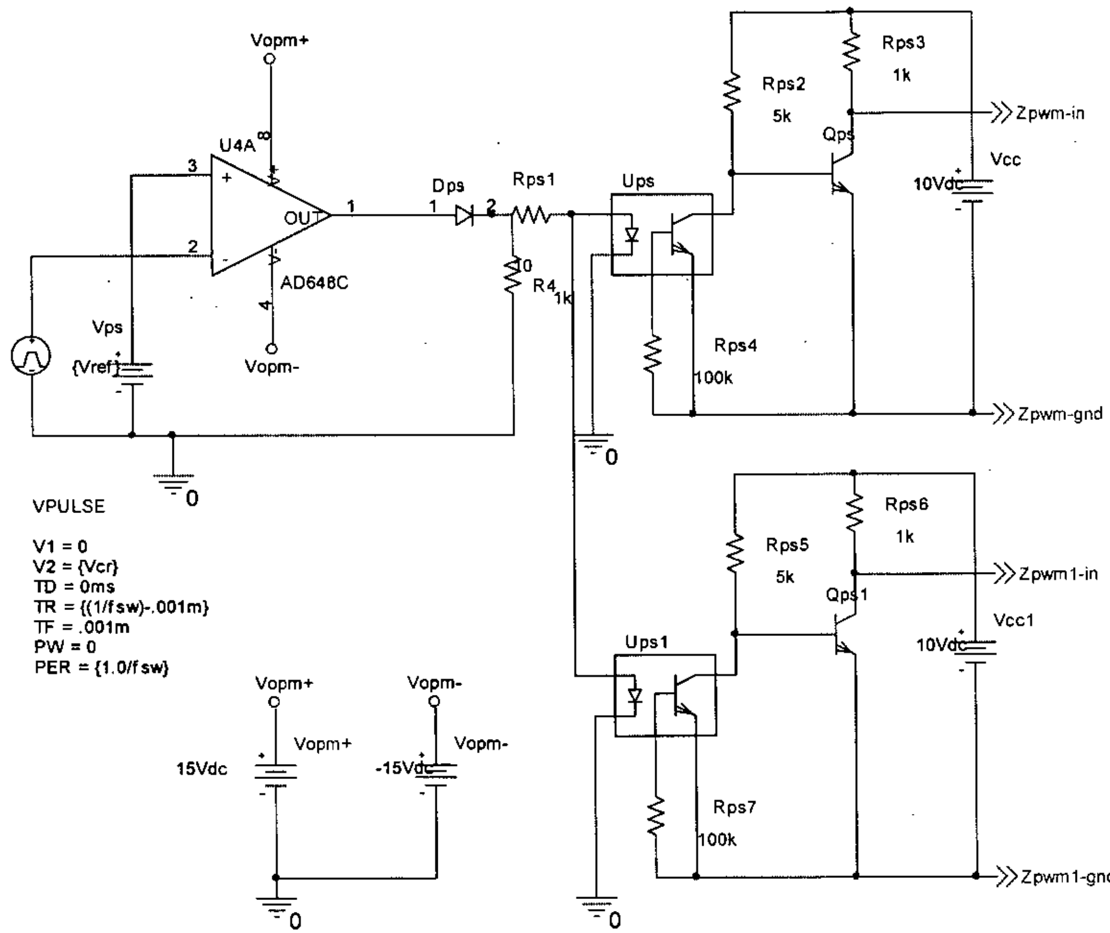


Figure 4.46 (b): Schematic diagram of PWM module for Active Filtering Scheme of Twelve Pulse Rectifier using Double Boost Converter

4.2.1.1 Simulation outputs of the active filtering scheme using DBC

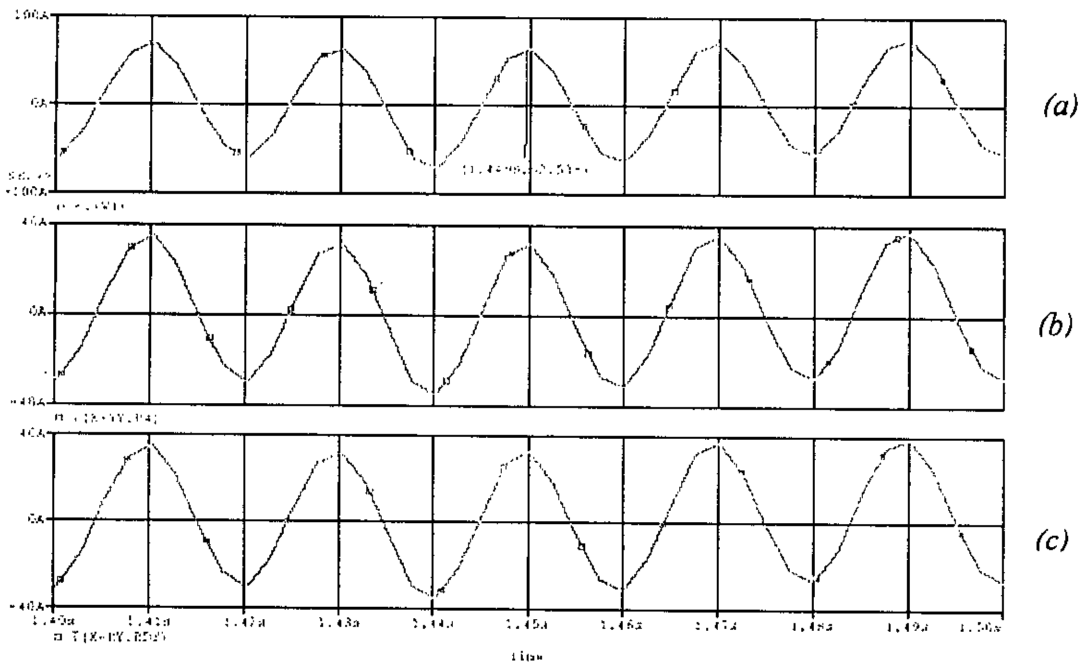


Figure 4.23: Input current wave shapes of (a) supply, (b) wye-wye and (c) delta-wye transformer for $C_i = 20\mu F$, $L_i = 5mH$ and duty cycle, $D = 0.0$.

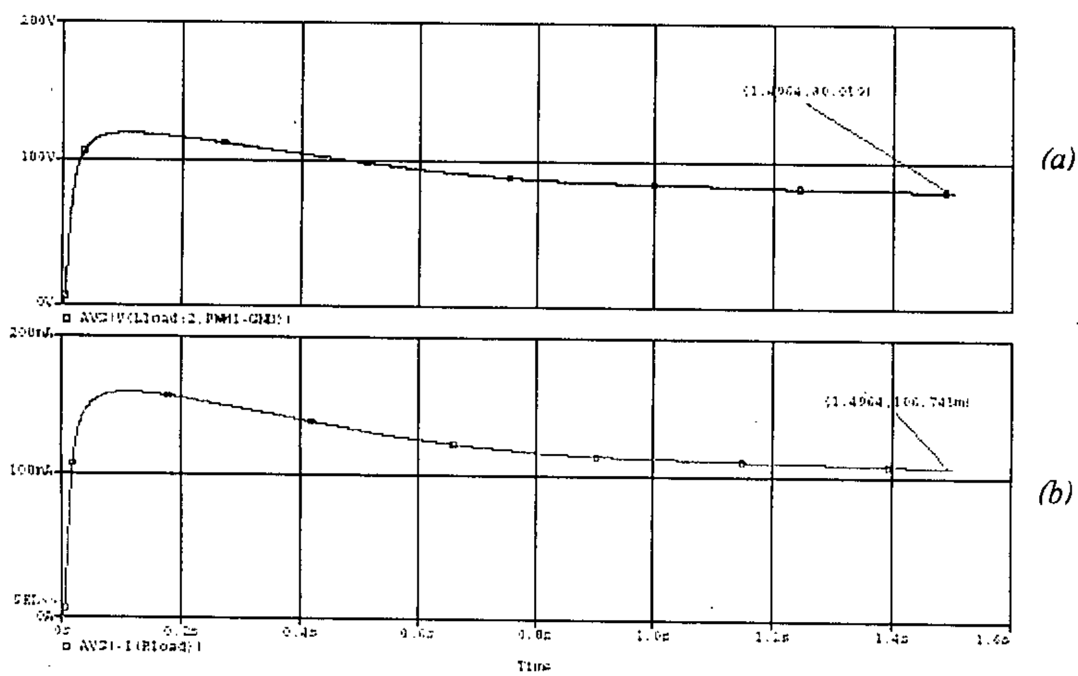


Figure 4.24: Wave shapes of (a) output voltage and (b) current for $C_i = 20\mu F$, $L_i = 5mH$ and duty cycle, $D = 0.0$.

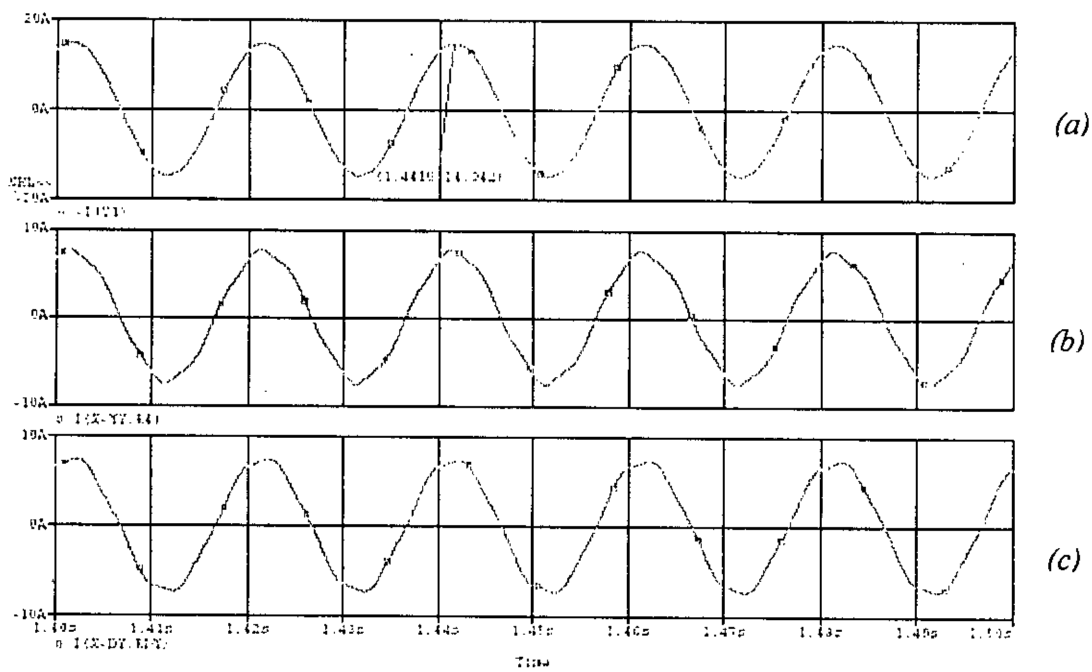


Figure 4.25: Input current wave shapes of (a) supply, (b) wye-wye and (c) delta-wye transformer for $C_i = 20\mu F$, $L_i = 5mH$ and duty cycle, $D = 0.1$.

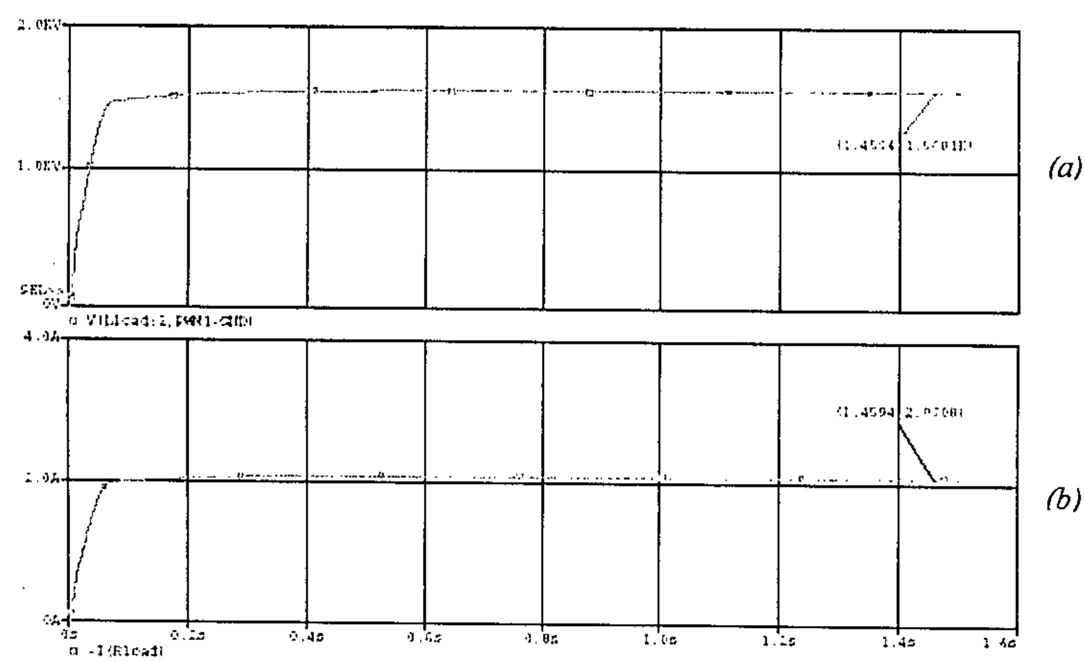


Figure 4.26: Wave shapes of (a) output voltage and (b) current for $C_i = 20\mu F$, $L_i = 5mH$ and duty cycle, $D = 0.1$.

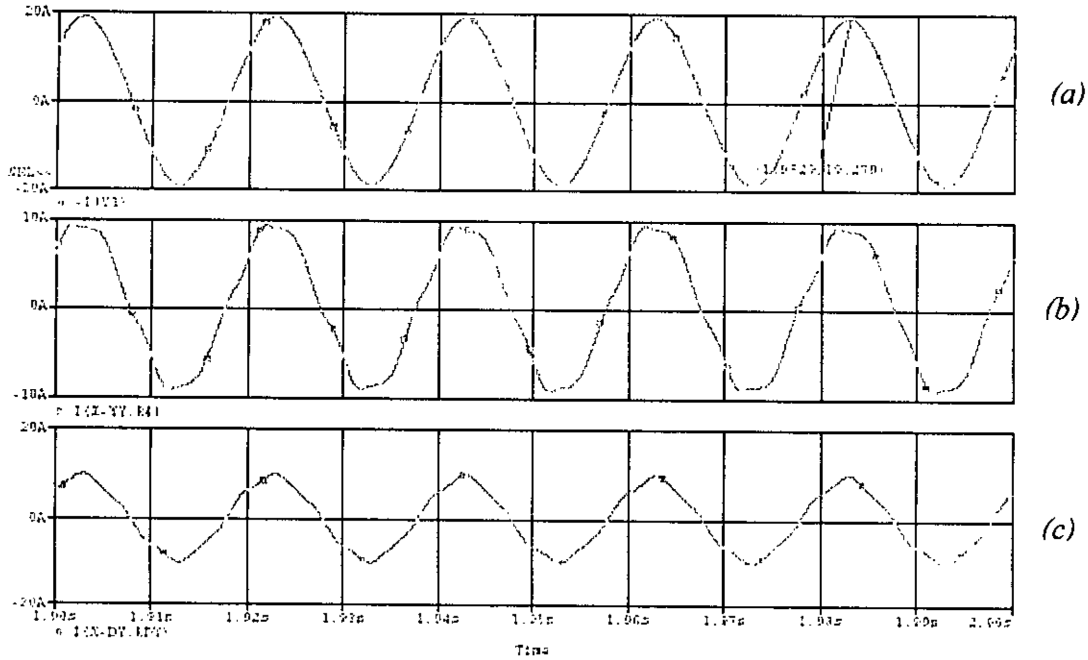


Figure 4.27: Input current wave shapes of (a) supply, (b) wye-wye and (c) delta-wye transformer for $C_i = 20\mu F$, $L_i = 5mH$ and duty cycle, $D = 0.2$.

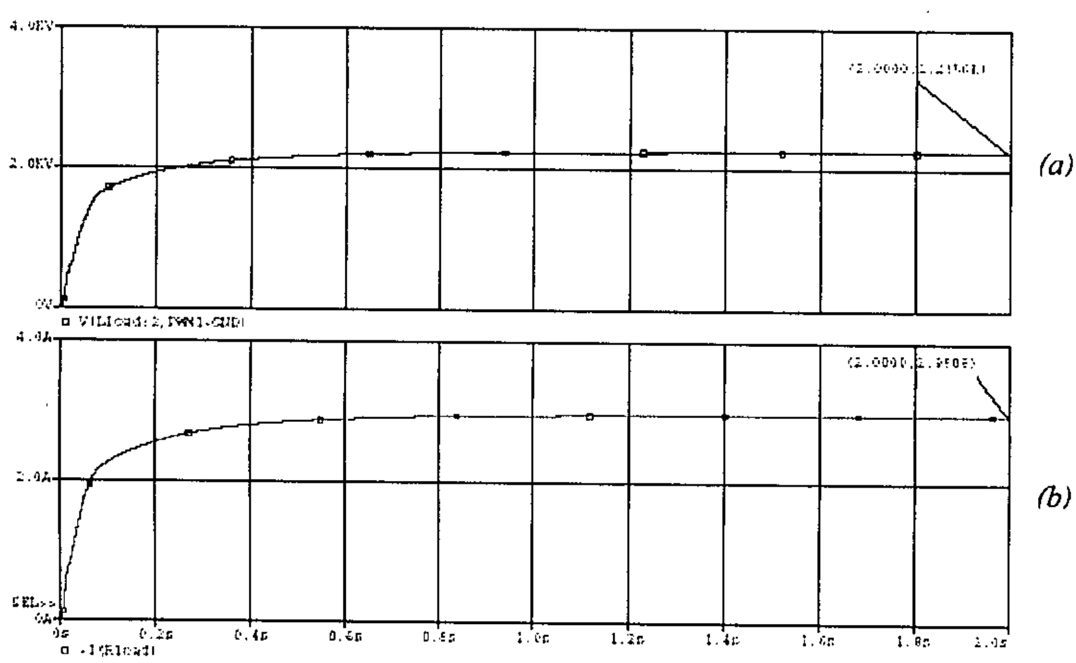


Figure 4.28: Wave shapes of (a) output voltage and (b) current for $C_i = 20\mu F$, $L_i = 5mH$ and duty cycle, $D = 0.2$.

