Input Current Shaping of A Three Phase Rectifier By Current Injection Using Active Power Control

A Thesis Submitted to the Department of electrical and Electronic Engineering
in Partial Fulfillment of the Requirement for the Degree of

MASTERS OF SCIENCE

By

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The thesis titled **"Input Current Shaping of A Three Phase Rectifier By Current Injection Using Active Power Control"** Submitted by Most. Sumaiya Hasan, Student No. 100506217P Session October/2005 has been accepted as satisfactory in partial fulfillment of the requirement for the degree of Masters of Science .

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Abstract

The goal of this thesis is to obtain a simple and easily implementable scheme for input power factor correction and harmonic reduction in a three phase rectifier. A basic three phase diode rectifier having specified voltage(300V P-P) is analyzed. The input current contains harmonic current . The input power factor has also been found poor. The cause of having low PF and high THD for a diode bridge rectifiers is related to non-linearity of the input current. Method of re-shaping the input current waveform to be similar pattern as the sinusoidal input voltage is done by the non sinusoidal input current injection technique. A delta modulated inverter is used to neutralize the harmonic current by injecting the difference of a reference sine wave and non sinusoidal input current in opposite direction to the rectifier input current.

Conventional three phase diode bridge rectifier is connected with 3 phase supply. The difference current (error signal) between the sine wave and the non sinusoidal input current is injected to a common node which is compared with a reference sinusoidal(desired) current. The error current is injected from a current source inverter rectifier circuit, where, the free wheeling diodes and capacitor is used as a dc source. Switching pulses for the inverter are generated from the vertices of the error signal using delta modulation. A High frequency filter is designed to retrieve the error signal from inverter output. Thus the error current applied to the rectifier input in opposite direction to neutralize the distortion of input current and make the input current having less THD. Separate dc source is not used for the current injection. The concept of static VAR compensation is used in this work to obtain dc source necessary for providing the harmonic current for injection. The aim of the thesis of a three phase rectifier having low THD and good power factor is achieved successfully.

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Chapter 1
Introduction

1.1 Introduction

This thesis presents a harmonic injection technique, which reduces the line current harmonics of the three phase rectifier and improves the input power factor. As a result , conversion efficiency of rectifier increases substantially.

DC power supplies are used in most of electrical and electronic appliance such as computer, monitors, televisions, telecommunication equipments, audio sets and others. In dc power supplies and power converters diode rectifiers are used in the front end as an interface with ac electric utility. The rectifiers are nonlinear device which generate harmonic voltage and currents. The nonlinear operation of diode rectifiers causes highly distorted input currents. The non sinusoidal input current drawn by rectifier's causes problems in the sensitive electronic equipment and in the power distribution network. The distorted input current flowing through the system produces distorted voltages at the point of the common coupling. The increased harmonic currents require increase in volt-ampere ratings of the utility equipment, such as generators, transmission lines and transformers. In addition to the inefficient use of electric energy, the discontinuous conduction of the bridge rectifier results in a high total harmonic distortion in the input lines and can lead to malfunctioning of sensitive electronic equipment. Also nonsinusoidal current drawn by a load causes interference with voltage being supplied to another load [1]. The distorted voltage waveform presented to a load may be caused by harmonic currents drawn by distant loads [2]. The proposed scheme contains a source of harmonic currents that can be injected into the rectifier input that demands harmonic currents thus relieving the utility system of furnishing this necessity and eliminating the drop and losses due to nonsinusoidal current.

The purpose of the proposed scheme is to improve input power factor and reduce the current harmonics with a better efficiency.

1.2 Literature Review

In order to meet a cost effective and economical solution to mitigate harmonics generated by rectifiers is of high interest in present researches. To overcome these problems number of passive and active current wave shaping techniques [1-12] have been suggested. One approach is to use three single phase power factor corrected rectifier in cascade [10]. The main advantage of this configuration is that a well-known single –phase power factor correction technique can be used in three phase applications. However, this approach suffers from disadvantages, which include cascading three single phase PFC circuits requiring the use of additional diodes, increased component count and complicated input synchronization logic. Three phase PFC circuits are required for higher power processing to lower the cost.

Amongst the three – phase ac-to dc rectifiers, boost type topologies are frequently used because of continuous input current and high output voltage. Basically, two topologies are most popular: a six switch full-bridge boost rectifier and a single switch boost rectifier. The first one uses six switches to achieve sinusoidal input current control and to share the output power, resulting in features, which include continuous input current, excellent power factor and low switch current rating [11-13]. However, this circuit is very complicated in power stage and control, making it expensive for medium and high power levels (5-10 and above kW) applications. The second one uses six diodes and one switch to control input currents and output power [14, 15]. Since these rectifiers have a single switch and perform input wave shaping naturally, without a need for a complex control circuitry, they are suitable for low cost three phase ac-dc conversions. In addition, they can achieve high efficiencies because the reverse-recovery-related losses of the boost diode are eliminated. In a discontinuous conduction mode (DCM) PWM boost rectifier is implemented with the conventional constant frequency low bandwidth output voltage feed back control, which keeps the duty cycle of the switch constant during a rectified line period, the rectifier input current exhibits a large fifth-order harmonic. As previous studies have shown, the distortion level depends on the ratio of the output voltage to the input line voltage. If for example, the output voltage is 720 V and the input phase voltage 230 V, the maximum power of the converter must be limited to about 4.5 kW in order to keep input current harmonics under the limits set by IEC 1000-3. Although increasing the output voltage would permit higher maximal power, it is not practical considering the voltage handling capability of commercially available high frequency power semiconductor devices (MOSFET's and IGBT's).

To alleviate this problem, different modulation techniques have been proposed to reduce the harmonic distortion of the input currents without increasing the output voltage beyond practical levels. The first approach proposed to improve the harmonic distortion of the input currents involved operating the single switch boost rectifier in the critical mode. To do [16-17] this, the power switch must be turned on at the instant at which the boost diode current reaches zero. As a result, the switching frequency becomes variable and the effective duty cycle modulation over the line cycle results in reduced THD of the input currents. The drawback of operating the discontinuous conduction mode (DCM) boost rectifier in the critical mode in the wide range of switching frequency variation depends on both load and input voltage limits. Another approach for improving the THD of the input currents involves controlling to a constant level the average current in the boost diode. In order to keep the average current [13] constant through the boost diode, the duty cycle must be modulated over the line cycle, resulting in an improved input current waveform. The drawback of this method is the extra current sensor required to control the average boost diode current. Boost rectifiers are used in low power applications because in high power applications the switching loss of the schemes is very high.

A simple technique that can be used to reduce the harmonic distortion of the input current is the so-called harmonic injection method. The principles for achieving harmonic injection are described in [18-20]. The injected signal modifies the duty cycle of the [18] rectifier switch so that the fifth-order harmonic of the input current and the overall THD's are reduced to meet the IEC1000-3 requirement. However, if the phase of the injected signal is not well synchronized with the fifth -order harmonic of the input current, the expected reduction of the fifth-order harmonic and the improvement of the THD's cannot be achieved.

A low cost harmonic injection method for single switch three-phase DCM boost rectifier and its implementation are presented in [22]. To reduce the fifth-order harmonic and improve THD's of the rectifier input currents, a periodic voltage signal, which utilizes the voltage ripple of the rectifier output voltage, is injected to modify the duty cycle of the rectifier within line cycle. The injected voltage signal is proportional to the ac component of the rectified three-phase line-to-line input voltages. As a result, the injected signal is naturally synchronized with the three-phase line-to-neutral input voltages. The closed loop feedback control of the DCM boost rectifier is not affected by the open loop harmonic injection method.

1.3 Objective and expected result of the thesis

The goal of this thesis is to obtain a simple and cost effective scheme for input Power factor improvement and harmonic current reduction of a three phase diode bridge rectifier. In the proposed scheme delta modulated current source inverter will be used to neutralize the non sinusoidal input current of a rectifier by injecting the difference of a reference sine wave and non sinusoidal input current in opposite direction to the input of the rectifier. Delta modulation technique uses the harmonic current wave from another rectifier for inverter switching.

The objectives of the present research work is as follows:

[I] A scheme based on var compensation method for current injection scheme will be developed,

[II] To design a delta modulator circuit for inverter switching,

[III] To design a high frequency filter for inverter output,

[IV] To design a harmonic current source rectifier for the modulator as to use the harmonic current wave as modulating wave,

[v] To make the power factor close to unity,

[VI] To ensure sinusoidal input current,

[VII] Simulate and study of the proposed scheme in Spice and

[VII] To analyze the results.

Furthermore, comparison of performance between simulated result considering switches to be ideal and practical. It is expected that this research will yield a three phase rectifier with better power quality which will be practically implement able.

1.4 Thesis Outline

This dissertation is divided into three chapters. The development of a topology of current injection scheme is presented in Chapter 2. A three phase diode rectifier without and with filter has been studied. The simulation results, wave shapes and graphical representations are presented in chapter 2. Conclusions and future research directions are given in chapter 3.

Chapter 2

Delta Modulated Harmonic Injected Three Phase Rectifier

2.1 Introduction

The objective of this research has been to develop a scheme by means of which both the input power factor and efficiency can be improved and total harmonic distortion can be reduced to low value acceptable in accordance with various international regulations.

2.2 Conventional Three Phase Rectifier

A three phase full wave diode bridge rectifier is commonly used in high power application. This section analyzes the performance of a three phase full wave diode bridge rectifier shown in Fig. 2.1 having a supply voltage of 300 V AC, frequency, 50 Hz, and resistive load of 100 ohm.

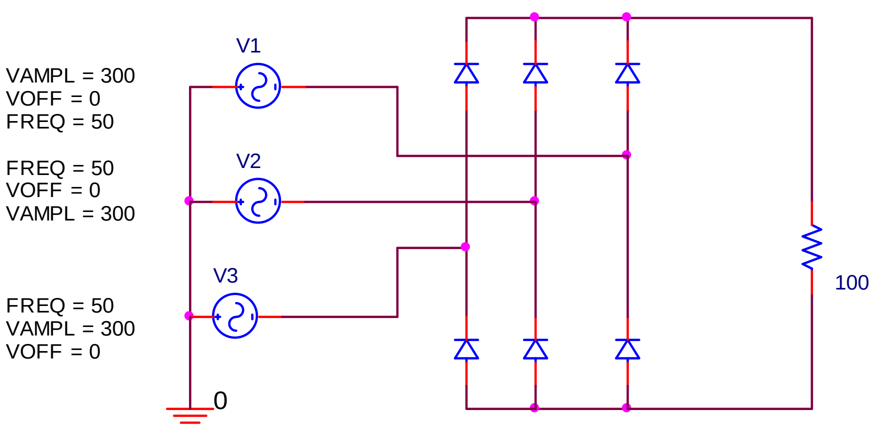


Figure 2.1: A three Phase Full Wave Rectifier with Resistive load

From simulation it is seen that the rectifier has a large of harmonic current at the input.

Also the input current and voltage are not in same phase. The efficiency of the rectifier is higher than a single phase rectifier. The waveforms of the circuit in Fig. 2.1 are shown in Fig. 2.2

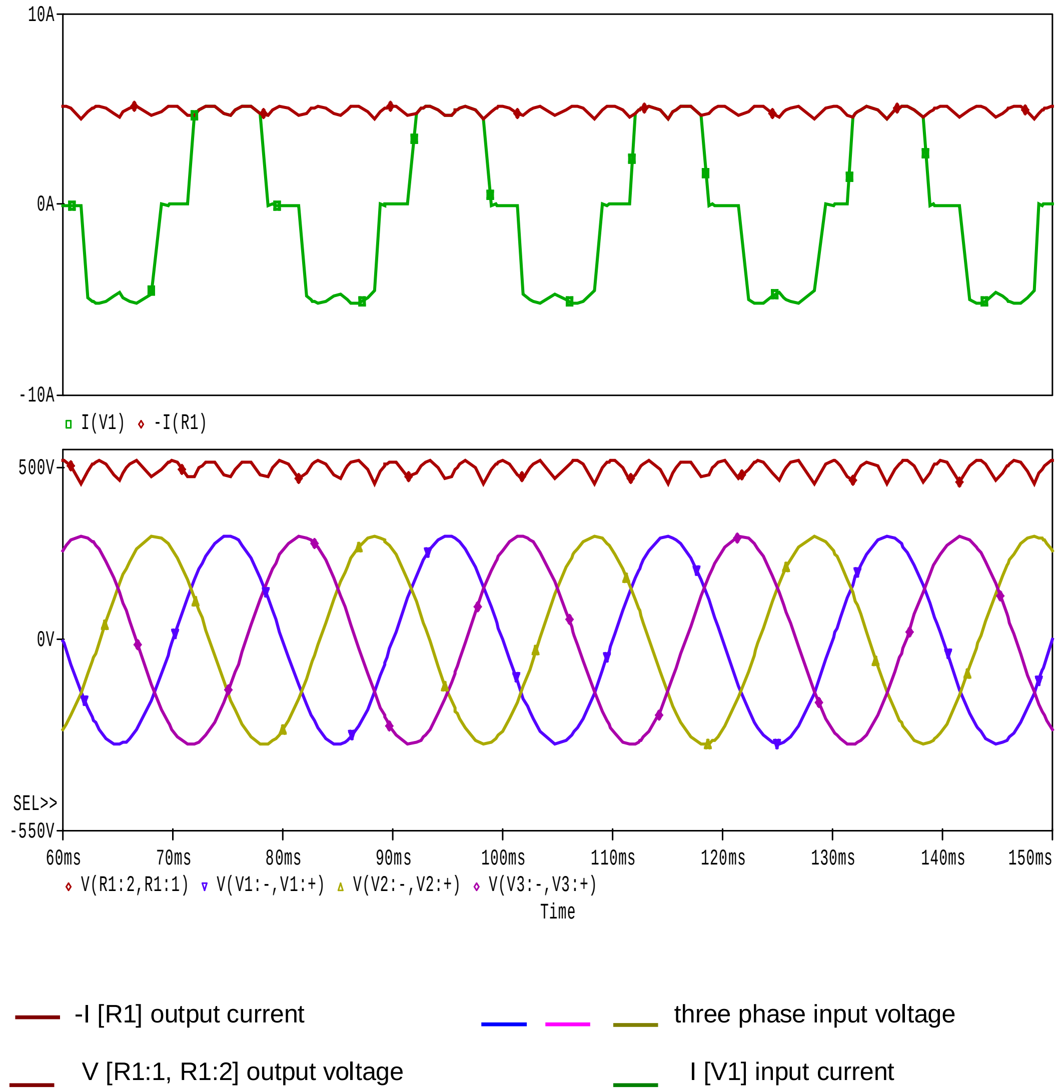


Figure 2.2: Input and output voltage and current of a three phase rectifier with Resistive load

The wave forms are supply voltage, input line current, load current and load voltage. The input line current lags the voltage and is nonsinusoidal.

The efficiency and the input power factor are calculated using following formula:

$$\text{Input PF}=\frac{AVG(V_{in}I_{in})}{RMS(V_{in})*RMS(I_{in})} \tag{2.1}$$

$$\text{Efficiency}=\frac{AVG(V_l*I_l)}{3*AVG(V_{ni}*I_{in})} \tag{2.2}$$

Where ,

V_{in} is the input voltage,

I_{in} is the input current,

V_l is the load voltage and

I_l is the load current.

The plot of efficiency and power factor obtained from simulation software is presented in Fig. 2.3. The power factor is found to be .95573 and the efficiency as 98.54% at steady state condition.

From Fourier analysis of simulation out put file, percentage of total harmonic distortion (THD) for 40 harmonic components is obtained as 25.88%. The amplitude and phase angle of each of the harmonics is tabulated in Table 2.1. However, the THD of the input current is high (beyond prescribed limit)

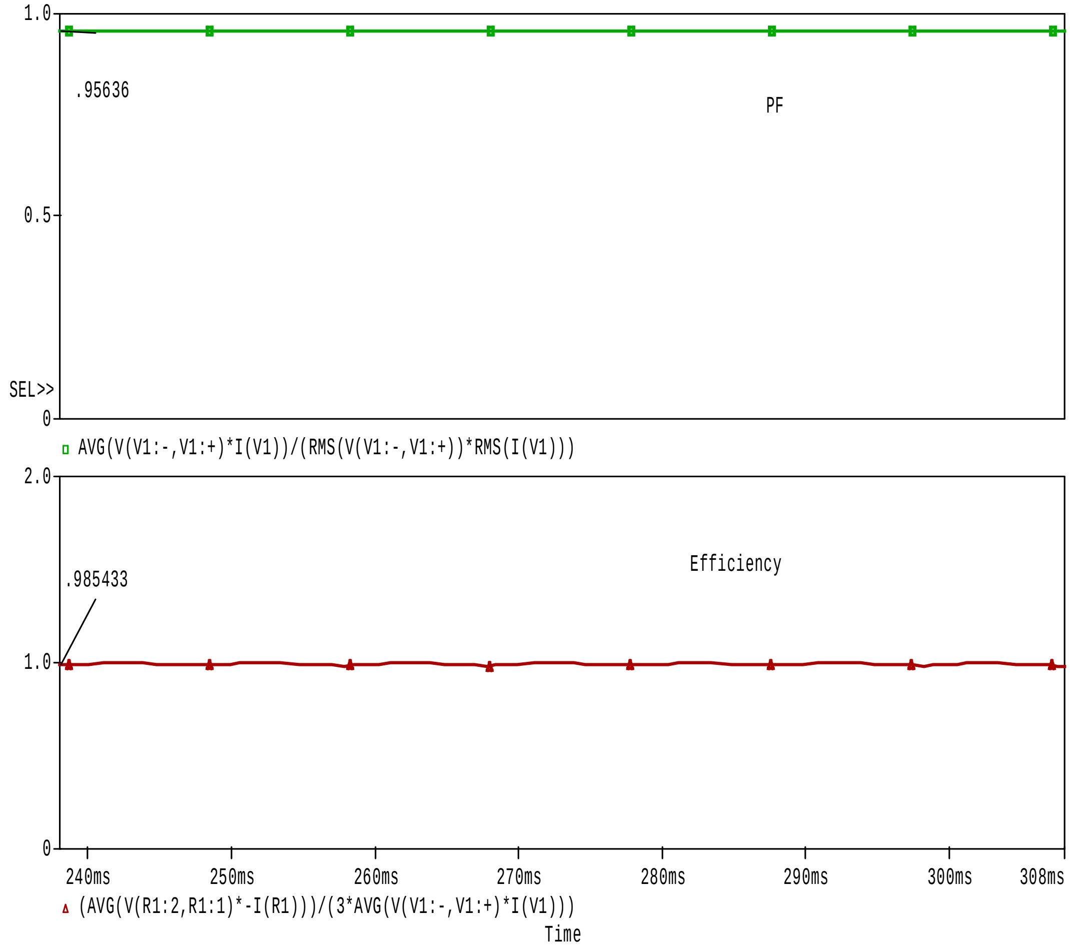


Figure 2.3: Efficiency and Input power factor of three a phase rectifier with Resistive Load