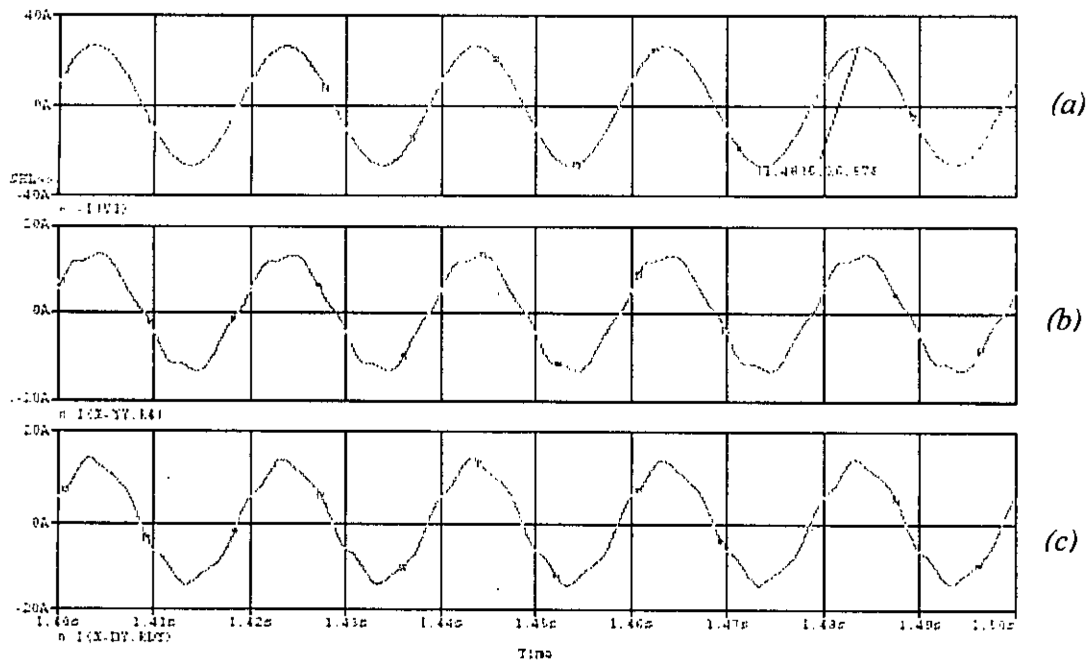


Figure 4.29: Input current wave shapes of (a) supply, (b) wye-wye and (c) delta-wye transformer for $C_i = 20\mu F$, $L_i = 5mH$ and duty cycle, $D = 0.3$.

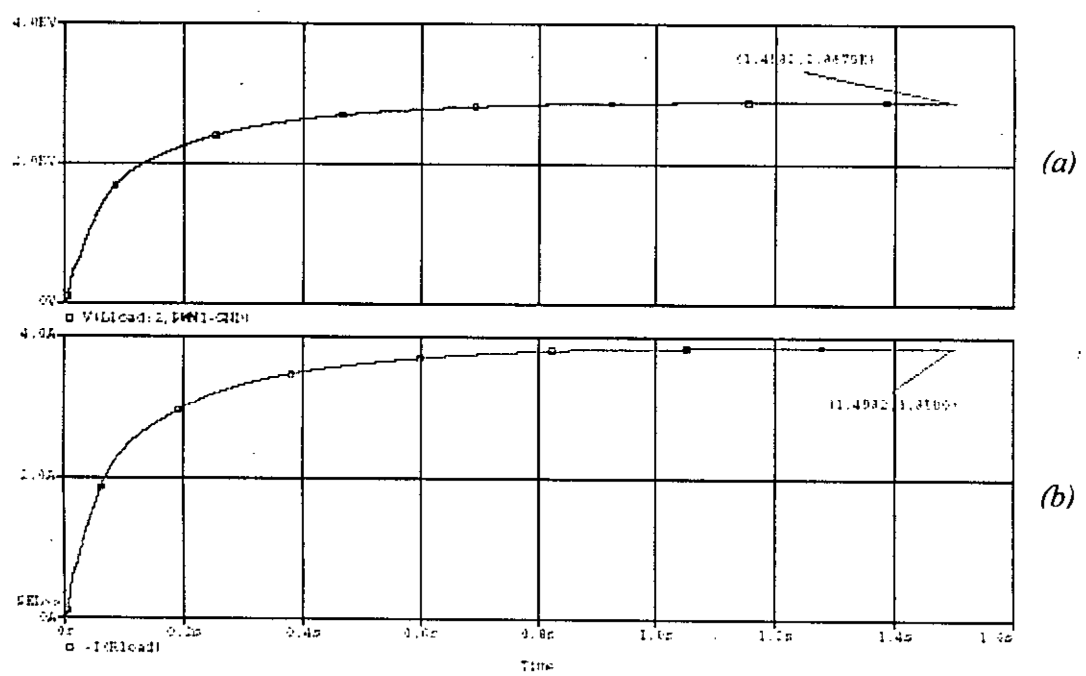


Figure 4.30: Wave shapes of (a) output voltage and (b) current for $C_i = 20\mu F$, $L_i = 5mH$ and duty cycle, $D = 0.3$.

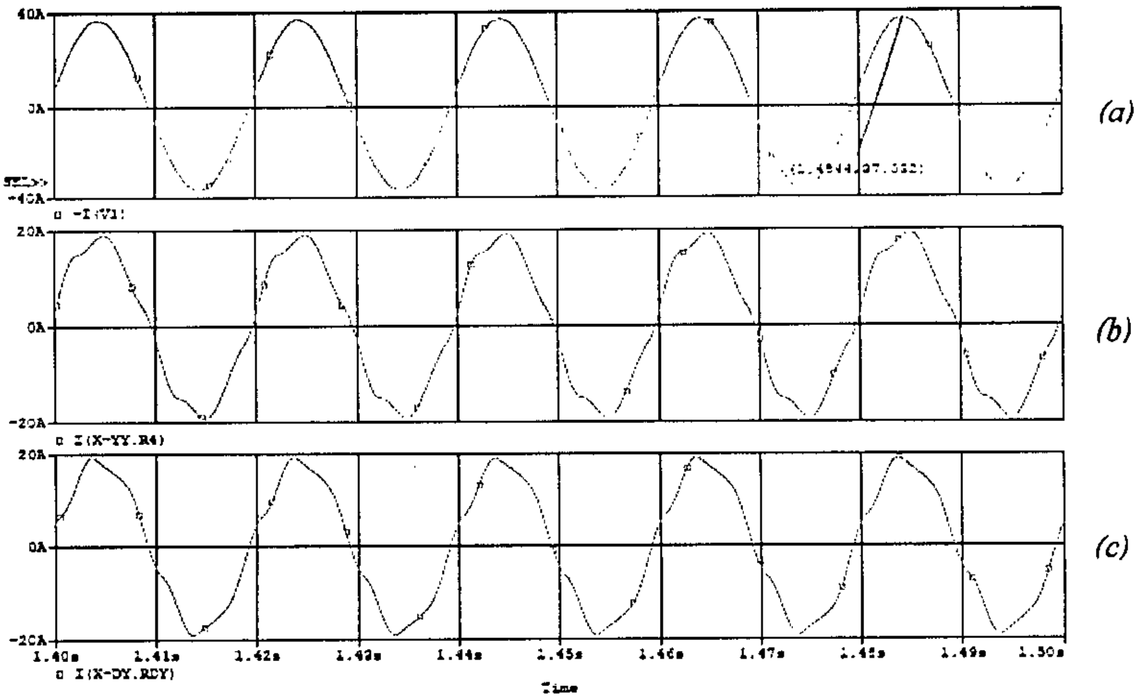


Figure 4.31: Input current wave shapes of (a) supply, (b) wye-wye and (c) delta-wye transformer for $C_i = 20\mu F$, $L_i = 5mH$ and duty cycle, $D = 0.4$.

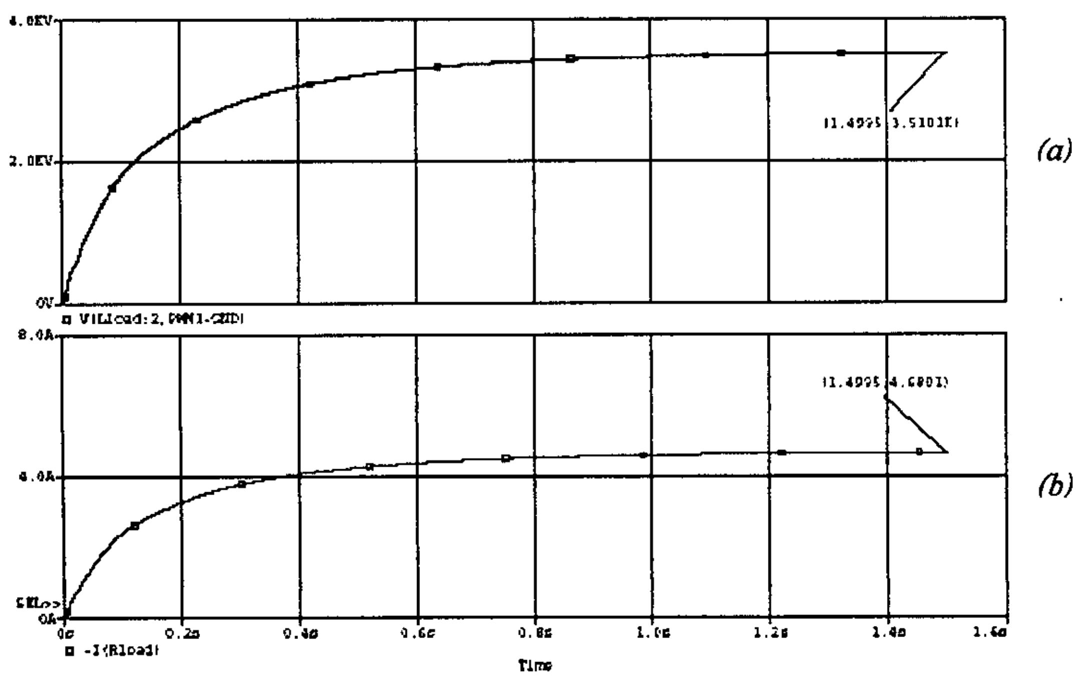


Figure 4.32: Wave shapes of (a) output voltage and (b) current for $C_i = 20\mu F$, $L_i = 5mH$ and duty cycle, $D = 0.4$.

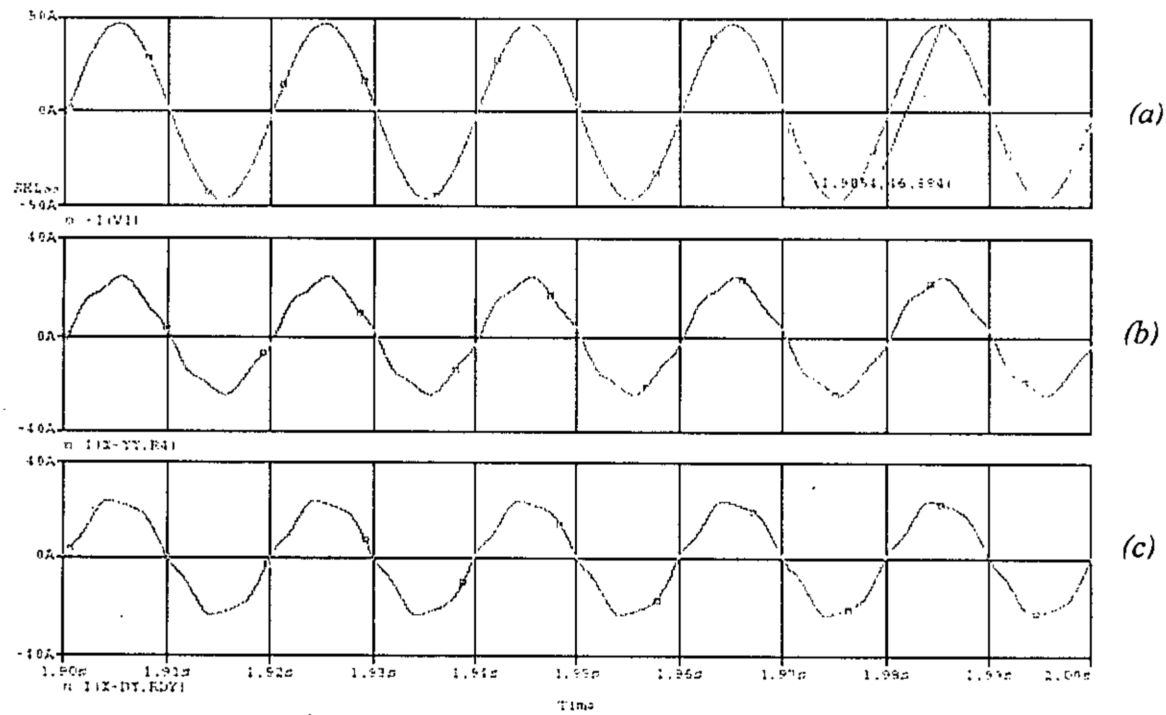


Figure 4.33: Input current wave shapes of (a) supply, (b) wye-wye and (c) delta-wye transformer for $C_i = 20\mu F$, $L_i = 5mH$ and duty cycle, $D = 0.5$.

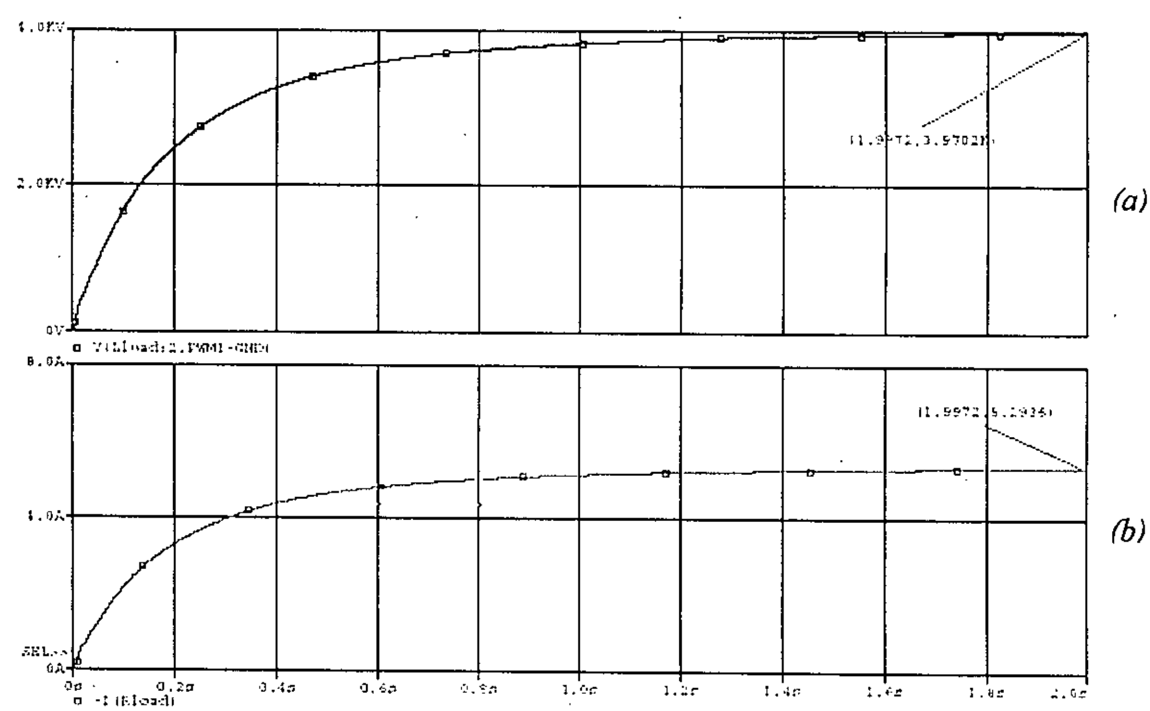


Figure 4.34: Wave shapes of (a) output voltage and (b) current for $C_i = 20\mu F$, $L_i = 5mH$ and duty cycle, $D = 0.5$.

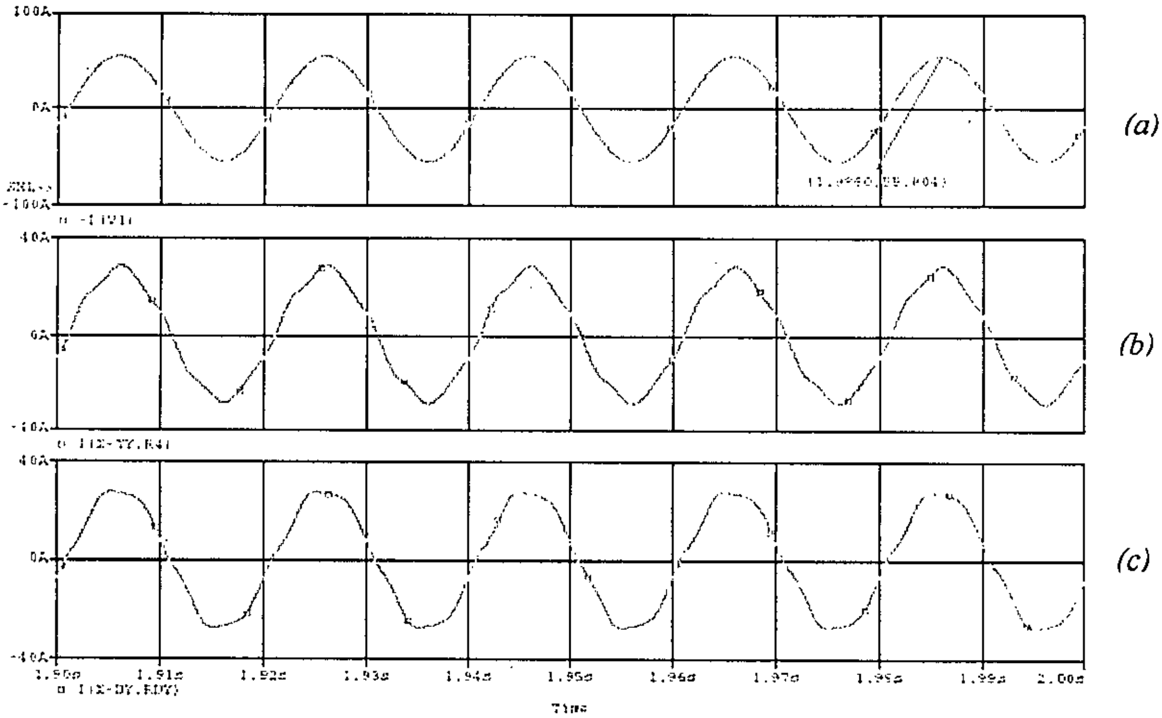


Figure 4.35: Input current wave shapes of (a) supply, (b) wye-wye and (c) delta-wye transformer for $C_i = 20\mu F$, $L_i = 5mH$ and duty cycle, $D = 0.6$.