Table 2.1: Table of significant Fourier transform coefficients of input current of three phase rectifier

HARMONIC NO	FREQUENCY (HZ)	FOURIER COMPONENT	NORMALIZED COMPONENT	PHASE (DEG)	NORMALIZED PHASE (DEG)
1	5.00E+01	5.46E+00	1.00E+00	-2.74E+00	0.00E+00
2	1.00E+02	2.16E-01	3.95E-02	2.40E+01	2.95E+01
3	1.50E+02	5.79E-02	1.06E-02	2.91E+01	3.73E+01
4	2.00E+02	2.07E-01	3.79E-02	-4.34E+01	-3.25E+01
5	2.50E+02	1.11E+00	2.04E-01	1.67E+02	1.81E+02
6	3.00E+02	1.88E-01	3.43E-02	-1.15E+02	-9.82E+01
7	3.50E+02	5.56E-01	1.02E-01	1.59E+02	1.78E+02
8	4.00E+02	1.89E-01	3.46E-02	-1.78E+02	-1.56E+02
9	4.50E+02	9.62E-02	1.76E-02	-1.52E+02	-1.27E+02
10	5.00E+02	1.51E-01	2.76E-02	1.14E+02	1.42E+02
11	5.50E+02	3.00E-01	5.49E-02	-3.50E+01	-4.92E+00
12	6.00E+02	1.27E-01	2.32E-02	4.11E+01	7.40E+01
13	6.50E+02	2.41E-01	4.42E-02	-2.75E+01	8.06E+00
14	7.00E+02	1.26E-01	2.31E-02	-1.30E+01	2.53E+01
15	7.50E+02	1.12E-01	2.06E-02	1.08E+01	5.18E+01
16	8.00E+02	8.90E-02	1.63E-02	-7.56E+01	-3.18E+01
17	8.50E+02	7.91E-02	1.45E-02	1.22E+02	1.68E+02
18	9.00E+02	7.09E-02	1.30E-02	-1.61E+02	-1.12E+02
19	9.50E+02	1.25E-01	2.30E-02	1.51E+02	2.03E+02
20	1.00E+03	6.96E-02	1.27E-02	1.57E+02	2.11E+02
21	1.05E+03	9.35E-02	1.71E-02	1.68E+02	2.25E+02
22	1.10E+03	3.76E-02	6.88E-03	1.14E+02	1.74E+02
23	1.15E+03	6.06E-03	1.11E-03	-1.24E+02	-6.12E+01
24	1.20E+03	2.06E-02	3.78E-03	1.39E+01	7.96E+01
25	1.25E+03	6.45E-02	1.18E-02	-3.06E+01	3.78E+01
26	1.30E+03	3.70E-02	6.77E-03	-1.83E+01	5.29E+01
27	1.35E+03	6.10E-02	1.12E-02	-3.67E+01	3.72E+01
28	1.40E+03	3.20E-02	5.86E-03	-3.49E+01	4.17E+01
29	1.45E+03	1.72E-02	3.15E-03	-9.21E+01	-1.28E+01
30	1.50E+03	7.20E-03	1.32E-03	-6.49E+01	1.72E+01
31	1.55E+03	2.61E-02	4.77E-03	1.41E+02	2.26E+02
32	1.60E+03	2.65E-02	4.85E-03	1.69E+02	2.56E+02
33	1.65E+03	2.49E-02	4.56E-03	1.18E+02	2.09E+02
34	1.70E+03	2.84E-02	5.21E-03	1.43E+02	2.36E+02
35	1.75E+03	1.75E-02	3.20E-03	6.80E+01	1.64E+02
36	1.80E+03	9.17E-03	1.68E-03	1.00E+02	1.99E+02
37	1.85E+03	3.81E-03	6.99E-04	2.51E+01	1.26E+02
38	1.90E+03	1.19E-02	2.17E-03	-1.42E+01	8.97E+01
39	1.95E+03	2.19E-03	4.02E-04	-1.39E+02	-3.19E+01
40	2.00E+03	1.78E-02	3.26E-03	-6.05E+01	4.89E+01

TOTAL HARMONIC DISTORTION = 25.88%

2.3 Conventional Three Phase Rectifier With Input Filter

In order to render the input current supplied by the voltage source sinusoidal and in phase with the voltage supplied by that source, it is necessary to connect another component to the system.

An example of basic technique is the use of passive (L-C) input and output filter as shown in Fig. 2.4. Two inductors of 25mH and 1mH are connected in series and a combination of 2 uf capacitor and 2mH inductors are connected in parallel to the rectifier input. From simulation result the graph of supply voltage, input line current, load current, load voltage, power factor and efficiency for this case are found as shown in Fig. 2.5 and Fig. 2.6

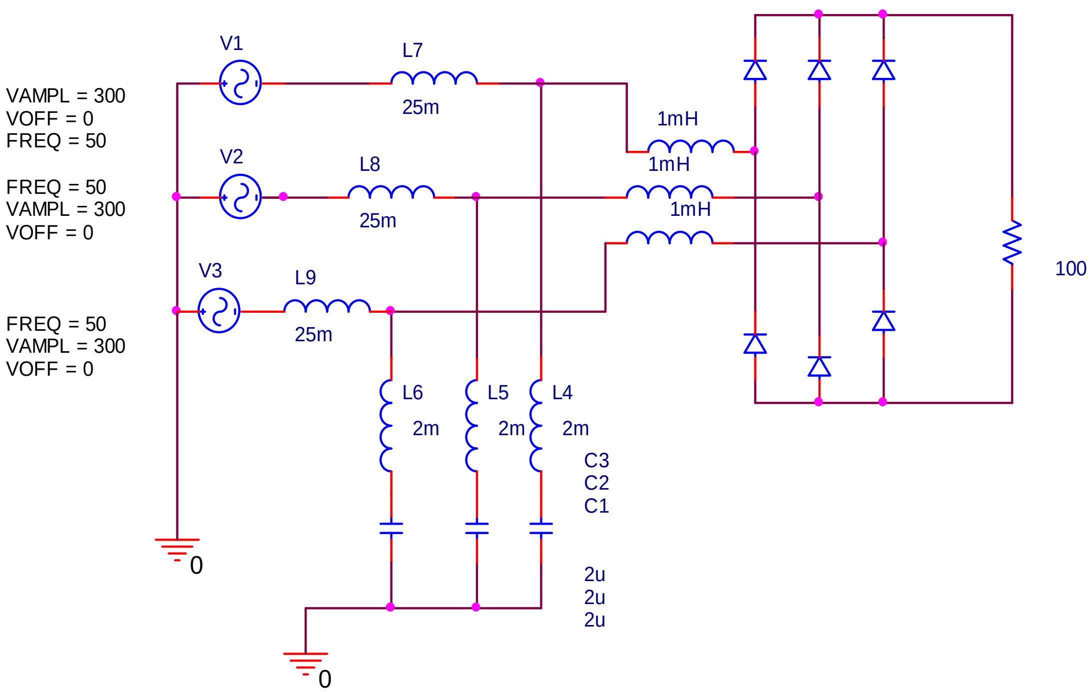


Figure 2.4: A three phase rectifier with input filter (load is resistive)

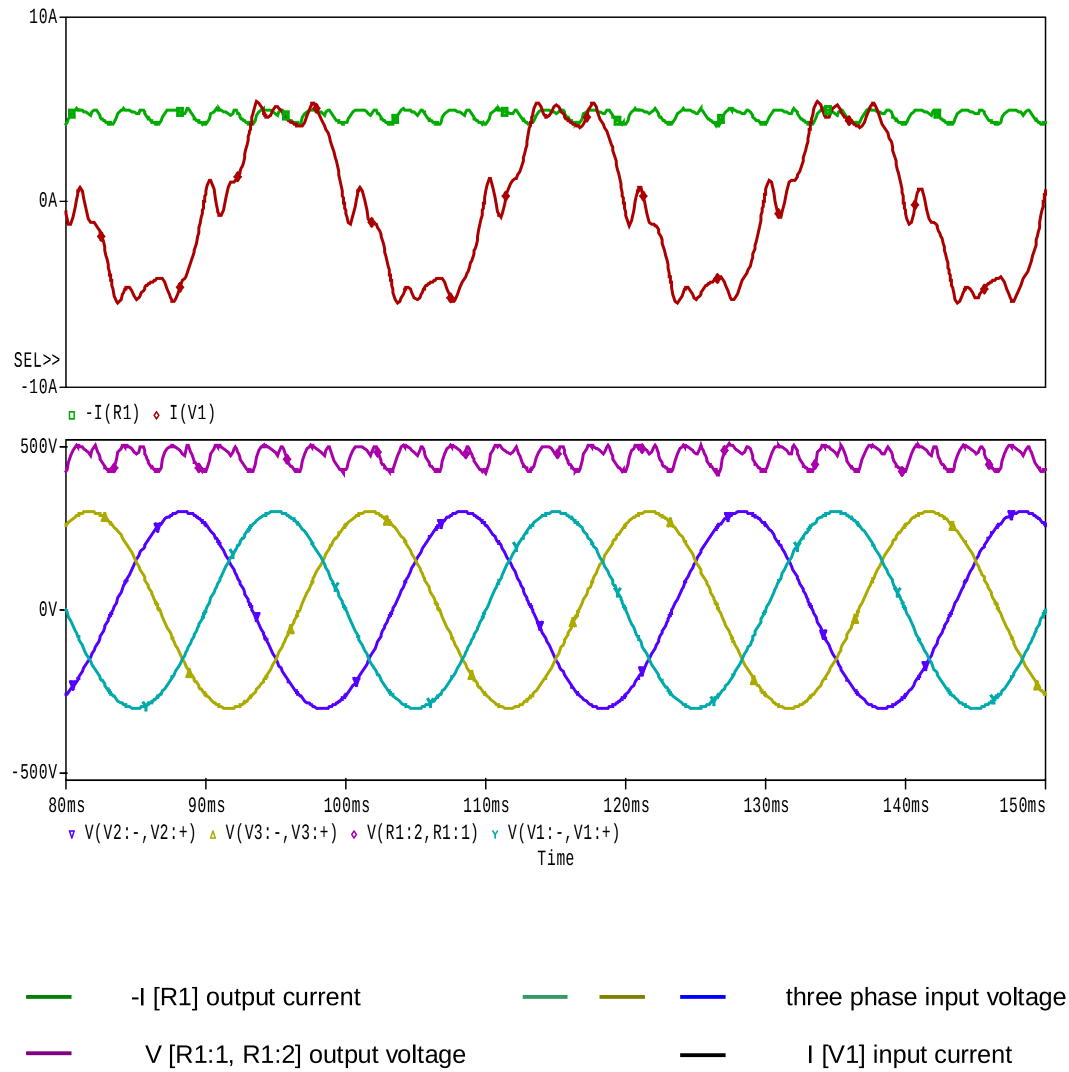


Figure 2.5: Input and output voltage and current of a three phase rectifier with input filter (load is resistive)

The presentation of input and output voltage and current show that the addition of input filter can reduces the harmonic component of input current. However, it cannot reduce the harmonic to the desired value with small filters. Besides, input current still has considerable distortion. Large filter at the input/output would affect the output voltage magnitude considerably due to their impedance drops.

The plot of efficiency and power factor are presented in Fig. 2.6 and the power factor is found as .945 and the efficiency as 99% at steady state condition.

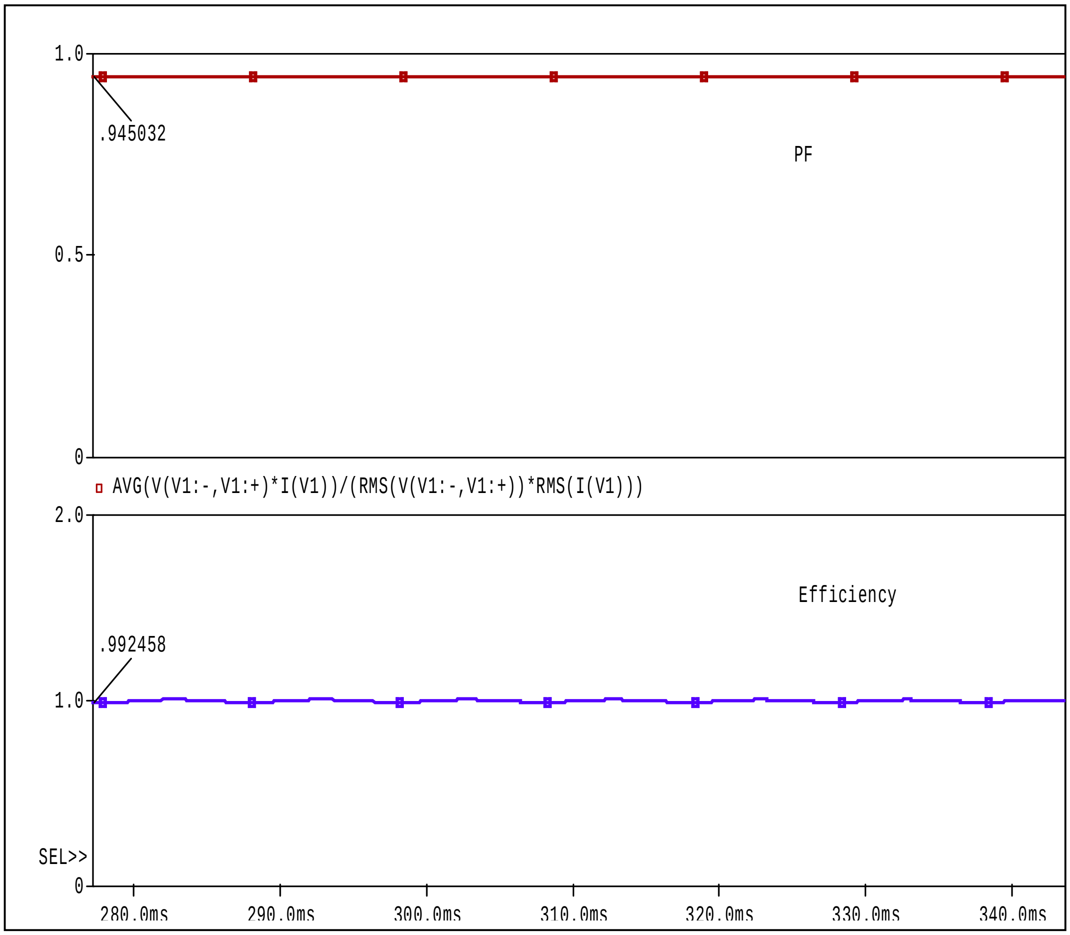


Figure 2.6: Power Factor and Efficiency of a three phase rectifier with input filter (load is resistive)

Table 2.2: Table of significant Fourier transforms coefficients of input current of three phase rectifier with input filter (load is resistive)

HARMONIC NO	FREQUENCY (HZ)	FOURIER COMPONENT	NORMALIZED COMPONENT	PHASE (DEG)	NORMALIZED PHASE (DEG)
1	5.00E+01	5.11E+00	1.00E+00	-1.40E+01	0.00E+00
2	1.00E+02	1.25E-02	2.45E-03	7.91E+00	3.60E+01
3	1.50E+02	4.06E-03	7.94E-04	1.52E+02	1.94E+02
4	2.00E+02	8.39E-03	1.64E-03	-1.33E+02	-7.71E+01
5	2.50E+02	1.02E+00	1.99E-01	8.97E+01	1.60E+02
6	3.00E+02	1.28E-02	2.51E-03	-1.75E+02	-9.07E+01
7	3.50E+02	3.66E-01	7.16E-02	8.70E+01	1.85E+02
8	4.00E+02	5.05E-03	9.88E-04	1.36E+02	2.48E+02
9	4.50E+02	7.23E-03	1.41E-03	-1.68E+02	-4.14E+01
10	5.00E+02	2.90E-03	5.67E-04	1.56E+02	2.96E+02
11	5.50E+02	4.07E-01	7.96E-02	7.55E+01	2.30E+02
12	6.00E+02	1.40E-02	2.73E-03	1.02E+02	2.70E+02
13	6.50E+02	3.00E-01	5.86E-02	3.01E+01	2.13E+02
14	7.00E+02	3.46E-03	6.78E-04	-2.04E+00	1.95E+02
15	7.50E+02	3.51E-03	6.87E-04	1.25E+02	3.35E+02
16	8.00E+02	1.33E-03	2.60E-04	9.20E+01	3.17E+02
17	8.50E+02	1.41E-01	2.76E-02	-2.37E+01	2.15E+02
18	9.00E+02	7.95E-03	1.56E-03	-3.81E+00	2.49E+02
19	9.50E+02	6.95E-02	1.36E-02	-6.30E+01	2.04E+02
20	1.00E+03	1.27E-03	2.49E-04	-4.89E+01	2.32E+02
21	1.05E+03	3.22E-03	6.30E-04	1.41E+02	4.36E+02
22	1.10E+03	1.75E-03	3.42E-04	-1.57E+02	1.52E+02
23	1.15E+03	1.32E-02	2.59E-03	1.29E+02	4.51E+02
24	1.20E+03	2.35E-03	4.60E-04	-1.46E+02	1.91E+02
25	1.25E+03	4.27E-03	8.36E-04	1.14E+02	4.65E+02
26	1.30E+03	2.09E-03	4.09E-04	-1.06E+02	2.59E+02
27	1.35E+03	3.04E-03	5.95E-04	9.31E+01	4.72E+02
28	1.40E+03	3.05E-03	5.96E-04	1.43E+02	5.36E+02
29	1.45E+03	8.06E-03	1.58E-03	-5.47E+01	3.52E+02
30	1.50E+03	1.02E-03	1.99E-04	1.06E+02	5.27E+02
31	1.55E+03	7.77E-03	1.52E-03	-8.58E+01	3.49E+02
32	1.60E+03	2.20E-03	4.30E-04	-1.43E+02	3.06E+02
33	1.65E+03	1.33E-03	2.60E-04	1.61E+02	6.25E+02
34	1.70E+03	1.63E-03	3.19E-04	1.10E+02	5.88E+02
35	1.75E+03	7.62E-03	1.49E-03	2.48E+01	5.16E+02
36	1.80E+03	2.42E-03	4.73E-04	1.45E+02	6.50E+02
37	1.85E+03	6.93E-03	1.36E-03	-1.31E+01	5.06E+02
38	1.90E+03	1.23E-03	2.41E-04	-1.66E+02	3.67E+02
39	1.95E+03	5.52E-04	1.08E-04	1.47E+02	6.95E+02
40	2.00E+03	2.11E-03	4.13E-04	-1.53E+02	4.08E+02

TOTAL HARMONIC DISTORTION = 23.54%

From tabulated value of harmonic component of input current it is shown that the input current has a THD of 23.54% which is still beyond the prescribed standard.