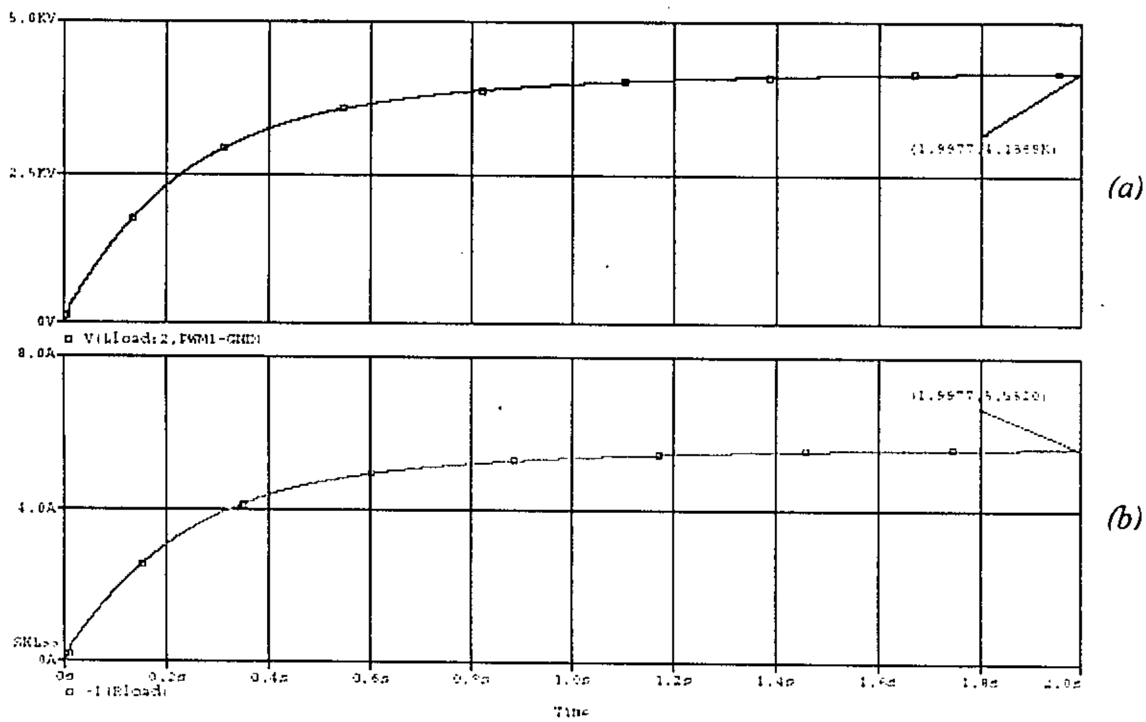


Figure 4.36: Wave shapes of (a) output voltage and (b) current for $C_i = 20\mu F$, $L_i = 5mH$ and duty cycle, $D = 0.6$.

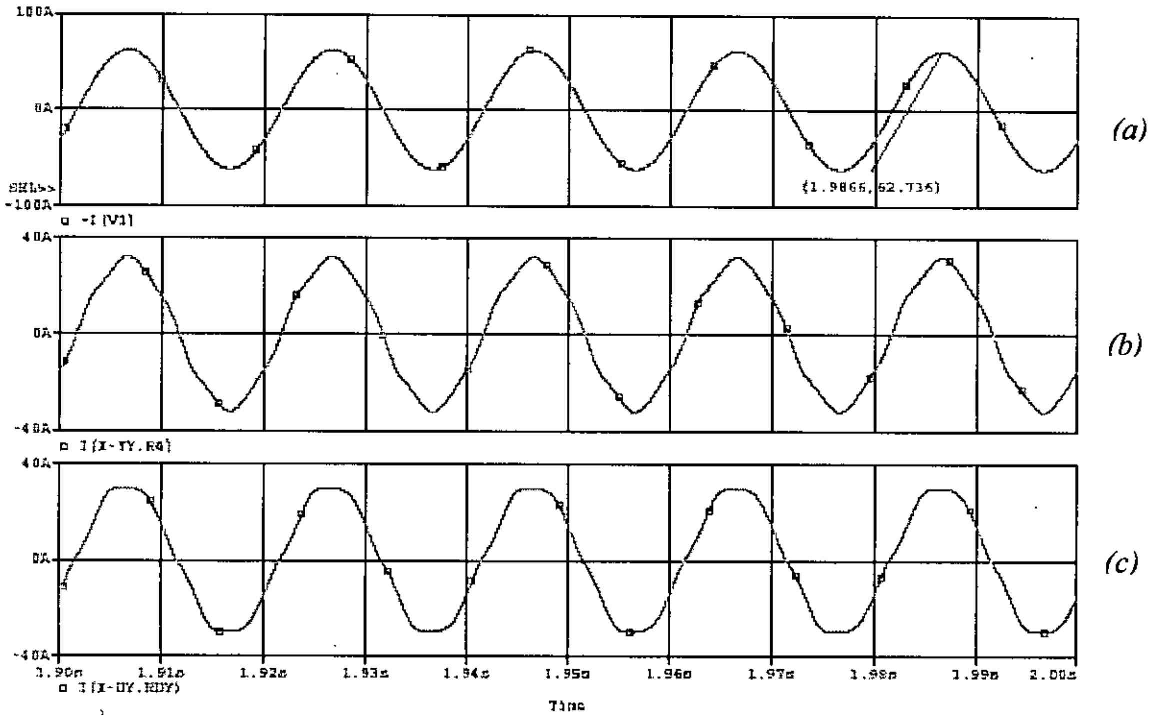


Figure 4.37: Input current wave shapes of (a) supply, (b) wye-wye and (c) delta-wye transformer for $C_i = 20\mu F$, $L_i = 5mH$ and duty cycle, $D = 0.7$.

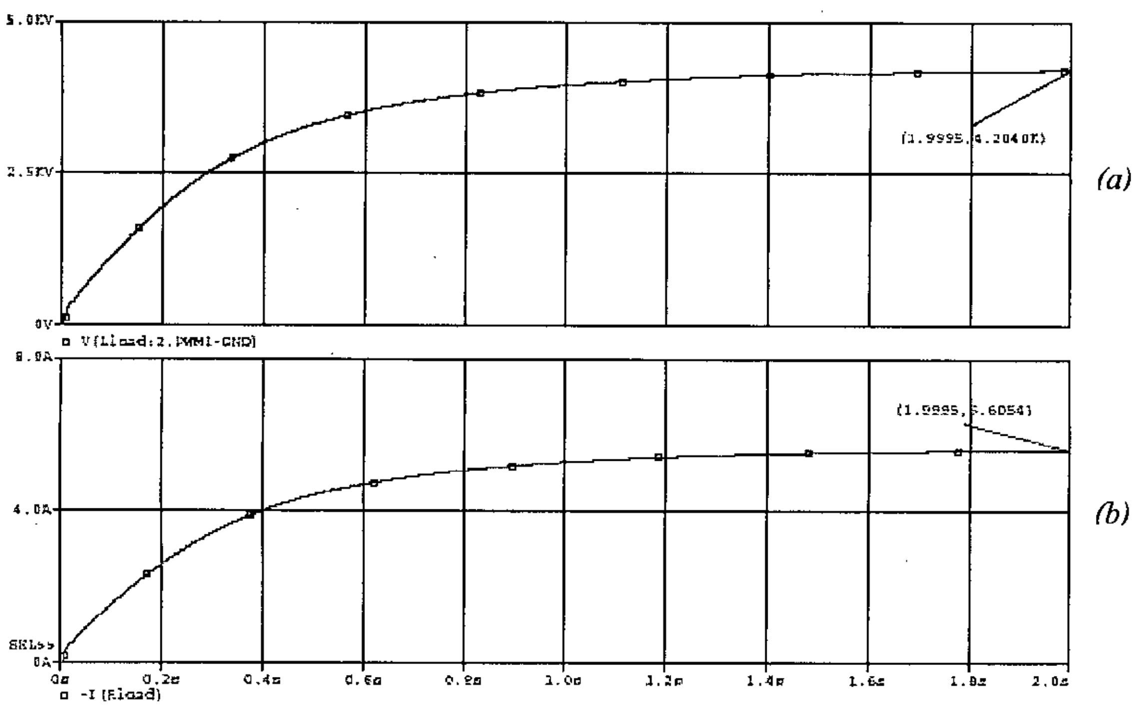


Figure 4.38: Wave shapes of (a) output voltage and (b) current for $C_i = 20\mu F$, $L_i = 5mH$ and duty cycle, $D = 0.7$.

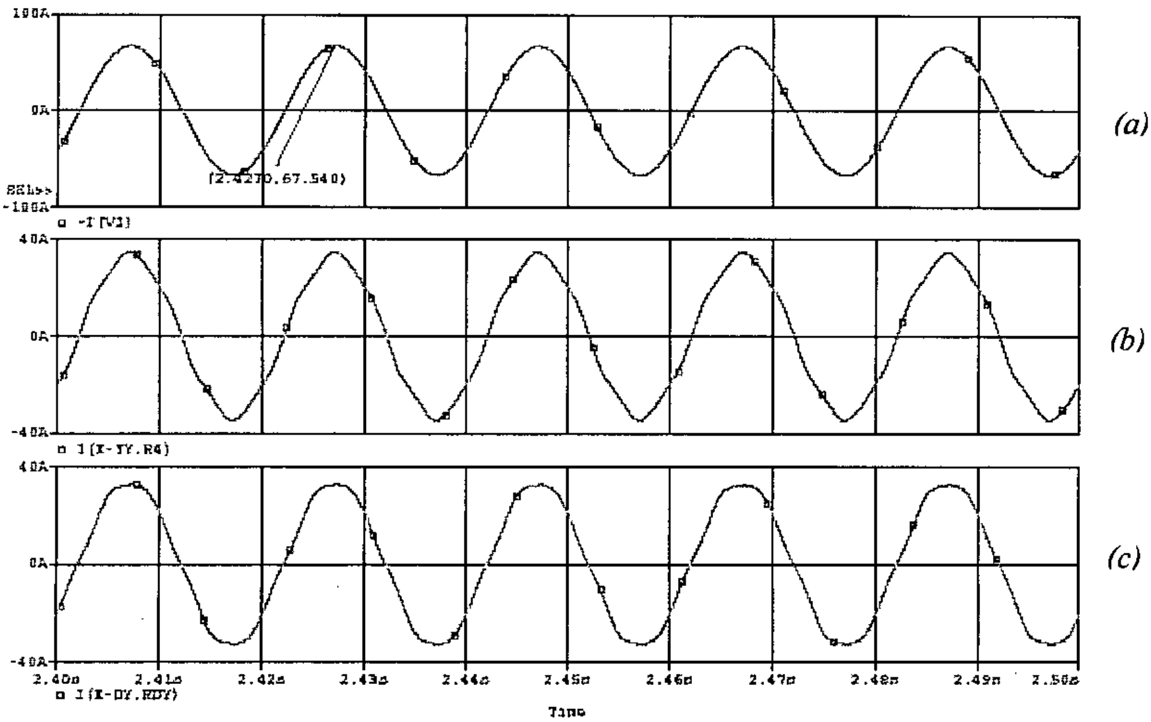


Figure 4.39: Input current wave shapes of (a) supply, (b) wye-wye and (c) delta-wye transformer for $C_i = 20\mu F$, $L_i = 5mH$ and duty cycle, $D = 0.8$.

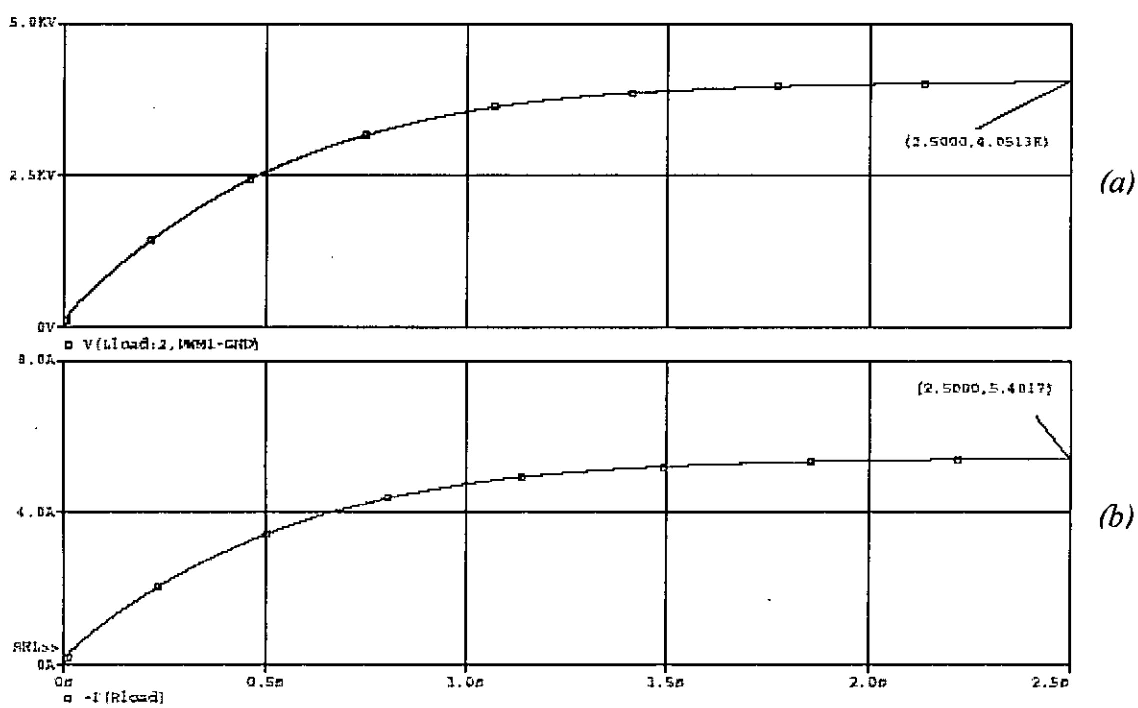


Figure 4.40: Wave shapes of (a) output voltage and (b) current for $C_i = 20\mu F$, $L_i = 5mH$ and duty cycle, $D = 0.8$.

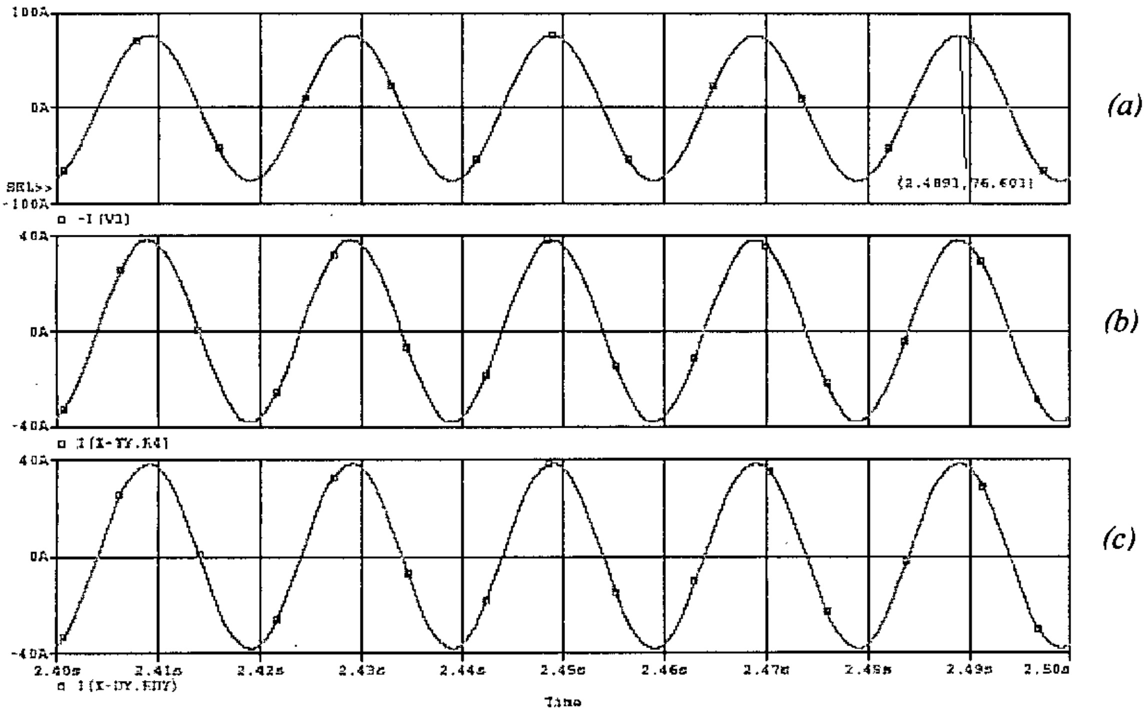


Figure 4.41: Input current wave shapes of (a) supply, (b) wye-wye and (c) delta-wye transformer for $C_i = 20\mu F$, $L_i = 5mH$ and duty cycle, $D = 0.9$.

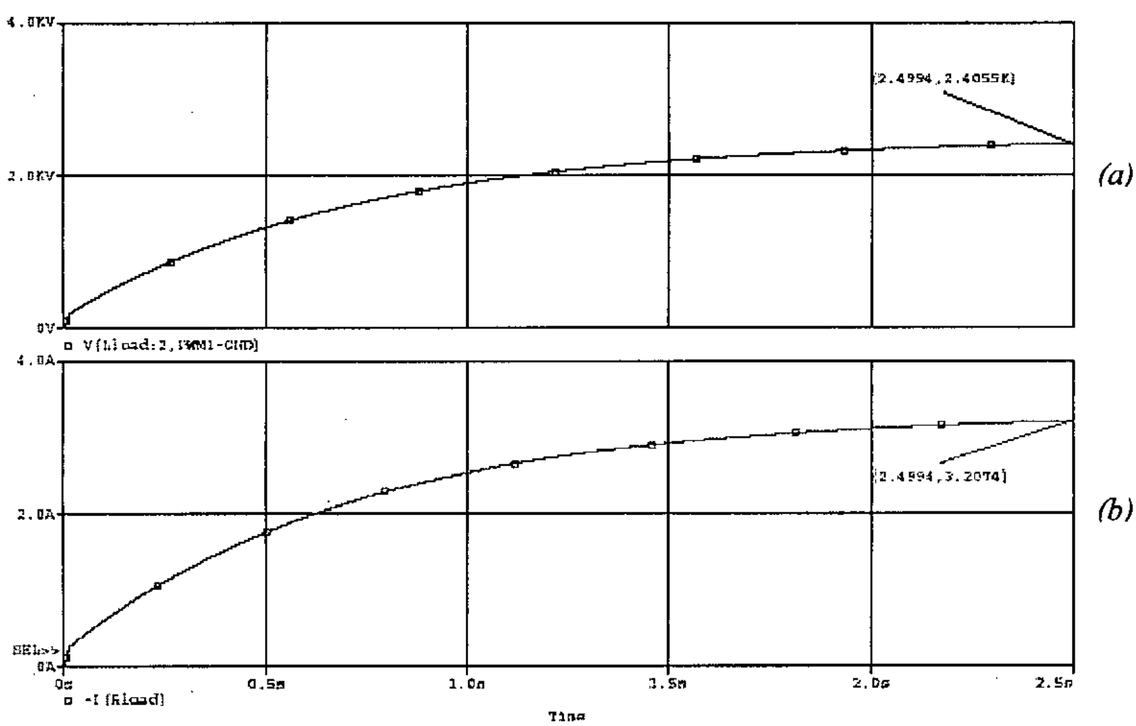


Figure 4.42: Wave shapes of (a) output voltage and (b) current for $C_i = 20\mu F$, $L_i = 5mH$ and duty cycle, $D = 0.9$.

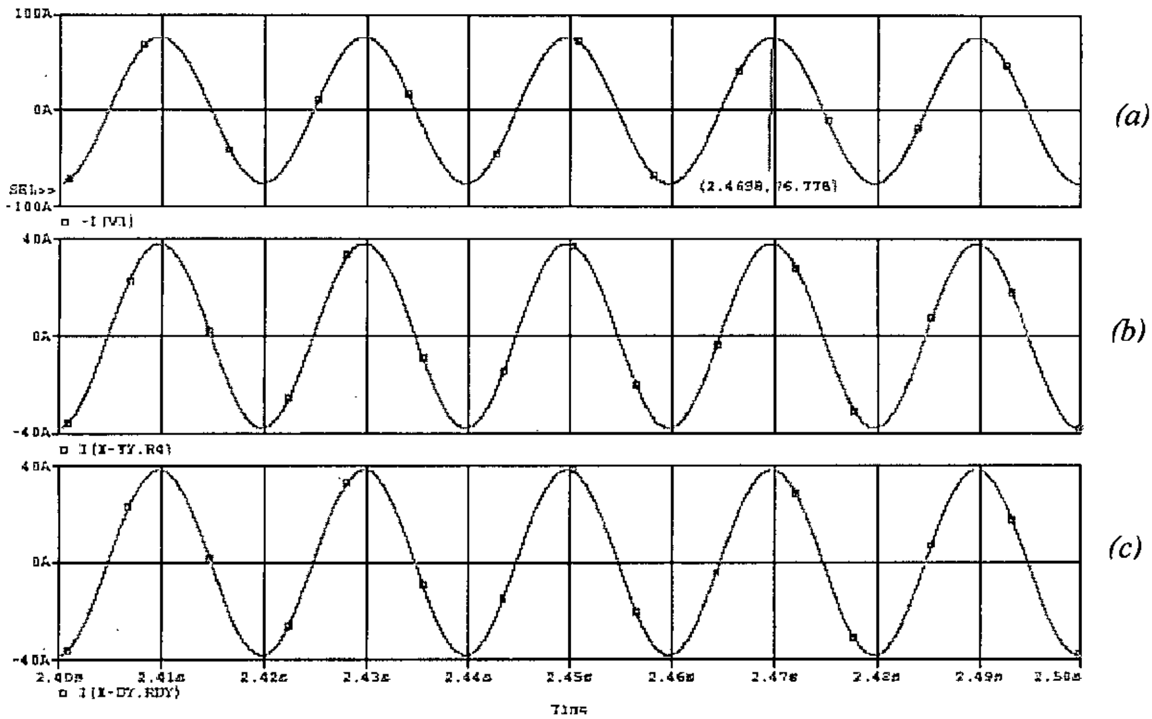


Figure 4.43: Input current wave shapes of (a) supply, (b) wye-wye and (c) delta-wye transformer for $C_i = 20\mu F$, $L_i = 5mH$ and duty cycle, $D = 1.0$.

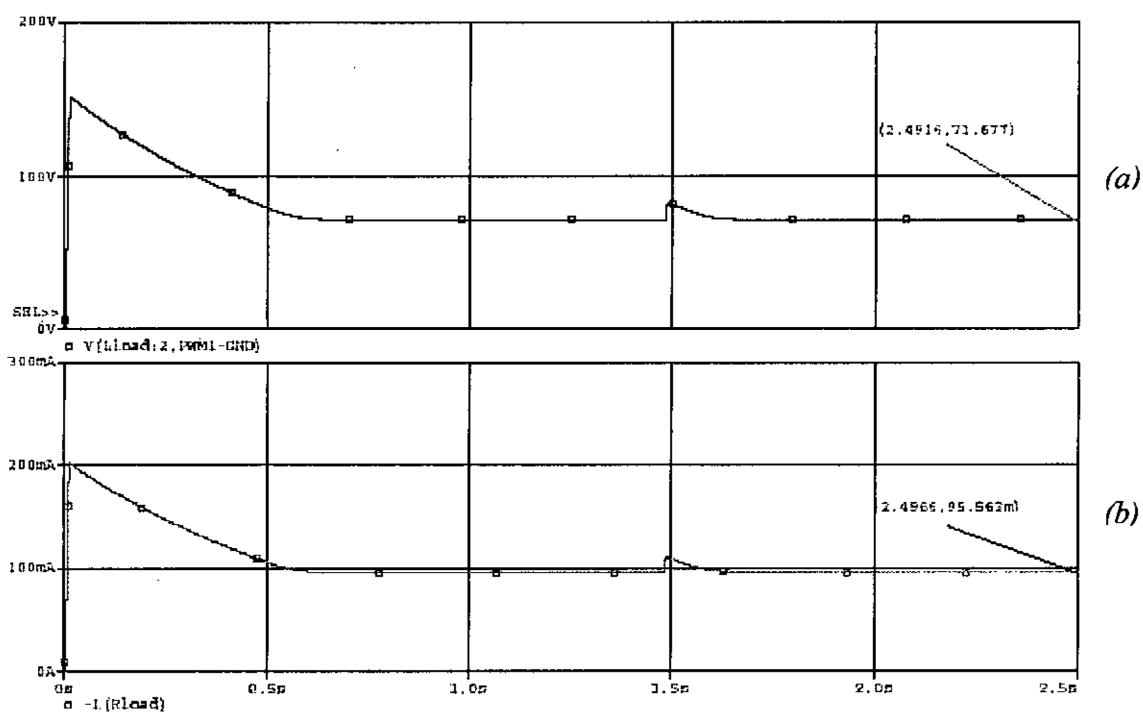


Figure 4.44: Wave shapes of (a) output voltage and (b) current for $C_i = 20\mu F$, $L_i = 5mH$ and duty cycle, $D = 1.0$.

Table 4.3: Summary of the simulation results for active filter using Double Boost Cconverter with ac input filter at rectifier input

	AC Input Filter		DC Output Filter									
Dutycycle, D	**Li (mH)**	**Ci (μF)**	**Lo (mH)**	**Co (μF)**	**Input Current, Is (A)**	**Output Voltage,Vo (V)**	**Output Current, Io (A)**	**Power Factor**	**Efficiency, η (%)**	**THD_Is (%)**	**THD_Iyy (%)**	**THD_Idy (%)**
0.0	5	20	7	1000	63.42	80.06	0.11	0.999	0.03	2.93	2.91	2.99
0.1	5	20	7	1000	14.73	1568.10	2.09	0.999	49.51	0.8	4.28	4.22
0.2	5	20	7	1000	18.87	2235.60	2.98	0.999	78.56	1.5	5.765	6.58
0.3	5	20	7	1000	26.61	2887.50	3.85	0.999	92.93	0.84	6.83	6.92
0.4	5	20	7	1000	36.90	3510.10	4.68	0.999	99.03	0.74	7.26	7.06
0.5	5	20	7	1000	46.71	3970.20	5.29	0.999	100.00	0.43	6.38	6.36
0.6	5	20	7	1000	55.53	4186.50	5.58	0.999	93.61	0.39	5.43	5.36
0.7	5	20	7	1000	62.25	4204.00	5.61	0.999	84.21	0.37	4.57	4.55
0.8	5	20	7	1000	67.10	4051.30	5.40	0.999	72.55	0.366	3.91	3.91
0.9	5	20	7	1000	76.59	2405.50	3.21	0.999	22.41	0.25	1.35	1.345
1.0	5	20	7	1000	76.53	71.68	0.10	0.999	0.02	0.11	0.41	0.41

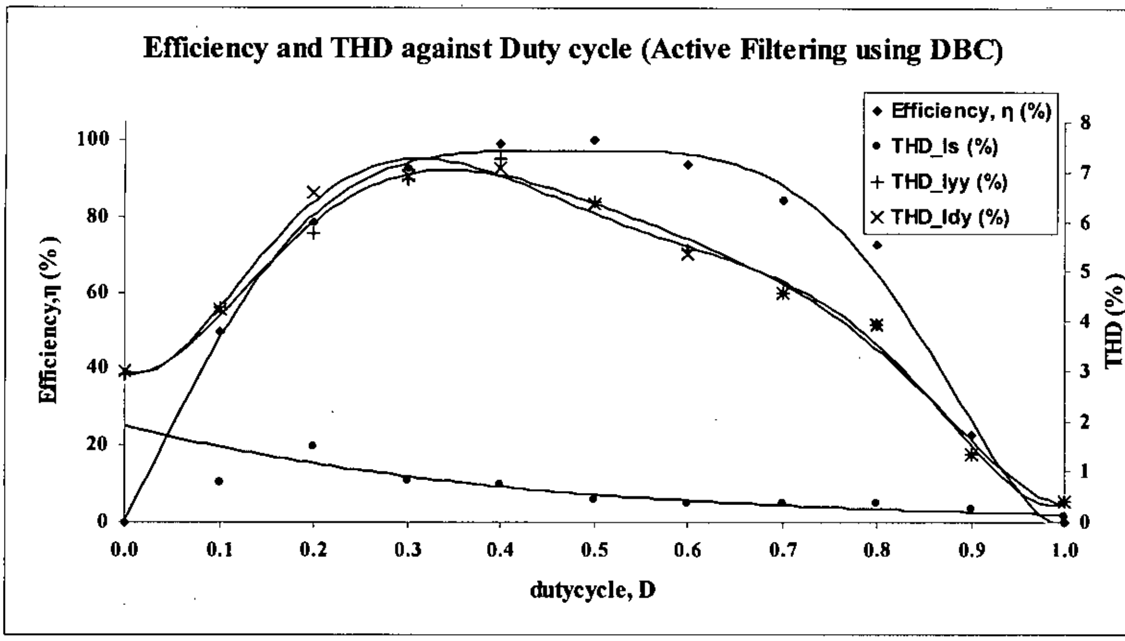


Figure 4.45: Efficiency and THD curve against Duty cycle for active filtering scheme using Double Boost Converter (DBC)

Table 4.3 summarizes the results at different duty cycles for the active filtering scheme of Twelve-Pulse Rectifier using double boost converter at the outputs of the two pulse rectifier unit with AC Filters used at Rectifier inputs with ac input filter inductance value, $L_i = 5mH$ and capacitance value, $C_i = 20\mu F$. Also figure 4.45 shows the efficiency and THD curve against duty cycle for active filtering scheme using Double Boost Converter (DBC). From the graph, table and the simulation outputs of input current, transformer currents, output voltage and output current it is found that incorporating active filtering scheme using double boost converter significantly reduces the total harmonic distortion of the input current and the wye-wye and delta-wye transformer currents with an aid of very small size of ac input filter. Here it is found that for the ac input filter with $L_i = 5mH$ and $C_i = 20\mu F$ the duty cycle in the range of 0.3 to 0.7 gives the maximum efficiency for the module. Beyond the range the efficiency drops down rapidly. The maximum efficiency of 100% is found at the duty cycle of 0.5. The total harmonic distortion of the input current decreases exponentially as the duty cycle increases. THDs of the wye-wye and delta-wye transformer currents are maximum of about 7% at 0.4 duty cycle. After that THDs decrease gradually.

4.2.2 Active filter with single Boost converter at the rectifier output

Figure 4.46 shows the schematic diagram of the active filtering scheme using Hierarchical Block for the twelve-pulse rectifier configuration with PWM module. Here a single PWM Boost Converter has been used at the output of the two six pulse rectifier with ac filters at the rectifier inputs for reducing the total harmonic distortion of the input current and transformer currents. The boost inductor and the boost filter capacitor have been taken 1mH and 10μF respectively. Following the schematic diagram of the active filtering scheme the simulation outputs of input current, transformer currents, output voltage and output current have been presented at different duty cycles with ac input filter inductance value, $L_i = 5mH$ and capacitance value, $C_i = 20\mu F$ along with a table and a graph that have summarized the simulation results obtained.

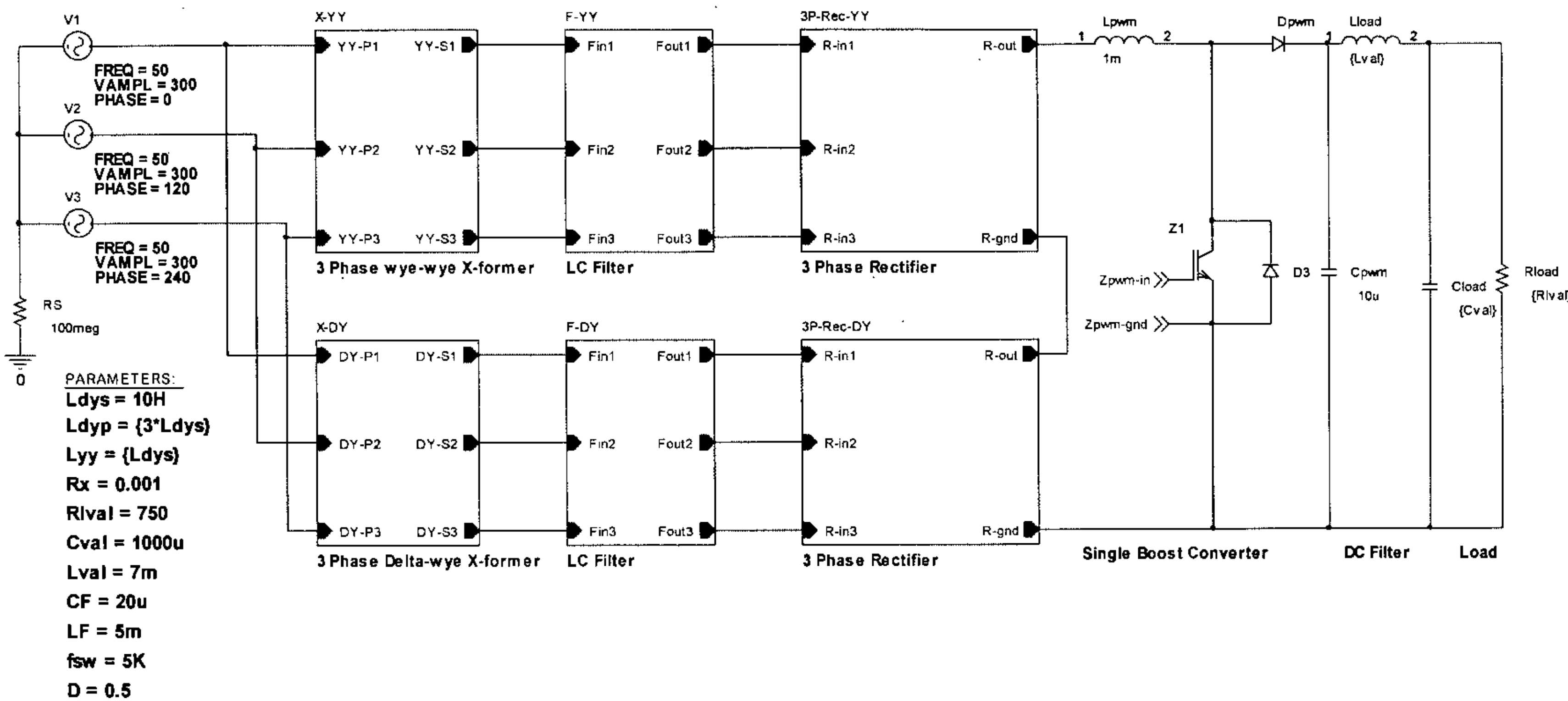


Figure 4.46 (a): Schematic diagram using Hierarchical Block of Active Filtering Scheme of Twelve Pulse Rectifier using Single Boost Converter with AC Filter at rectifier input.

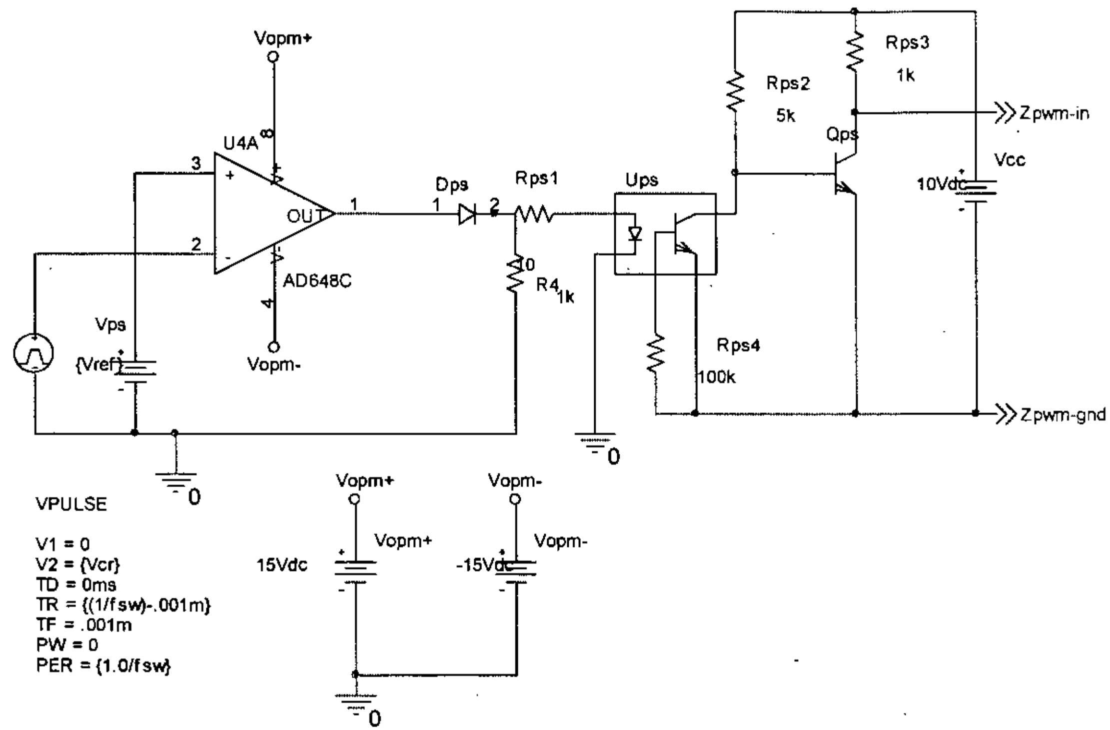


Figure 4.46 (b): Schematic diagram of PWM module for Active Filtering Scheme of Twelve Pulse Rectifier using Single Boost Converter

4.2.2.1 Simulation outputs of the active filtering scheme using SBC

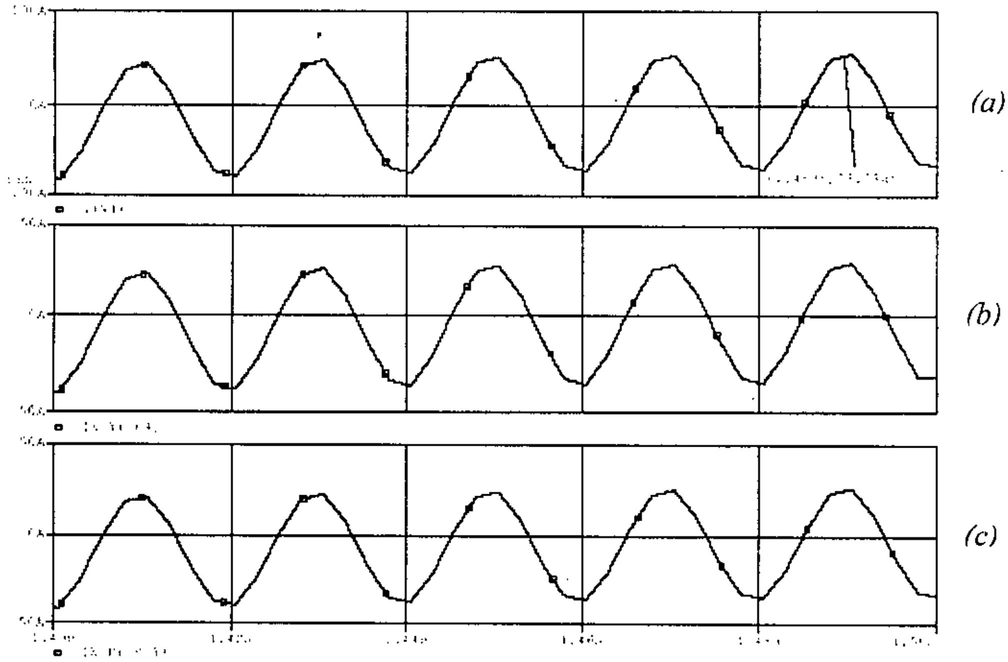


Figure 4.47: Input current wave shapes of (a) supply, (b) wye-wye and (c) delta-wye transformer for $C_i = 20\mu F$, $L_i = 5mH$ and duty cycle, $D = 0.0$.