2.4 Conventional Three Phase Rectifier With Input and Output Filter

To smooth output voltage, an out put filter is usually used. An out put filter of 200uf capacitor and 10 mH inductor with the previous circuit is shown in Fig. 2.7.

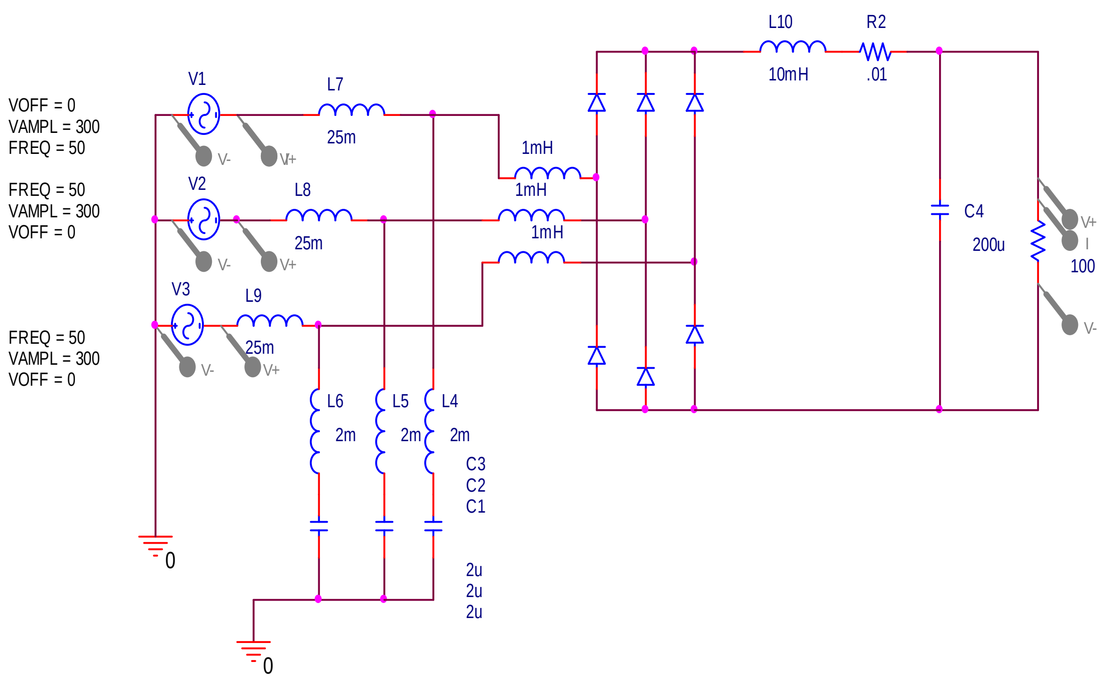


Figure 2.7: A three Phase rectifier with input and output filter (load is resistive)

Plot of input and output current and voltage are shown in Fig. 2.8.

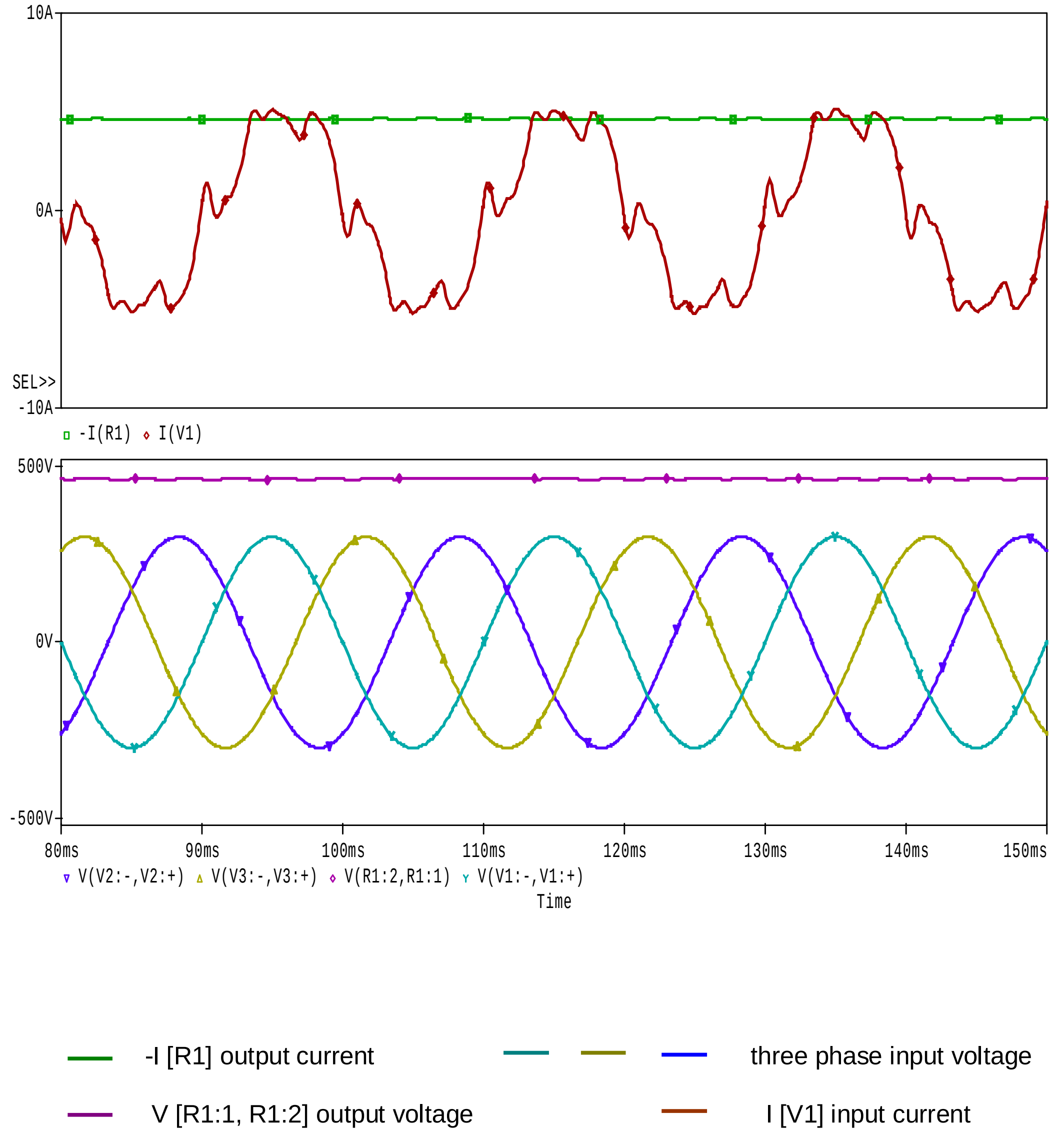


Figure 2.8: Input and output voltage and current of a three phase rectifier with input and output filter (Load is resistive)

Power factor and efficiency are found using equations 2.1 and 2.2 and are shown in Fig. 2.9.

From tabulated value, harmonic current shows increased THD of 24.53%.

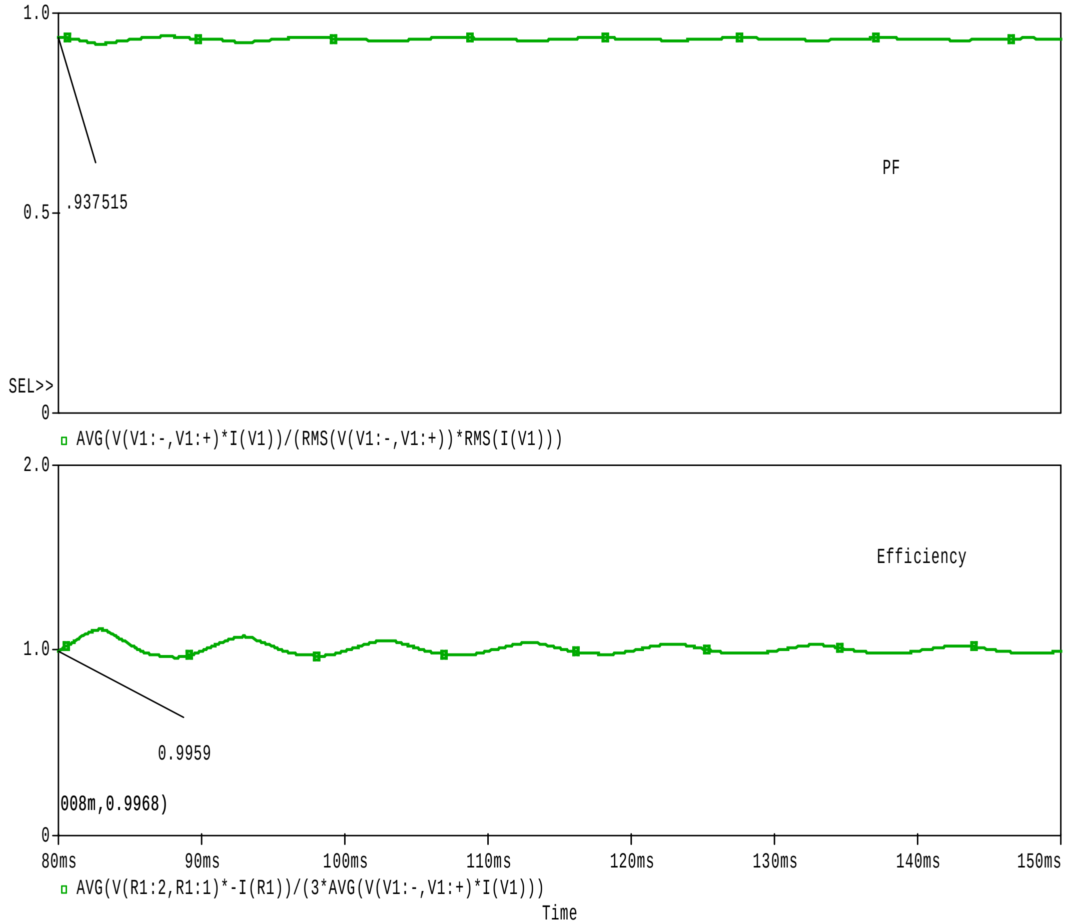


Figure 2.9: Efficiency and Power factor of a three phase rectifier with input and output filter.