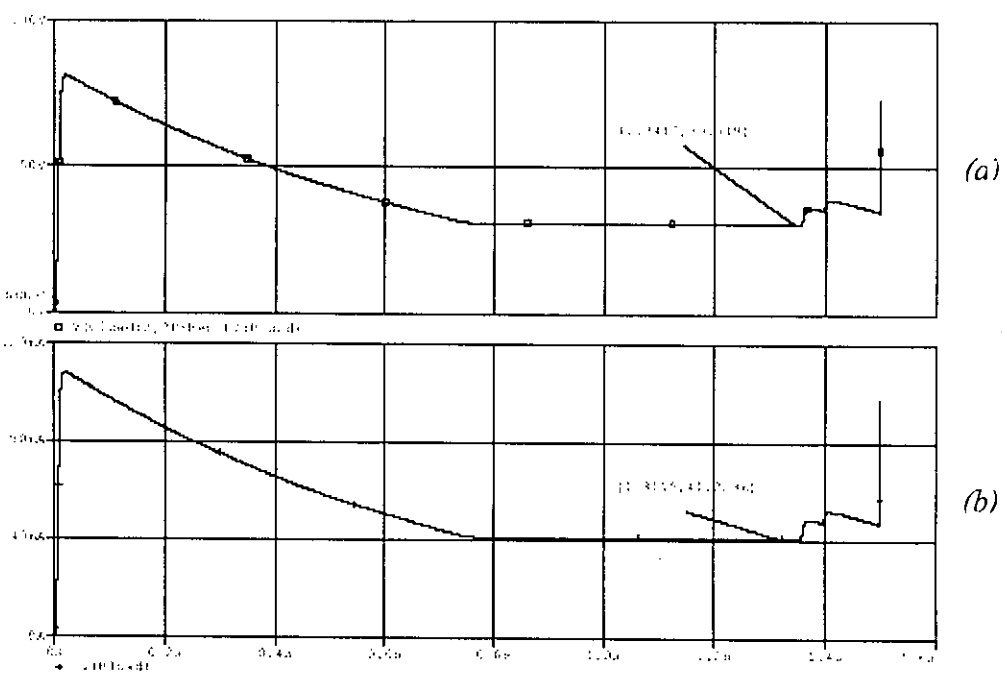


Figure 4.48: Wave shapes of (a) output voltage and (b) current for $C_i = 20\mu F$, $L_i = 5mH$ and duty cycle, $D = 0.0$.

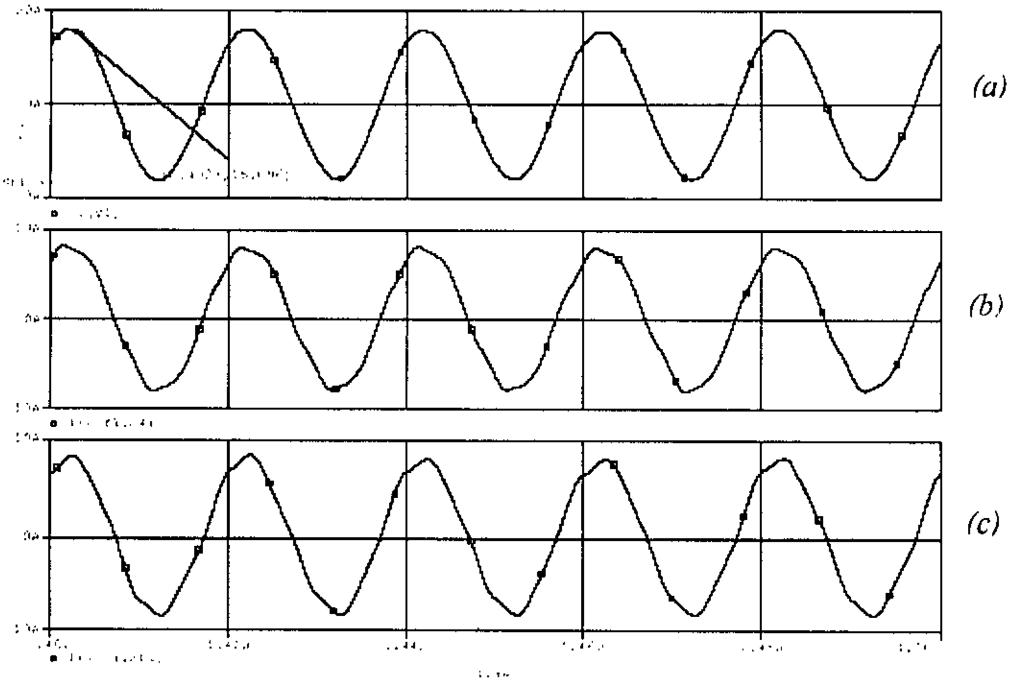


Figure 4.49: Input current wave shapes of (a) supply, (b) wye-wye and (c) delta-wye transformer for $C_i = 20\mu F$, $L_i = 5mH$ and duty cycle, $D = 0.1$.

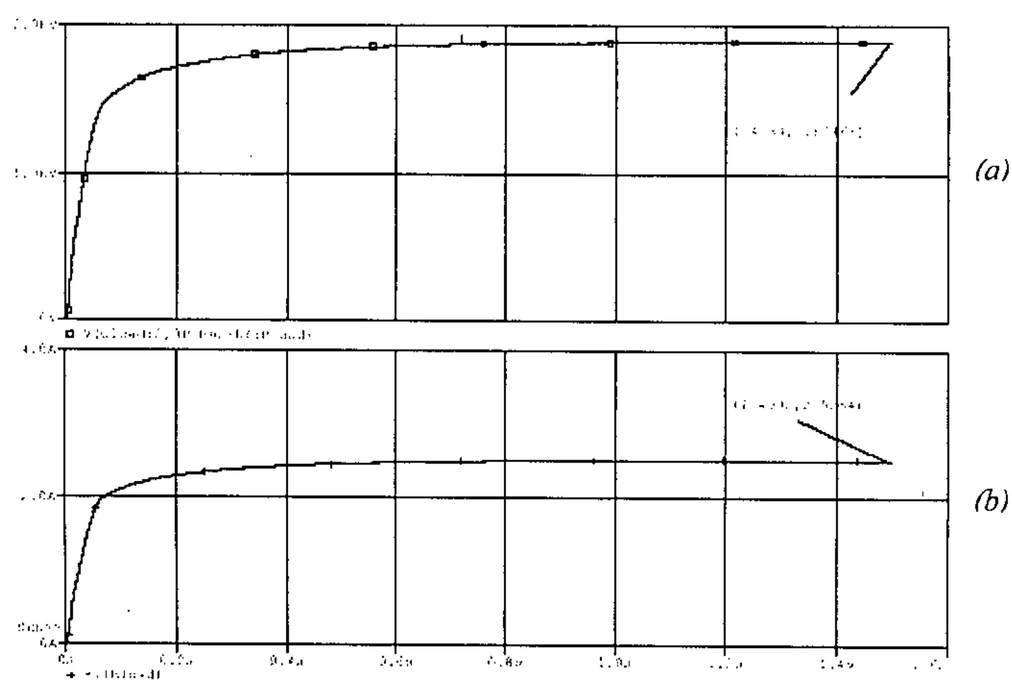


Figure 4.50: Wave shapes of (a) output voltage and (b) current for $C_i = 20\mu F$, $L_i = 5mH$ and duty cycle, $D = 0.1$

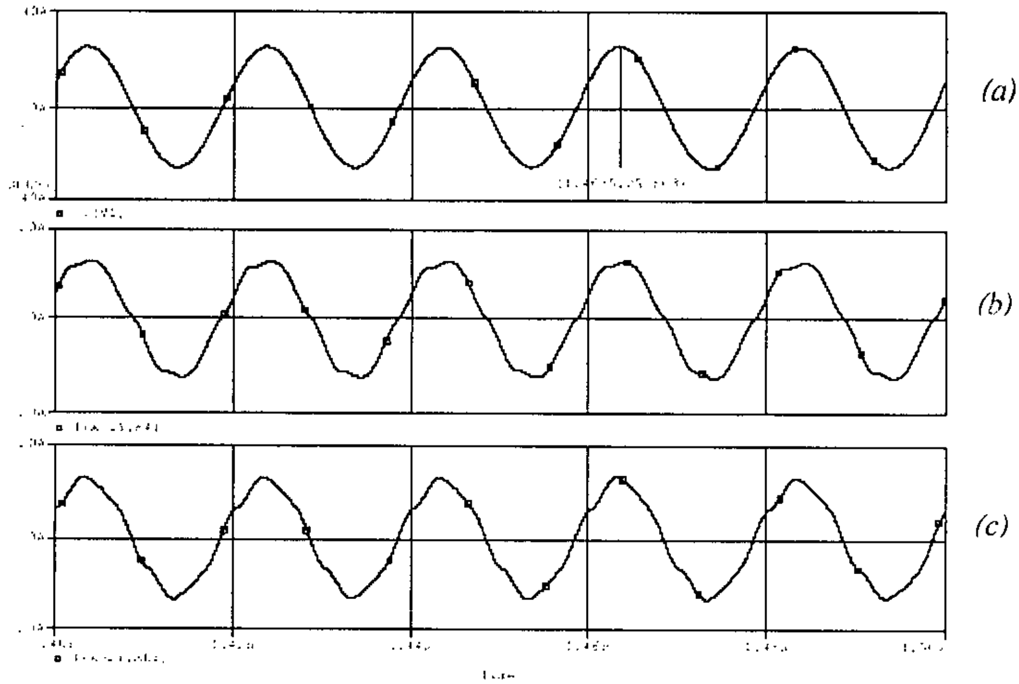


Figure 4.51: Input current wave shapes of (a) supply, (b) wye-wye and (c) delta-wye transformer for $C_i = 20\mu F$, $L_i = 5mH$ and duty cycle, $D = 0.2$.

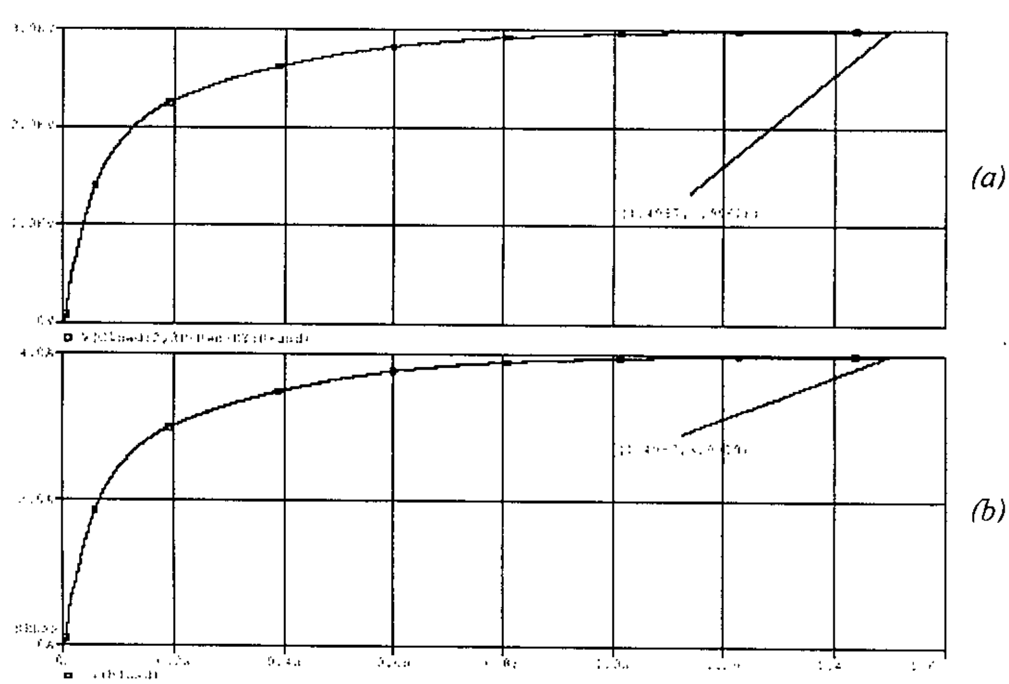


Figure 4.52: Wave shapes of (a) output voltage and (b) current for $C_i = 20\mu F$, $L_i = 5mH$ and duty cycle, $D =$ 0.2.

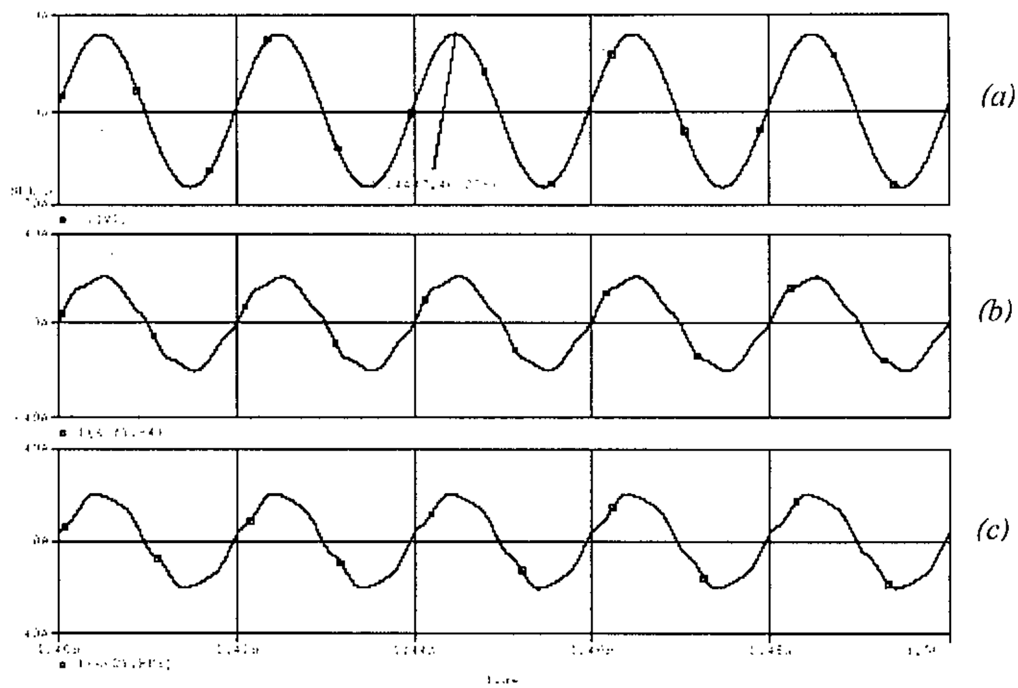


Figure 4.53: Input current wave shapes of (a) supply, (b) wye-wye and (c) delta-wye transformer for $C_i = 20\mu F$, $L_i = 5mH$ and duty cycle, $D = 0.3$.

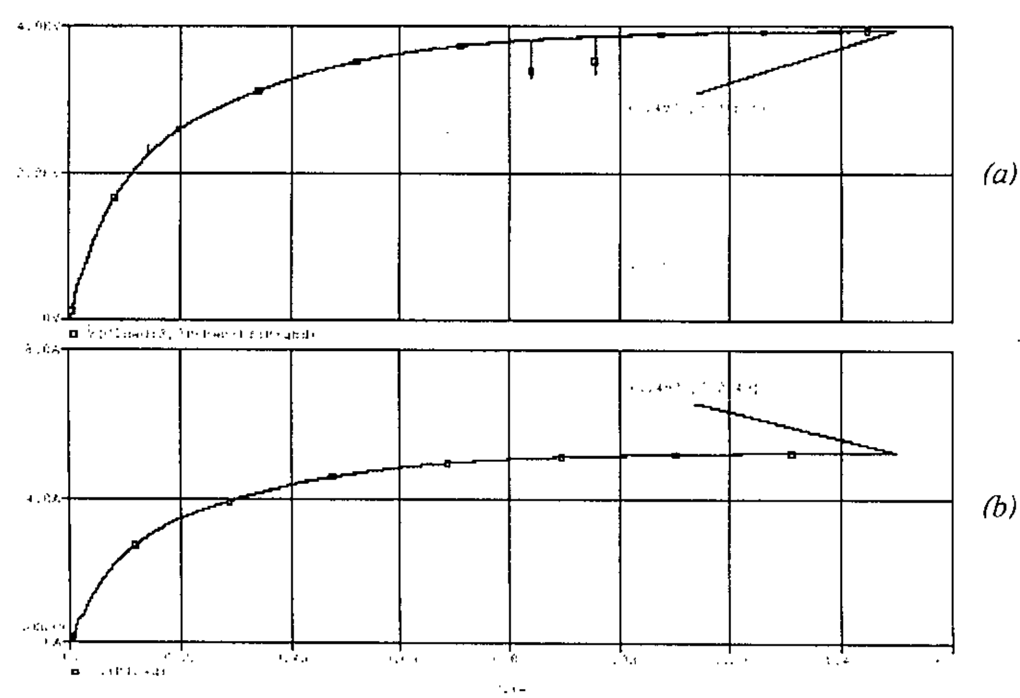


Figure 4.54: Wave shapes of (a) output voltage and (b) current for $C_i = 20\mu F$, $L_i = 5mH$ and duty cycle, $D =$ 0.3.

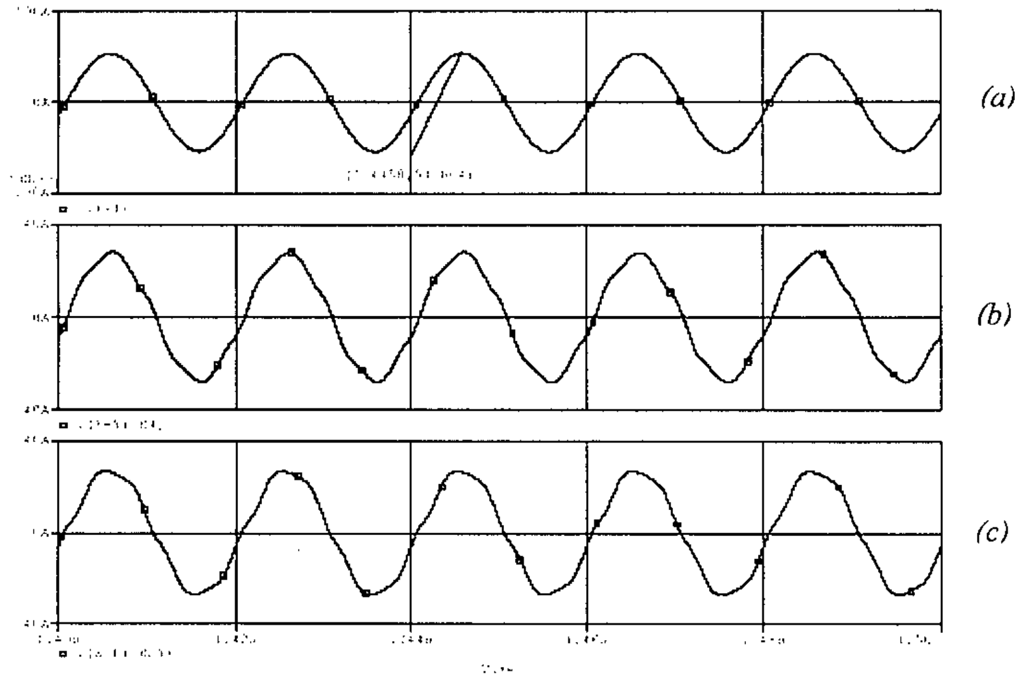


Figure 4.55: Input current wave shapes of (a) supply, (b) wye-wye and (c) delta-wye transformer for $C_i = 20\mu F$, $L_i = 5mH$ and duty cycle, $D = 0.4$.

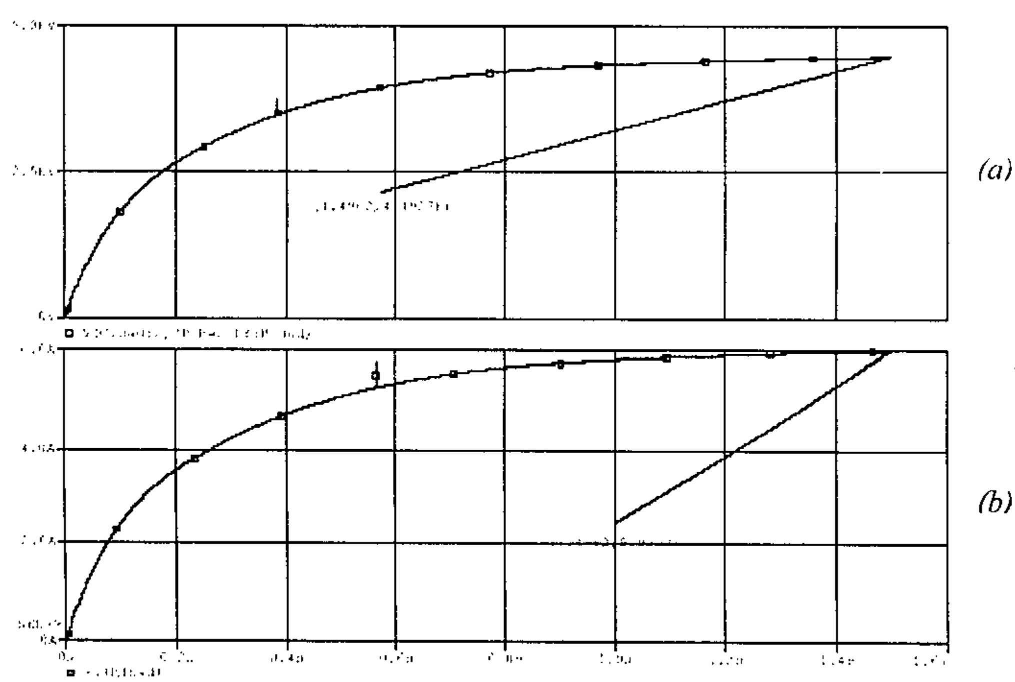


Figure 4.56: Wave shapes of (a) output voltage and (b) current for $C_i = 20\mu F$, $L_i = 5mH$ and duty cycle, $D = 0.4$.

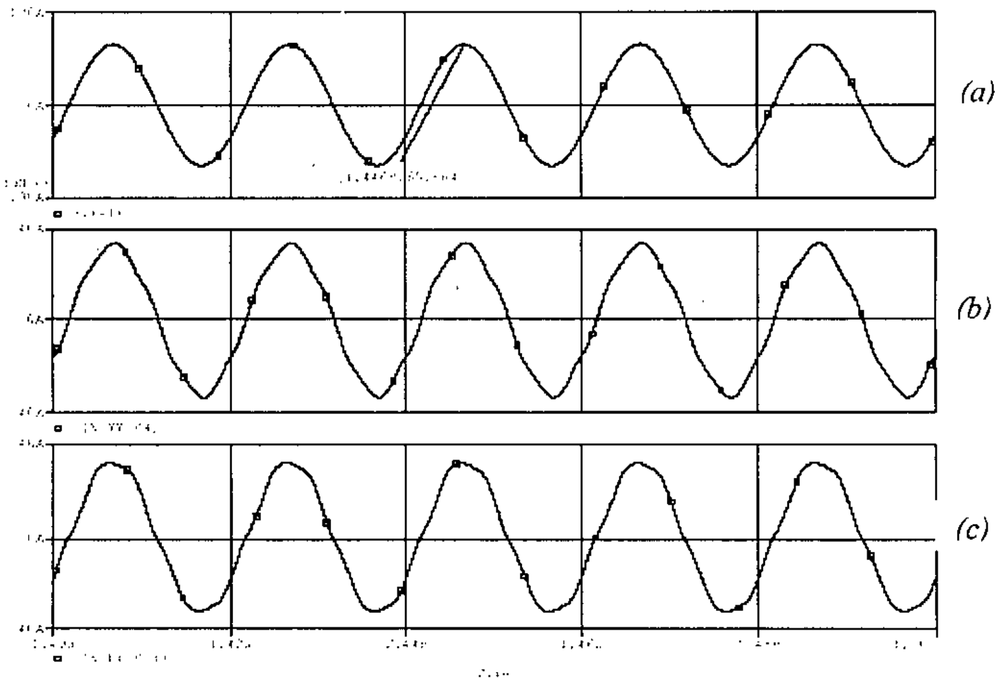


Figure 4.57: Input current wave shapes of (a) supply, (b) wye-wye and (c) delta-wye transformer for $C_i = 20\mu F$, $L_i = 5mH$ and duty cycle, $D = 0.5$.

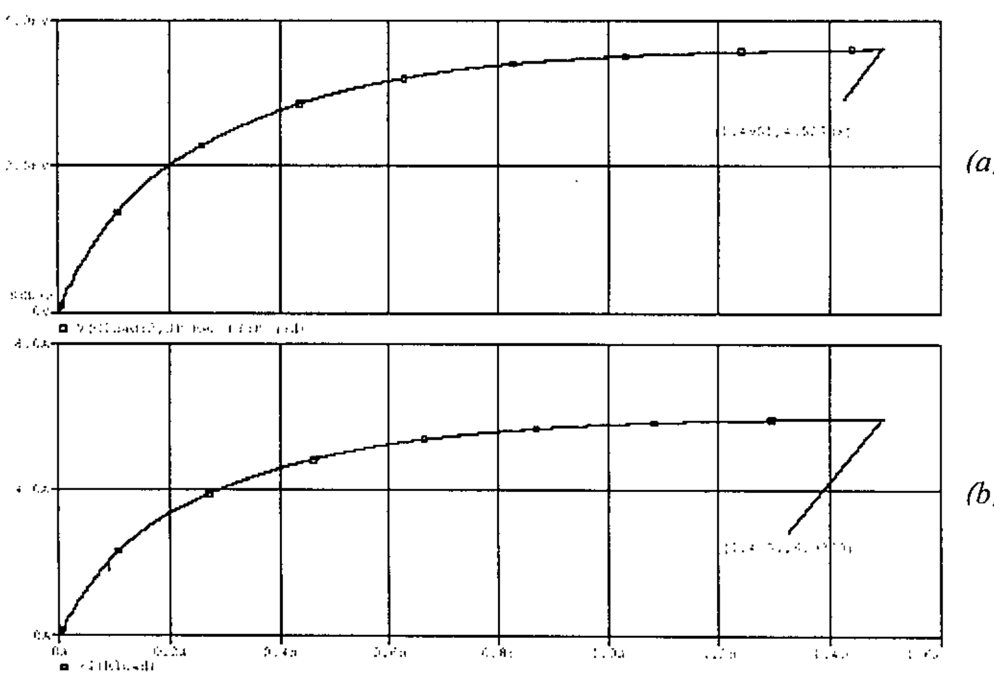


Figure 4.58: Wave shapes of (a) output voltage and (b) current for $C_i = 20\mu F$, $L_i = 5mH$ and duty cycle, $D = 0.5$.

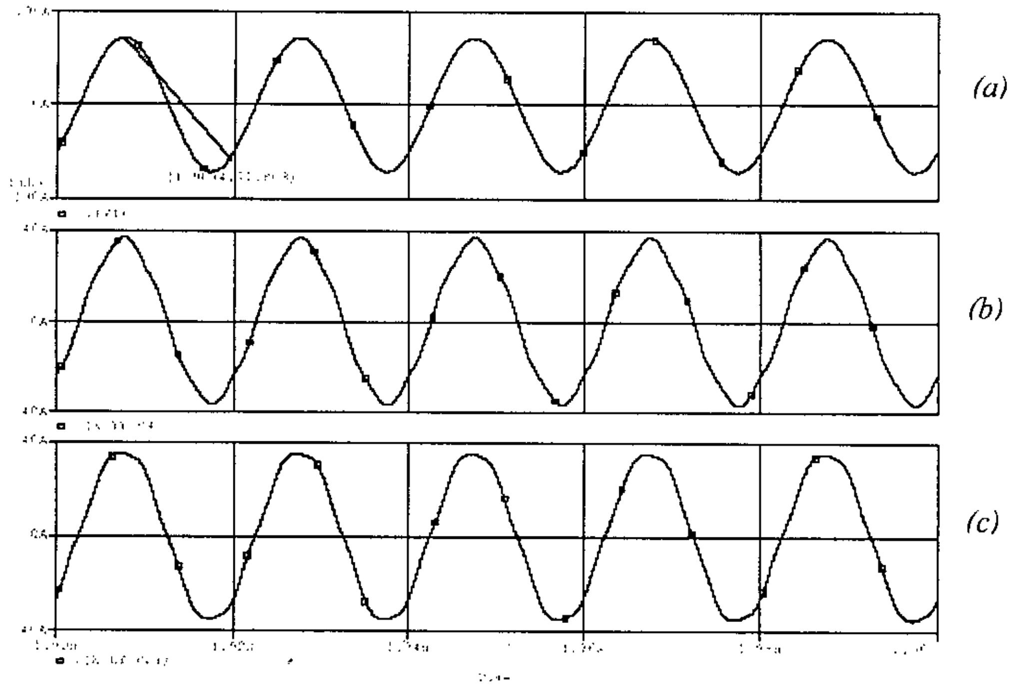


Figure 4.59: Input current wave shapes of (a) supply, (b) wye-wye and (c) delta-wye transformer for $C_i = 20\mu F$, $L_i = 5mH$ and duty cycle, $D = 0.6$.

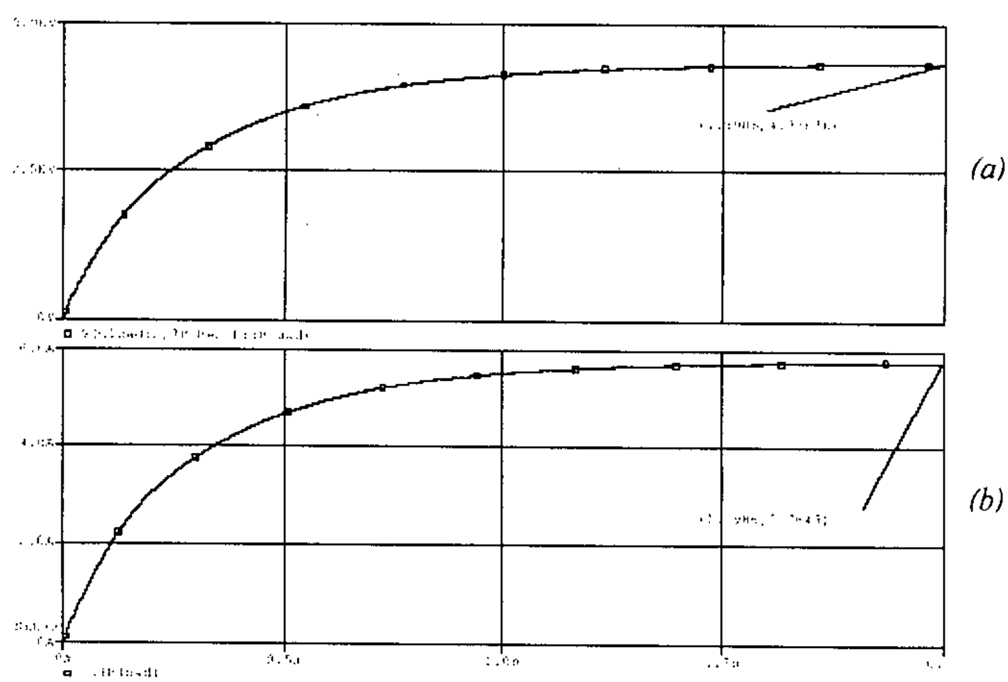


Figure 4.60: Wave shapes of (a) output voltage and (b) current for $C_i = 20\mu F$, $L_i = 5mH$ and duty cycle, $D = 0.6$.

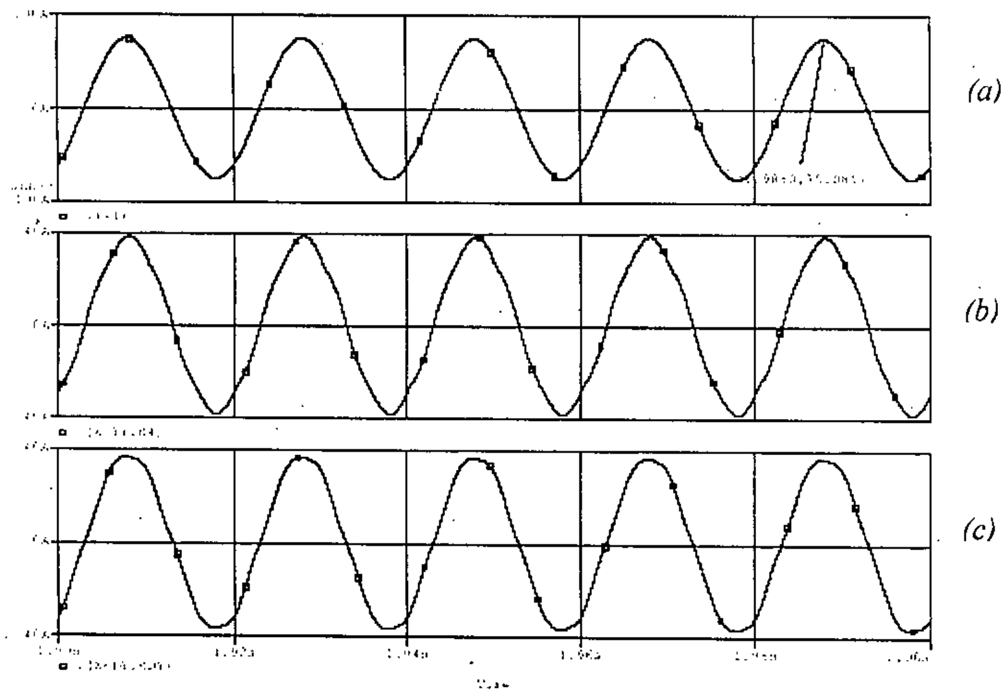


Figure 4.61: Input current wave shapes of (a) supply, (b) wye-wye and (c) delta-wye transformer for $C_i = 20\mu F$, $L_i = 5mH$ and duty cycle, $D = 0.7$.

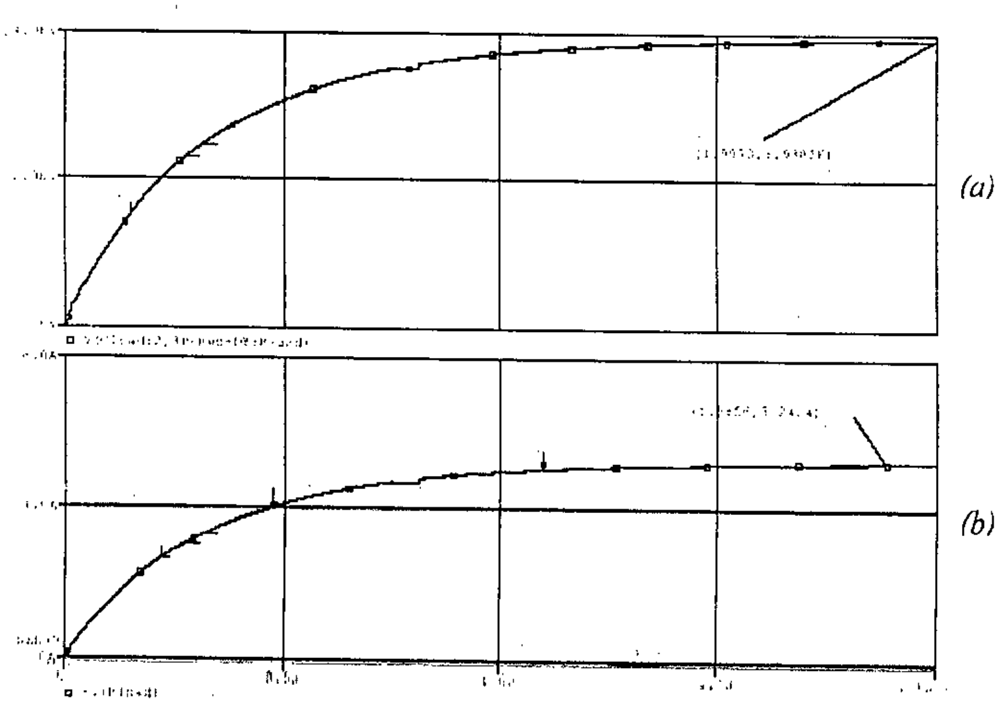


Figure 4.62: Wave shapes of (a) output voltage and (b) current for $C_i = 20\mu F$, $L_i = 5mH$ and duty cycle, $D = 0.7$.