Table 2.3: Table of significant Fourier transform coefficients of input current of three phases rectifier with input and output filter (load is resistive)

HARMONIC NO	FREQUENCY (HZ)	FOURIER COMPONENT	NORMALIZED COMPONENT	PHASE (DEG)	NORMALIZED PHASE (DEG)
1	5.00E+01	5.00E+00	1.00E+00	-1.58E+01	0.00E+00
2	1.00E+02	2.13E-02	4.27E-03	1.21E+02	1.53E+02
3	1.50E+02	1.81E-02	3.62E-03	7.14E+01	1.19E+02
4	2.00E+02	1.52E-02	3.04E-03	9.50E+01	1.58E+02
5	2.50E+02	1.02E+00	2.04E-01	6.91E+01	1.48E+02
6	3.00E+02	9.30E-03	1.86E-03	1.80E+02	2.75E+02
7	3.50E+02	5.33E-01	1.07E-01	6.83E+01	1.79E+02
8	4.00E+02	4.36E-03	8.72E-04	6.14E+01	1.88E+02
9	4.50E+02	1.12E-02	2.24E-03	-2.08E+01	1.22E+02
10	5.00E+02	7.14E-03	1.43E-03	-3.78E+01	1.20E+02
11	5.50E+02	3.08E-01	6.15E-02	5.73E+01	2.31E+02
12	6.00E+02	6.85E-03	1.37E-03	1.05E+02	2.94E+02
13	6.50E+02	2.71E-01	5.41E-02	3.26E+01	2.38E+02
14	7.00E+02	3.86E-03	7.71E-04	1.15E+01	2.33E+02
15	7.50E+02	3.86E-03	7.72E-04	-1.26E+02	1.11E+02
16	8.00E+02	4.61E-03	9.21E-04	1.36E+02	3.88E+02
17	8.50E+02	1.15E-01	2.31E-02	-1.28E+01	2.56E+02
18	9.00E+02	1.41E-03	2.82E-04	2.83E+01	3.13E+02
19	9.50E+02	8.51E-02	1.70E-02	-4.19E+01	2.59E+02
20	1.00E+03	3.40E-03	6.80E-04	1.26E+02	4.42E+02
21	1.05E+03	2.88E-03	5.76E-04	-1.68E+01	3.15E+02
22	1.10E+03	6.14E-03	1.23E-03	2.08E+01	3.69E+02
23	1.15E+03	2.02E-02	4.03E-03	-1.44E+02	2.20E+02
24	1.20E+03	8.49E-03	1.70E-03	7.55E+01	4.55E+02
25	1.25E+03	3.57E-02	7.13E-03	-5.43E+01	3.41E+02
26	1.30E+03	9.77E-03	1.95E-03	-1.59E+02	2.52E+02
27	1.35E+03	6.55E-03	1.31E-03	-6.29E+00	4.21E+02
28	1.40E+03	3.40E-03	6.80E-04	-3.79E+01	4.05E+02
29	1.45E+03	1.08E-02	2.15E-03	-9.73E+01	3.61E+02
30	1.50E+03	3.86E-03	7.71E-04	4.82E+01	5.22E+02
31	1.55E+03	1.65E-02	3.29E-03	-7.61E+01	4.14E+02
32	1.60E+03	1.85E-03	3.69E-04	2.00E+00	5.08E+02
33	1.65E+03	1.44E-04	2.88E-05	1.18E+02	6.40E+02
34	1.70E+03	3.08E-03	6.15E-04	-6.37E+01	4.74E+02
35	1.75E+03	6.21E-03	1.24E-03	4.41E+01	5.97E+02
36	1.80E+03	2.20E-03	4.40E-04	-6.71E+01	5.02E+02
37	1.85E+03	3.64E-03	7.28E-04	2.34E+00	5.87E+02
38	1.90E+03	1.05E-03	2.10E-04	-1.60E+01	5.85E+02
39	1.95E+03	1.23E-03	2.46E-04	-4.25E+01	5.74E+02
40	2.00E+03	1.20E-03	2.40E-04	-1.61E+02	4.71E+02

TOTAL HARMONIC DISTORTION = 24.63%

From the above analysis it is recommended that other techniques need to be investigated to obtain the desired result.

2.5 The Proposed Scheme:

In the proposed scheme a current source is connected across the rectifier input. The purpose of the current source is to inject a current, into the point of common coupling of the load and the supply. Let us consider a single phase rectifier circuit. The input current of rectifier contains a harmonic current I_{load1} from load. This current can be neutralized by injection of same current I_{inj} *in* the opposite direction. This is the basic principle of the proposed scheme. In reported work this is achieved by a separate dc source and a current source inverter.

Applying Kirchhoff's Law at node A

$$I_{input1} - I_{load1} + I_{inj} - I_{load} = 0 \qquad [I_{inj} = I_{load1}] \qquad [2.3]$$

$$I_{input1} - I_{load1} + I_{load1} - I_{load} = 0$$

$$I_{input1} = I_{load}$$

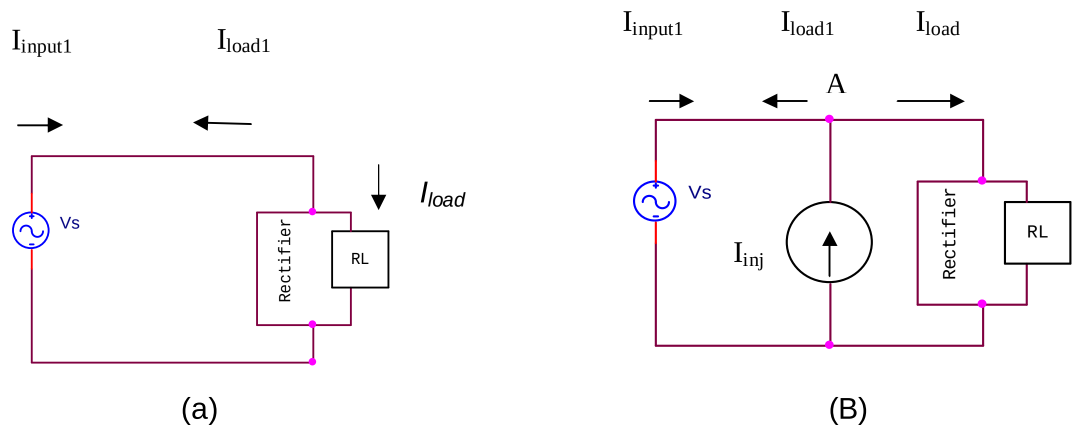


Figure 2.10: (a) Normal Single Phase rectifier Circuit (b) The proposed scheme of harmonic current injection

2.5.1 Current Source Inverter In The Present Research

In this section the ac current source required for the proposed scheme has been described. It consists of a true current source inverter and output filter. In a current –source inverter (CSI), the input behaves as a current source. The output current is maintained constant in shape irrespective of load on the inverter and the output voltage is forced to change. The inverter uses dc current source as input.

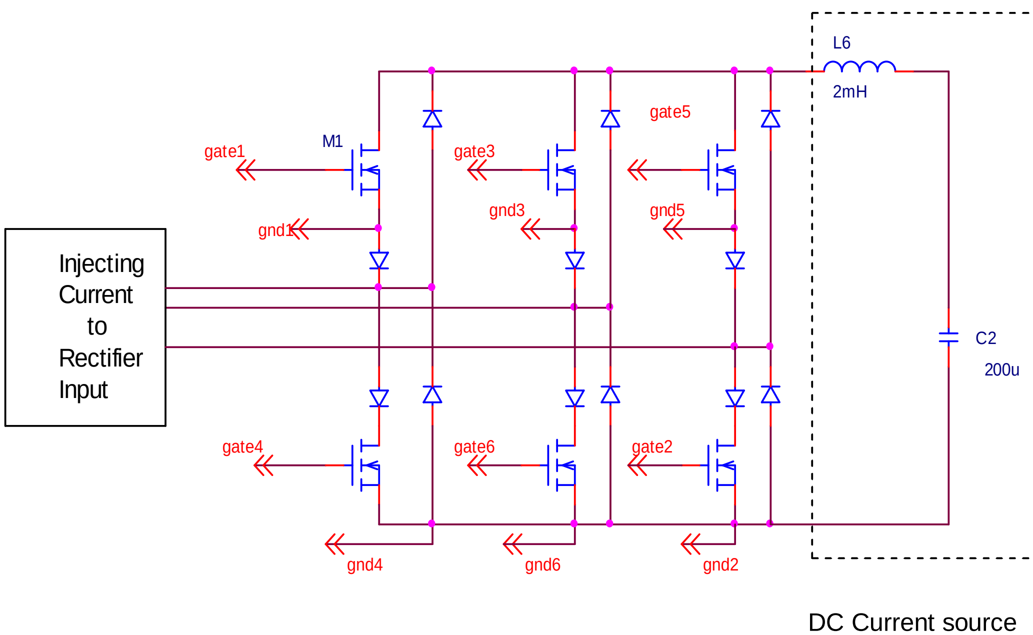


Figure 2.11: A three phase Current Source Inverter Rectifier Circuit

The circuit diagram of the true three phase current source inverter (CSI) is shown in Fig. 2.11. The current source inverter consists of full bridge inverter having 6 MOSFET switches numbered 1 to 6 and a dc current source to supply the inverter. The switches are numbered according to standard pattern.