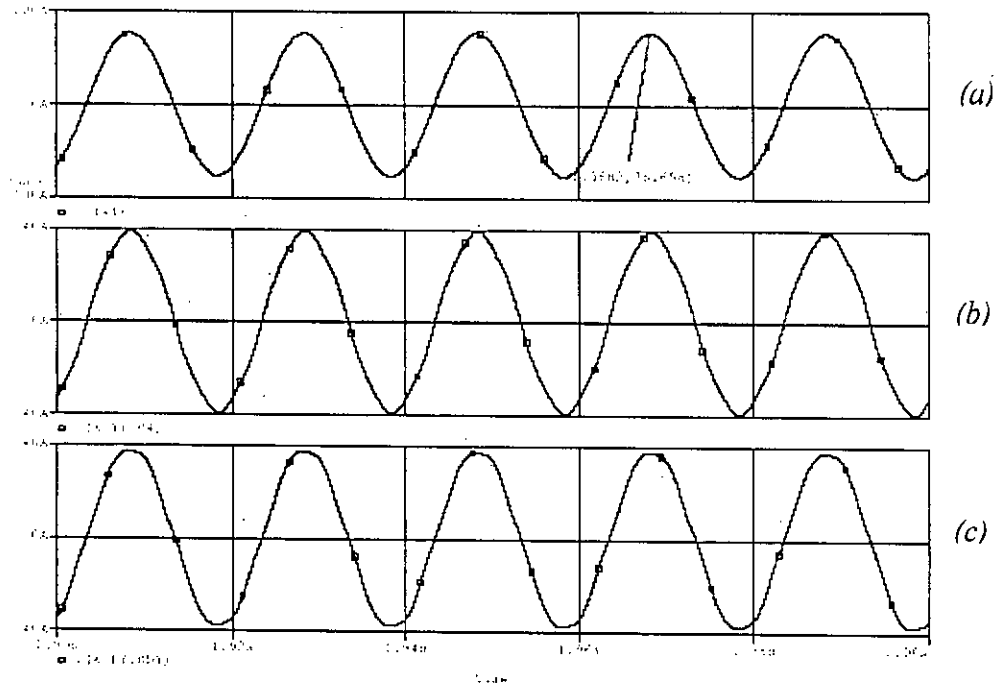


Figure 4.63: Input current wave shapes of (a) supply, (b) wye-wye and (c) delta-wye transformer for $C_i = 20\mu F$, $L_i = 5mH$ and duty cycle, $D = 0.8$.

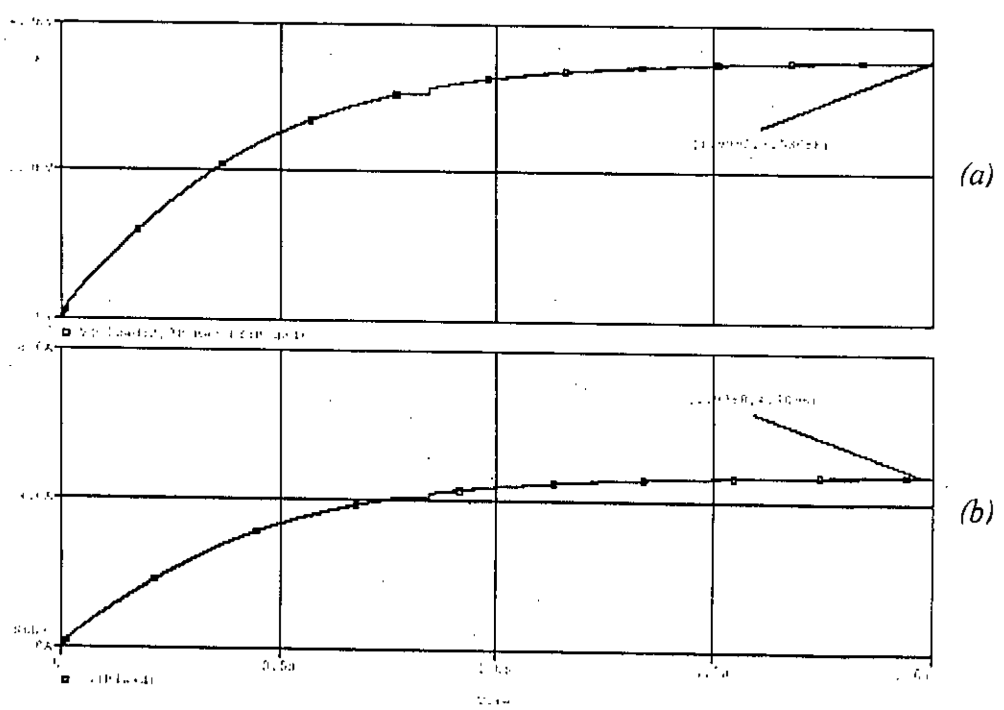


Figure 4.64: Wave shapes of (a) output voltage and (b) current for $C_i = 20\mu F$, $L_i = 5mH$ and duty cycle, $D = 0.8$.

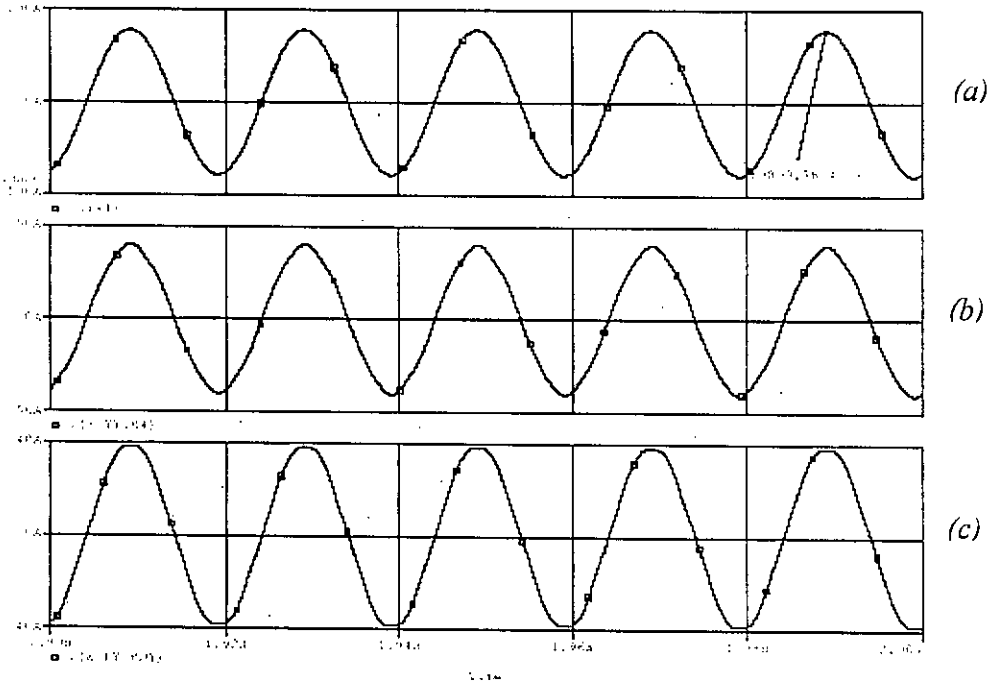


Figure 4.65: Input current wave shapes of (a) supply, (b) wye-wye and (c) delta-wye transformer for $C_i = 20\mu F$, $L_i = 5mH$ and duty cycle, $D = 0.9$.

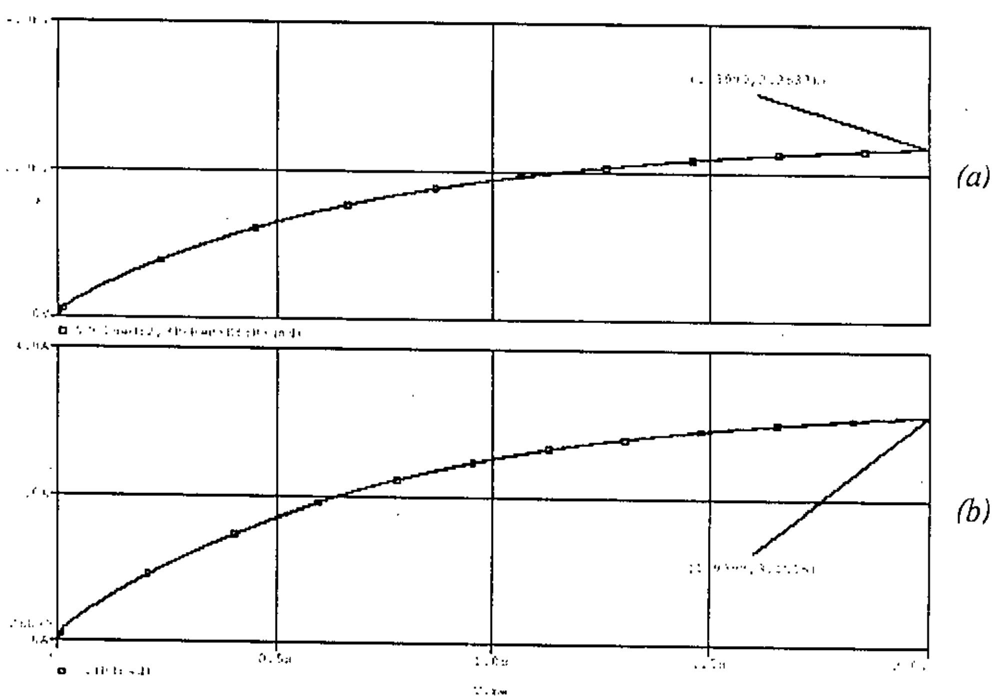


Figure 4.66: Wave shapes of (a) output voltage and (b) current for $C_i = 20\mu F$, $L_i = 5mH$ and duty cycle, $D = 0.9$

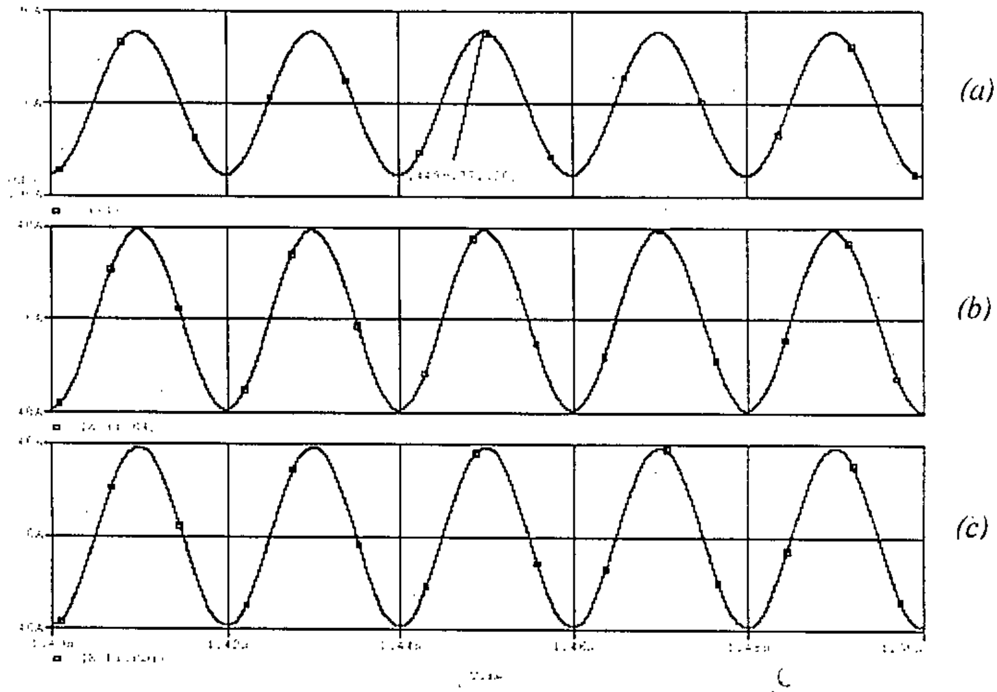


Figure 4.67: Input current wave shapes of (a) supply, (b) wye-wye and (c) delta-wye transformer for $C_i = 20\mu F$, $L_i = 5mH$ and duty cycle, $D = 1.0$.

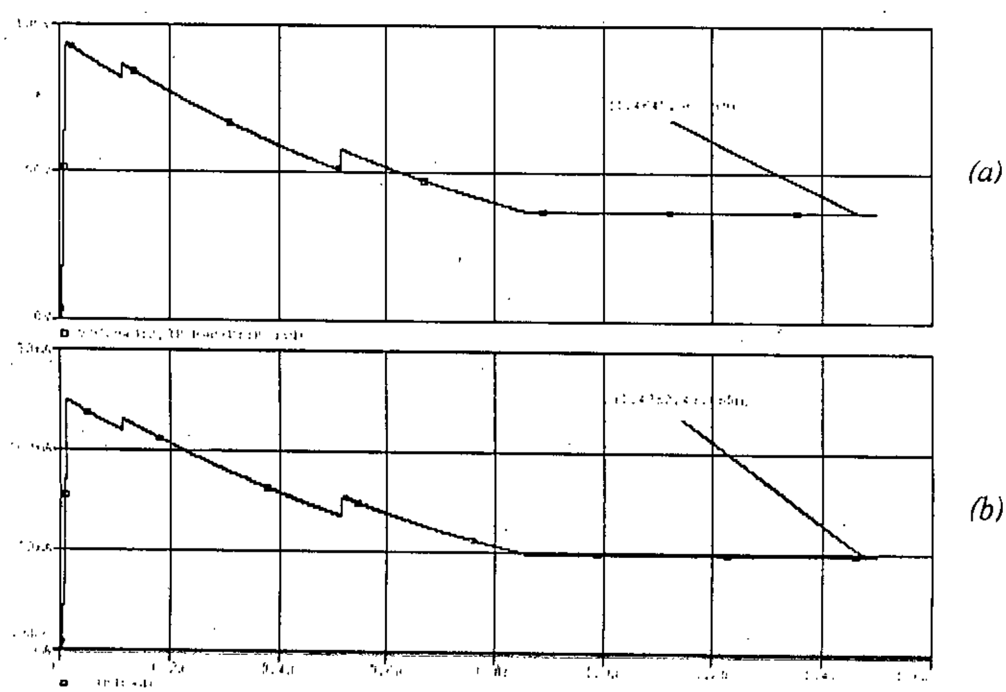


Figure 4.68: Wave shapes of (a) output voltage and (b) current for $C_i = 20\mu F$, $L_i = 5mH$ and duty cycle, $D = 1.0$.

Table 4.4: Summary of the simulation results for active filter using Single Boost Converter with ac input filter at rectifier input

	AC Input Filter		DC Output Filter									
Dutycycle, D	**Li (mH)**	**Ci (µF)**	**Lo (mH)**	**Co (µF)**	**Input Current, Is (A)**	**Output Voltage,Vo (V)**	**Output Current, Io (A)**	**Power Factor**	**Efficiency, η (%)**	**THD_Is (%)**	**THD_Iyy (%)**	**THD_Idy (%)**
0.0	5m	20u	7m	1000u	61.81	30.92	0.04	0.999	0.00	3.49	3.74	3.3
0.1	5m	20u	7m	1000u	15.97	1894.60	2.53	0.999	66.67	1.44	4.22	4.96
0.2	5m	20u	7m	1000u	25.39	2996.20	4.00	0.999	100.00	1.45	6.14	6.61
0.3	5m	20u	7m	1000u	40.10	3948.20	5.26	1.000	100.00	0.73	6.33	6.44
0.4	5m	20u	7m	1000u	54.29	4492.70	5.99	0.999	100.00	0.55	5.48	5.37
0.5	5m	20u	7m	1000u	65.12	4527.00	6.04	0.999	93.34	0.38	4.55	4.53
0.6	5m	20u	7m	1000u	71.49	4338.70	5.78	0.999	78.10	0.46	3.80	3.81
0.7	5m	20u	7m	1000u	74.80	3938.20	5.24	0.999	61.40	0.32	3.26	3.24
0.8	5m	20u	7m	1000u	76.48	3536.80	4.71	0.999	48.45	0.28	2.84	2.82
0.9	5m	20u	7m	1000u	78.31	2363.70	3.15	0.999	21.16	0.19	2.00	2.02
1.0	5m	20u	7m	1000u	76.91	36.80	0.05	0.999	0.01	0.05	0.71	0.69

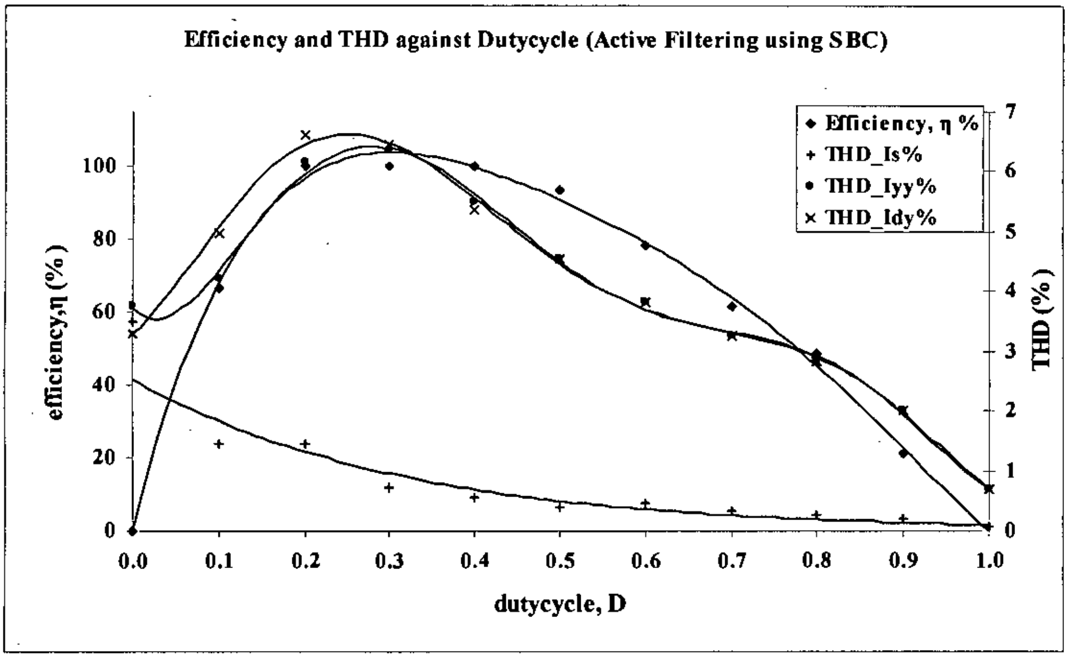


Figure 4.69: Efficiency and THD curve against Duty cycle for active filtering scheme using Single Boost Converter (SBC)

Table 4.4 summarizes the results at different duty cycles for the active filtering scheme of Twelve-Pulse Rectifier using single boost converter at the outputs of the two pulse rectifier unit with AC Filters used at Rectifier inputs with ac input filter inductance value, $L_i = 5mH$ and capacitance value, $C_i = 20\mu F$. Also figure 4.69 shows the efficiency and THD curve against duty cycle for active filtering scheme using Single Boost Converter (SBC). From the graph, table and the simulation outputs of input current, transformer currents, output voltage and output current it is found that incorporating active filtering scheme using single boost converter significantly reduces the total harmonic distortion of the input current and the wye-wye and delta-wye transformer currents with an aid of small size of ac input filter. Here it is found that for the ac input filter with $L_i = 5mH$ and $C_i = 20\mu F$ the duty cycle in the range of 0.2 to 0.5 gives the high efficiency range for the module. Beyond the range the efficiency drops rapidly. The maximum efficiency of 100% is found at 0.2 to 0.4 duty cycle. Again, the total harmonic distortion of the input current decreases exponentially as the duty cycle increases. And THDs of the wye-wye and delta-wye transformer currents are maximum of around 6% at 0.2 and 0.3 duty cycle. After that THDs decrease gradually.

4.3 Summary of Results

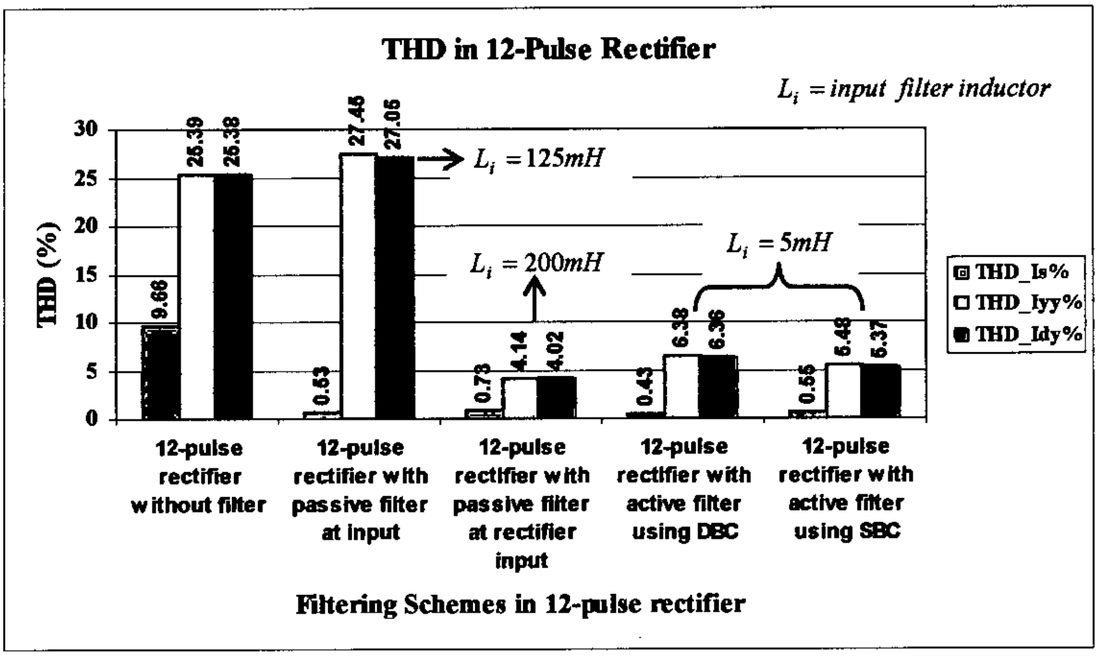


Figure 4.70: THDs (%) of input currents in 12-pulse rectifier with different filtering schemes at respective maximum efficiency point.

In order to harmonic mitigation in transformers of a twelve-pulse rectifier using active filter the performance of the both passive and active filtering schemes have been studied by simulation. The simulation results obtained and different performance parameters including total harmonic distortion (THD), efficiency etc. for different combinations have been presented to compare the proposed active filtering scheme with the passive filtering scheme under similar conditions in order to find a better harmonic mitigation method. Figure 4.70 shows the THDs (%) of input currents in 12-pulse rectifier with different filtering schemes at respective maximum efficiency point. The results can be summarized as follows.

- In a twelve-pulse rectifier without passive or active filter the total harmonic distortions (THD) of the wye-wye and delta-wye transformer currents were found more than 25%. The input line current for the twelve-pulse rectifier is close to sinusoidal waveform; the total harmonic distortion was found more than 9% which does not meet IEEE-519 harmonic standard without additional filtering.

- Incorporating passive filter at the input of the twelve pulse rectifier reduces the harmonic distortion of the input current, but the total harmonic distortion of the wye-wye and delta-wye transformer currents increases. It requires large input filter inductance of 125mH to achieve the high efficiency of the system.
- Using passive filters at the rectifier inputs significantly reduces the total harmonic distortion of the input current and the wye-wye and delta-wye transformer currents. But it requires large input filter inductance of 200mH to achieve the high efficiency of the system.
- Incorporating active filtering scheme using double boost converter considerably reduces the total harmonic distortion of the input current and the wye-wye and delta-wye transformer currents with an aid of small size of ac input filter. For the ac input filter with $L_i = 5mH$ and $C_i = 20\mu F$ the duty cycle in the range of 0.3 to 0.7 gives the high efficiency range for the module. Beyond the range the efficiency drops rapidly. The highest of 100% efficiency is found at the duty cycle of 0.5. At this condition, the total harmonic distortion of the input current decreases exponentially as the duty cycle increases. And THDs of the wye-wye and delta-wye transformer currents are about 7% at 0.4 duty cycle. After that THDs decrease gradually.
- Introducing active filtering scheme using single boost converter significantly reduces the total harmonic distortion of the input current and the wye-wye and delta-wye transformer currents with an aid of small size of ac input filter. For the ac input filter with $L_i = 5mH$ and $C_i = 20\mu F$ the duty cycle in the range of 0.2 to 0.5 gives the highest efficiency range for the module. Beyond the range the efficiency drops rapidly. The highest efficiency of 100% is found at 0.2 to 0.4 duty cycle. The total harmonic distortion of the input current decreases exponentially as the duty cycle increases. And THDs of the wye-wye and delta-wye transformer currents are maximum of around 6% at 0.2 and 0.3 duty cycle. After that THDs decrease gradually.

CHAPTER 5

Conclusion

The advances in the power semiconductor devices have led to the increase in the use of power-electronic converters in various applications such as heating, lighting, ventilating and air conditioning applications, large rated dc drives and ac drives, adjustable speed drives (ASDs), uninterruptible power supplies (UPSs), HVDC systems and utility interfaces with nonconventional energy sources such as solar photovoltaic systems (PVs), etc., battery energy storage systems (BESSs), in process technology such as electroplating, welding units etc., battery charging for electric vehicles, and power supplies for telecommunication systems. But the nonlinear operation of power electronic converters introduces harmonics in the supply current, which "pollute" the power system, thus deteriorating the power quality at the point of common coupling (PCC), thereby affecting the nearby consumers and, therefore, increasing attention is paid to their generation and control. In particular, several standards such as IEEE-519, have introduced important and stringent limits on harmonics that can be injected into the power supply, providing a benchmark for limiting current and voltage distortion. One basic and typical method to reduce input current harmonics is the use of multipulse connections such as 12-pulse or 18-pulse converter configurations based on transformers with multiple windings. However, 12 pulse front ends do not meet IEEE 519 harmonic standard without additional filtering. The use of active power filter to mitigate harmonic problems has drawn much attention since the 1970s. This thesis has proposed and studied an active filtering scheme for input current wave shaping and also currents of the transformers used in a 12-pulse rectifier system and compared the proposed technique with passive filtering scheme.

5.1 Summary of the Thesis

First the twelve-pulse rectifier circuit without input and output filter has been studied. From the simulation outputs it has been found that the individual transformer windings of the twelve pulse rectifier system carry nonsinusoidal current containing large low order harmonics such as 5^{th}, 7^{th}. Without filter the total harmonic distortions (THD) of the wye-wye and delta-wye transformer currents were found to be more than 25%. This requires over sizing of these transformers so that transformer windings are not overheated for a certain load. However, in the resultant input *ac* current, which is the sum of the two input currents of the star connected and delta connected transformers, the 5th, 7th, 17th, 19th, etc. harmonics are eliminated. Consequently, the input line current for the twelve-pulse rectifier is close to sinusoidal waveform; the total harmonic distortion is found more than 9%, which does not meet IEEE-519 harmonic standard without additional filtering. It has been found that the output of the 12-pulse rectifier contains ripples of twelve pulses in 20ms time duration whose frequency is 600Hz, which is twelve times that of the fundamental input frequency.

The inductive input dc filter has been designed to reduce the ripple content of the output voltage for 12-pulse rectifier. Then *L-C* input ac filter was designed and the most appropriate filter position was investigated and determined in passive filtering scheme. It was found that incorporating passive filter at the input of the twelve pulse rectifier reduces the harmonic distortion of the input current, but the total harmonic distortion of the wye-wye and delta-wye transformer currents increases. Incorporating passive filters at the rectifier inputs significantly reduced the total harmonic distortion of the input current and the wye-wye and delta-wye transformer currents.

Next the proposed active filtering scheme was introduced for 12-pulse rectifier system where with 5 KHz switching frequency PWM Boost converter was used at the output of the ac to dc rectifier to shape the input currents by eliminating high frequency harmonic components with the aid of very small sized filters. The number of Boost stages and its/their position at the output stage was worked out to get an improved solution to the problem. Simulations were performed for active filtering scheme using both double boost converter (DBC) and single boost converter (SBC) at the rectifier output for ac input filter parameters $L_i = 5mH$ and $C_i = 20\mu F$ at different duty cycles to get lower total harmonic distortion (THD) of input currents and higher efficiency of the rectifier circuit. From simulations it was found that the best operating range of duty cycle for active filtering scheme is at the range of 0.3 to 0.5. At this range the efficiency is more than 90% and THD of the transformer current is below 7%. The active filtering scheme using double boost converter (DBC) showed almost similar performance like the active filtering scheme using single boost converter (SBC) though the THD values are lower in SBC than in DBC. Thus in respect to cost and complexity the active filtering scheme using single boost converter (SBC) is the better choice.

From simulation outputs it is evident that 12-pulse rectifier with active wave shaping technique demonstrated superiority over the passive filtering scheme. Not only it has achieved the IEEE 519 standard with low harmonic content both in the rectifier and transformer input current wave but also it has shown higher overall efficiency and requirement of smaller reactive filter. In passive filtering technique it requires ac filter inductance of 200mH, whereas in active filtering scheme only 5mH value of inductance is sufficient to get lower total harmonic distortion (THD) of input currents and highest efficiency of the rectifier circuit. This implies that the passive filtering scheme would require 40 times higher value of inductance that would be much weightier than that of active filtering scheme.

5.2 Future Work

The review of the contributions of this thesis indicates the opportunities of extending this work in future to meet other goals.

- Only simulation is performed in this study. The proposed active filtering scheme may be implemented practically to investigate its actual potential. Such practical implementation would give an insight regarding the cost effectiveness of the proposed scheme compared to the passive filtering scheme for the similar purpose.

- The PWM module has been used to generate gating signals for switching the boost converter switch at varying duty cycles. Investigation can be made to improve the quality of the gating signals at different duty cycle.

- Regulation of the output voltage was not studied in this study. Investigation can be extended to regulate the output voltage.

- Varying loads results in load unbalances within building power distribution systems which add to the utility line voltage unbalance at the point of common coupling. Investigation may be made to see how twelve-pulse rectifier with proposed filtering scheme performs under actual operating conditions with unbalanced input line voltages.

References

[1] Prasad, A. R., Ziogas, P.D., and Manias, S., "An Active Power Factor Correction Technique for Three Phase Diode Rectifiers", IEEE Trans. on Power Electronics, vol. 6, no. 1, pp. 83-92, January 1991.

[2] Bashi, S.M., Mariun, N., Noor, S.B., and Athab, H.S., "Three-phase Single Switch Power Factor Correction Circuit with Harmonic Reduction", Journal of Applied Sciences, vol. 5, no. 1, pp. 80-84, 2005.

[3] Wyk, J. D. V., "Power Quality, Power Electronics and Control", in proceedings EPE. 93, pp. 17-32, 1993.

[4] "IEEE Recommended Practice and Requirements for harmonic Control on Electric Power Systems" IEEE Std. 519, 1992.

[5] Oscar, G., Jose, C., Roberto, P., Pedro, A., and Javier, U., "An alternative to Supply DC Voltages with High Power Factor", IEEE Trans. on Industrial Electronics, vol. 46, no. 4, pp. 703-709, August 1999.

[6] Yang Z. and Sen P. C., "Recent Developments in High Power Factor Switch – mode Converters", in IEEE proceedings CCECE 98, 1998, pp. 477-480.

[7] Huang, Q. and Lee, F.C., "Harmonic reduction in a single switch three-phase boost rectifier with high order harmonic injected", In IEEE PESC, 1996, 2: pp. 1266-1271.

[8] Simonetti, D.S.L., Sebastian, J., and Uceda, J., "Single-switch three-phase power factor preregulator under variable switching frequency and discontinuous input current", Conference Record IEEE PESC, pp: 657-662, 1993.

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

[10] Paice, D.A., "Power Electronic Converter Harmonics: Multipulse Methods for Clean Power", Piscataway, NJ: IEEE Press, 1996.

[11] Paice, D.A., "Calculating and controlling harmonics caused by power converters", in Proc. IEEE Ind. Appl. Soc. Annual Meeting, vol. 1, 1989, pp. 456-463.

[12] Cheng, P. T, Bhattacharya, S., Divan, D. M., "Application of dominant harmonic active filter system with 12 pulse nonlinear loads", IEEE transactions on power delivery, vol. 14, no. 2, pp. 642-647 (17 ref.), 1999.

[13] Erickson, R. W., "Some Topologies of High Quality Rectifiers", Keynote paper, First International Conference on Energy, Power and Motion Control, May 5-6, 1997, Tel Aviv, Israel.

[14] Raju, N. R., Daneshpooy, A., and Schwartzenberg, J., "Harmonic Cancellation for a Twelve-Pulse Rectifier using DC Bus Modulation", IEEE IAS Annual Conference Record, 2002, pp. 2526 – 2529.

[15] Mohan, N., Undeland, T. M., Robbins, W. P., "Power Electronics - Converters, Applications and Design", 2nd ed. New York: John Wiley& Sons, 1995.

[16] Fujita, H., and Akagi, H., "Design strategy for the combined system of shunt passive and series active filters", In IEEE/IAS Conference Proceedings, pp. 898-903, 1991.

[17] Fujita, H., and Akagi, H. "A practical approach to harmonic compensation in power systems - series connection of passive and active filters", In IEEE/IAS Conference Proceedings, pp. 1107-1112,1990.

[18] Peng, F. Z., Akagi, H., and Nabae, A., "A new approach to harmonic compensation in power systems", In IEEE/IAS Conference Proceedings, pp. 874-880, 1988.

[19] Miyairi, S., Iida, S., and Nakata, K., ''New method for reducing harmonics improved in input and output of rectifier with interphase transformer," IEEE Trans. on Ind. Appl., Vol. IA-22, NO. 5, pp.790-797, 1986.

[20] Choi, S., Enjeti, P. N., Lee, H., and Pitel, I. J., "A new active interphase reactor for 12-pulse rectifiers provides clean power utility interface," IEEE/IAS Anna. Meeting, pp.2464-2474, 1995.

[21] Tanaka, T., Koshio, N., Akagi, H., Nabae, A., "A novel method of reducing the supply current harmonics of a 12-Pulse Thyristor Rectifier with an Interphase Reactor", IEEE, pp. 1256-1262, 1996.

[22] Choi, S., Enjeti, P. N., Lee, H. H., Pitel, I. J., "A new active interphase reactor for 12-pulse rectifiers provides clean power utility interphase", IEEE Trans. on Ind. Appl., Vol. 32, No. 6, Novemver/December, 1996, pp. 1304-1311.

[23] Hahn, J., Kang, M., Enjeti, P. N., Pitel, I. J., "Analysis and Design of Harmonic Subtractors for Three Phase Rectifier Equipment to Meet Harmonic Compliance", Proc. of IEEE APEC Conf. 2000. Vol. 1, pp. 211-217.

[24] Hansen, S., Borup, U., Blaabjerg, F., "Quasi 12-Pulse Rectifier for Adjustable Speed Drives", IEEE, 2001, pp. 806-812.

[25] Paice, D. A., "Multipulse converter system", U.S. Patent 4 876 634, Oct 24, 1989.

[26] Miyairi, S., Iida, S., Nakata, K., and Masukawa, S., "New method for reducing harmonics involved in input and output rectifier with interphase transformer", IEEE Trans. Ind. App., vol. 22, no. 5, pp. 790-797.

[27] Villablanca, M. E., and Arrilaga, J. A., "Pulse multiplication in parallel converters by multi tap control of interphase reactor", Proc. Inst. Elect. Eng. B, vol. 139, no. 1, pp. 13-20, Jan. 1992.

[28] Choi, S., Lee, B. S., and Enjeti, P. N., "New 24-pulse diode rectifier systems for utility interphase of high power ac motor drives", IEEE Trans. Ind. App., vol. 33, no. 2, pp. 531-541, Mar./Apr. 1997.

[29] Hammond, P.W., "Autotransformer", U. S. Patent no. 5 619 407, Apr. 8, 1997.

[30] Paice, D. A., "Transformers for Multipulse AC/DC Converters", U. S. Patent no. 6 101 113, Aug. 8, 2000.

[31] Kamath, G. R., Runyan, B., and Wood, R., "A compact autotransformer based 12-pulse rectifier circuit", in Proc. IEEE IECON conf., 2001, pp. 1344-1349.

[32] Singh, B., Bhuvaneswari, G., Garg, V., "Harmonic mitigation using 12-pulse AC-DC converter in vector-controlled induction motor drives", IEEE Trans. on Power Delivery, vol. 21, No. 3, July 2006, pp. 1483-1492.