Because there must be a continuous current flow from the source, two switches must always conduct-one from the upper and one from the lower switches. The conduction sequence is 12, 23, 34, 45, 56, and 61. Each device conducts for 120º. If two switches, one upper and one lower, conduct at the same time such that the output current is $\pm I_{Load}$, the switch state is 1; whereas if these switches are off at the same time, the switch state is 0.

A CSI is a dual of the voltage source inverter (VSI). In a VSI, the load current depends on the load impedance, whereas, the load voltage in a CSI depends on the load impedance. For this reason, diodes are connected in series with the switching devices to block the reverse voltage to protect them from transient voltage due to load current switching.

The advantages of CSI are: (1) since the input dc current is controlled and limited , misfiring of switching devices, or short circuit , would not be serious problems (2) the peak current of power devices is limited (3) the communication circuits of switches are simpler (4) it has ability to handle reactive regenerative load without freewheeling diodes.

2.5.2 DC Current Source For The Inverter

DC current source are not generally available in the same sense as voltage sources. Therefore, it is proposed that a combination of series inductor of 2 mH, capacitor of 200uf and a rectifier is used to supply dc current to the inverter. This idea has been taken from VAR compensation techniques that do not require a separate source for the inverter.

2.5.3 Template Extraction

Template extraction is a term used in the literature for determining the current desired to inject into the point of common coupling. In this research it is desired to inject the current specified by Eq. (2.3). This current is the difference of sine wave (described) and non sinusoidal input current. This research has used a circuit for extracting the error signal. A three phase rectifier with a voltage source of 5V, frequency of 50 Hz is taken for this purpose. The circuit diagram is shown in Fig. 2.12: A differentiator is used to extract the difference of non sinusoidal input signal and the sine wave called the error signal. This error signal is modulated by delta modulator to generate the switching pulse of the current source inverter so as to obtain the injecting current which resembles the error signal. The shape of error signal obtained from circuit of Fig. 2.12 is shown in Fig. 2.13:

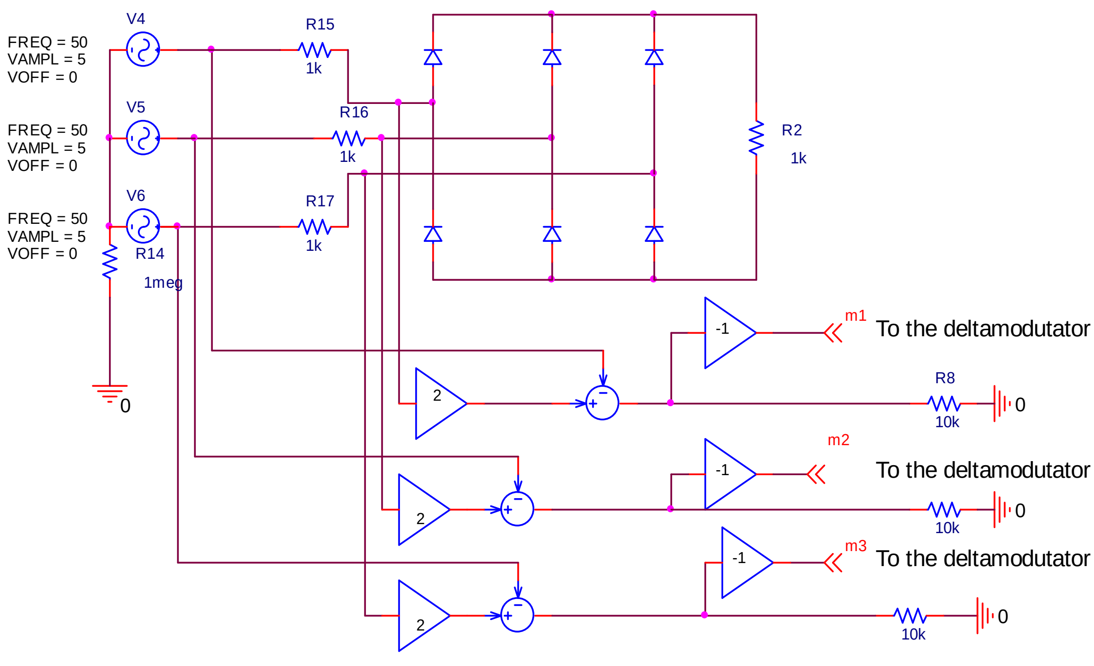


Figure 2.12: A three phase rectifier circuit designed to extract the error signal

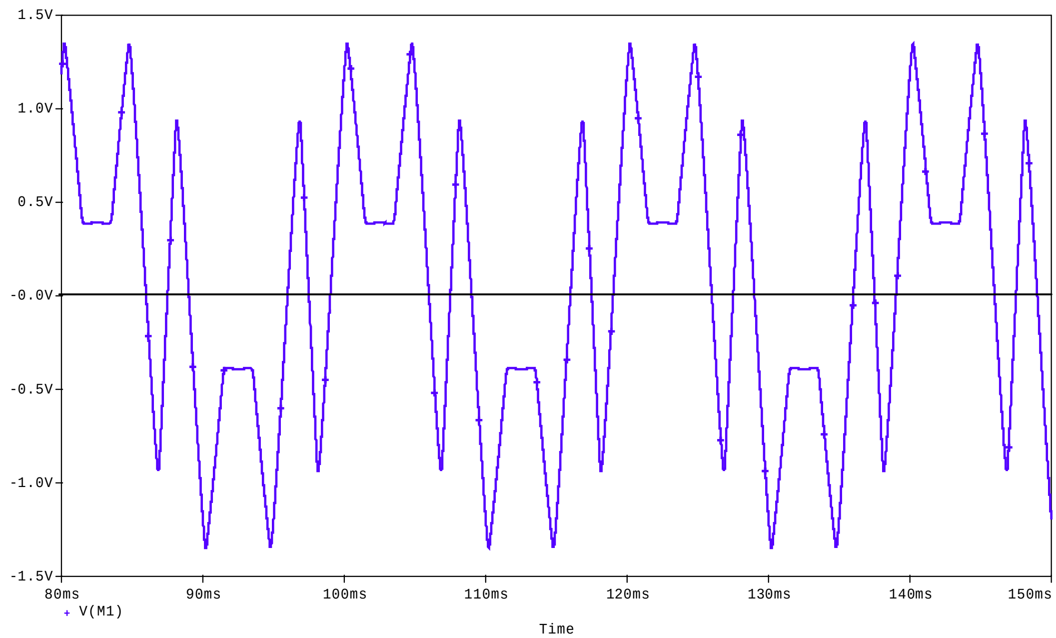


Figure 2.13: The error signal (difference of non sinusoidal signal and sine wave)

2.5.4 Selection Of Modulation Scheme For Inverter Switching

The inverter is supplied by a dc current source whose current must remain constant and uninterrupted at all times by the definition of a dc current source. The PWM, SPWM, MSPWM, MSPWN or other techniques can be applied to vary the load current and to improve the quality of its waveform. In this thesis common PWM technique is not used. Easily implementable Delta modulation technique with fewer components is used for inverter switching. In delta modulation a triangular wave is allowed to oscillate within a defined window above and below the reference error signal. The inverter switching function is generated from the vertices of the triangular wave. The delta modulator circuit used in this work is shown in Fig. 2.14. Triangular wave is generated automatically.

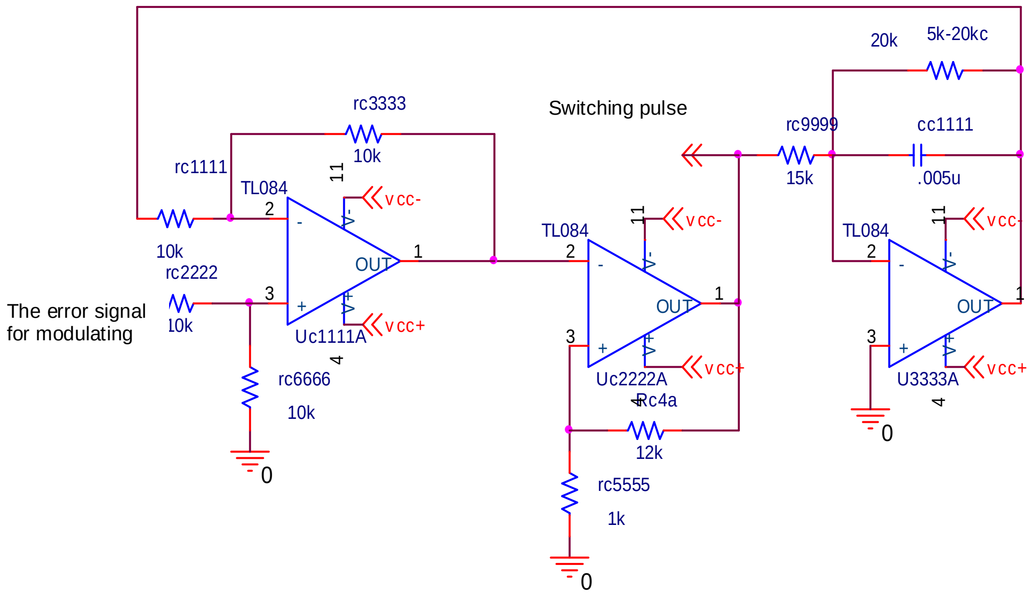
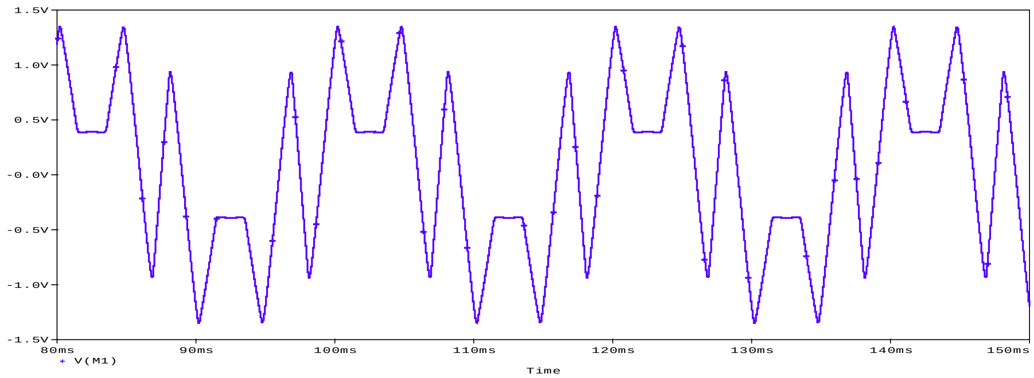
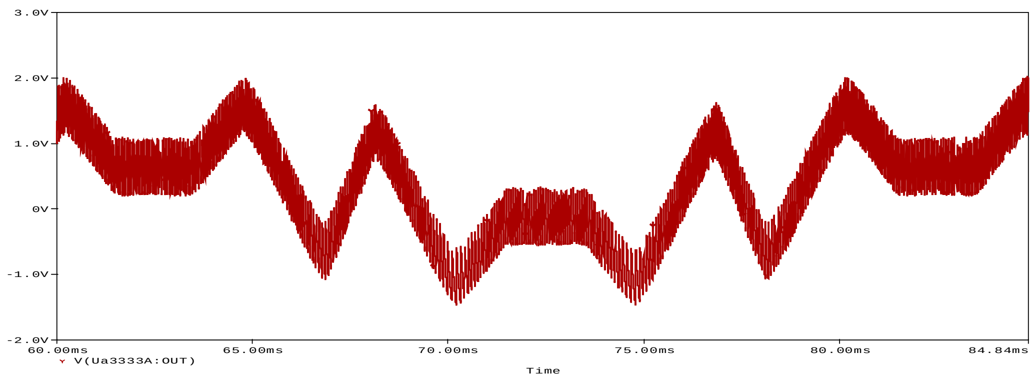


Figure 2.14 : Typical delta modulator

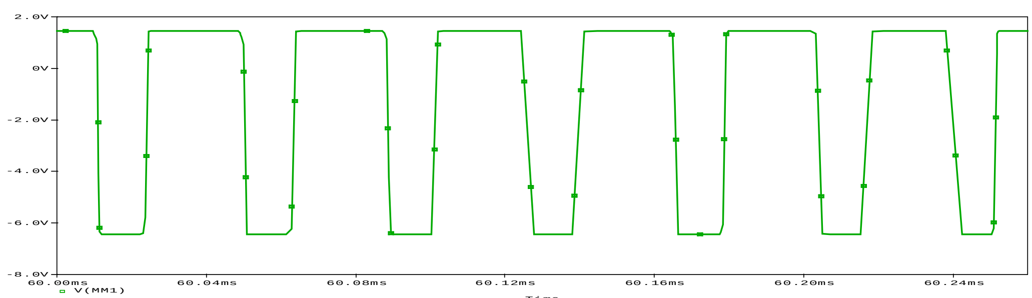
The carrier triangular signal, the reference template, delta modulated signal and switching pulse are shown in Fig. 2.15 (a-c)



(a) Modulating Signal



(b) Self generated Carrier



(c) Switching pulses

Figure 2.15: Waveforms of the delta modulator circuit

(a) Modulating signal(error from template circuit)

(b) Carrier generated by delta modulator

(c) Switching pulses(modulated signals)

2.5.5 Isolator Circuit

To avoid short circuit of source due to common ground via switch and gate logic circuit connection, gate pulses are provided to the gates via opto coupler circuit.

This requirement is met by using opto-couplers. Necessary circuits used for this purpose is shown in Fig. 2.16, where, gnd 4 and gnd 1 are separate grounds and are connected to switches 1 and 4 of the power circuit. Similar opto coupler circuits are used in switches 3-6 & 5-2 pairs of H Bridge of the inverter.

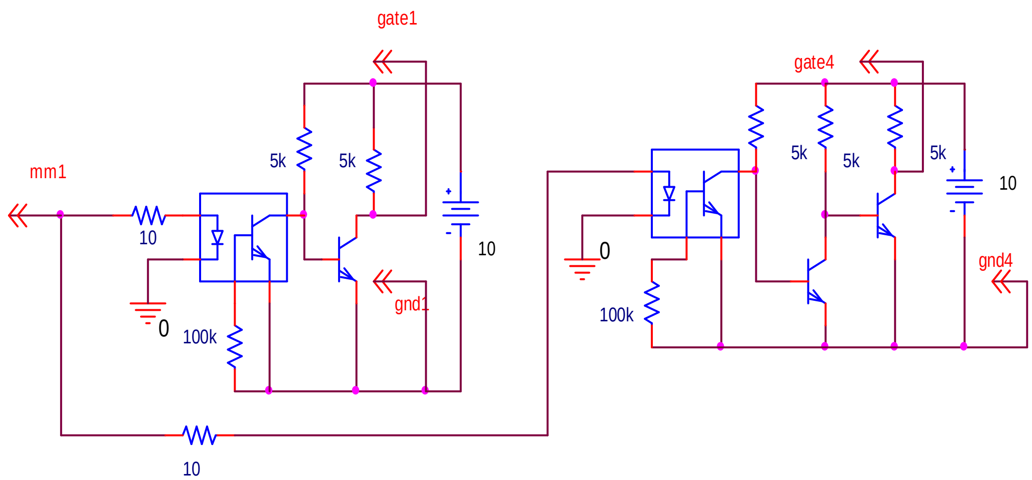


Figure 2.16: Circuit diagram of for isolating positive and negative pulse

2.5.6 Filter For The Current Source Output Current

The injected current produced by the CSI is shown in Fig. 2.17 which is pulsed in nature. The current contains high frequency harmonic component. Hence a filter is required at the output of the CSI in order to attenuate the high frequency carrier components while allowing the desired low frequency components to pass. This is done by connecting an inductor of 1mH in series to the inverter output. The output current of the CSI with filter is shown in Fig. 2.17

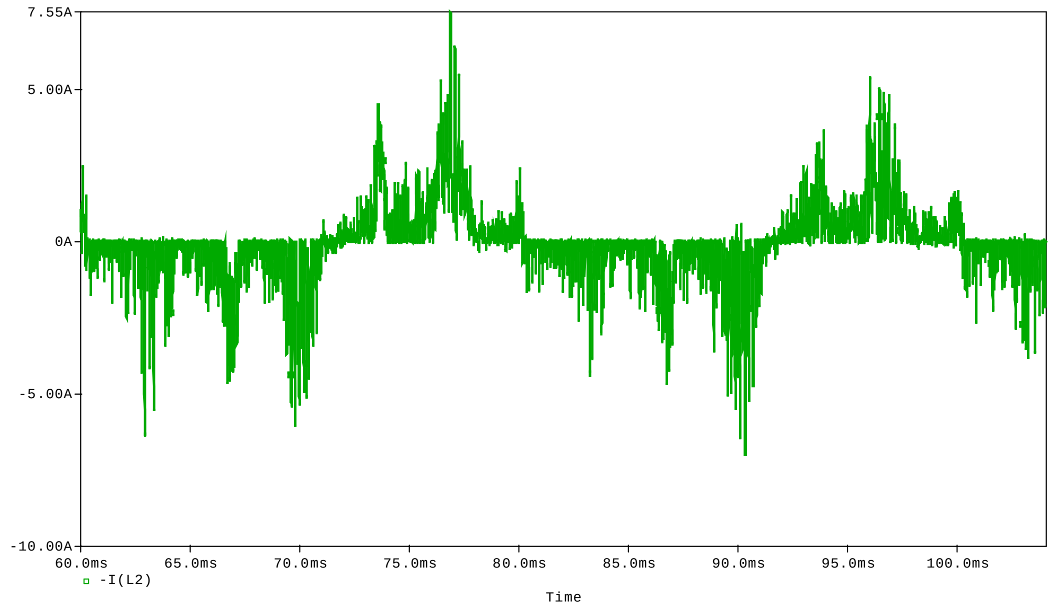


Figure 2.17: The output current of the CSI with 1mH inductor filter

2.5.7 The Complete Circuit Of The Proposed Three Phases Rectifier

The complete circuit of the proposed rectifier is presented in this section. Fig. 2.18 shows the main circuit with the supply voltages. The rectifier has resistive load, the input and output filters and the CSI. The modulating signal is extracted from the input of a rectifier circuit as shown in Fig. 2.19. The inverter switching signals are generated by a delta modulator as shown in Fig. 2.20. The isolated switching pulses are generated from the delta modulator by Opto coupler circuits as shown in Fig. 2.21.

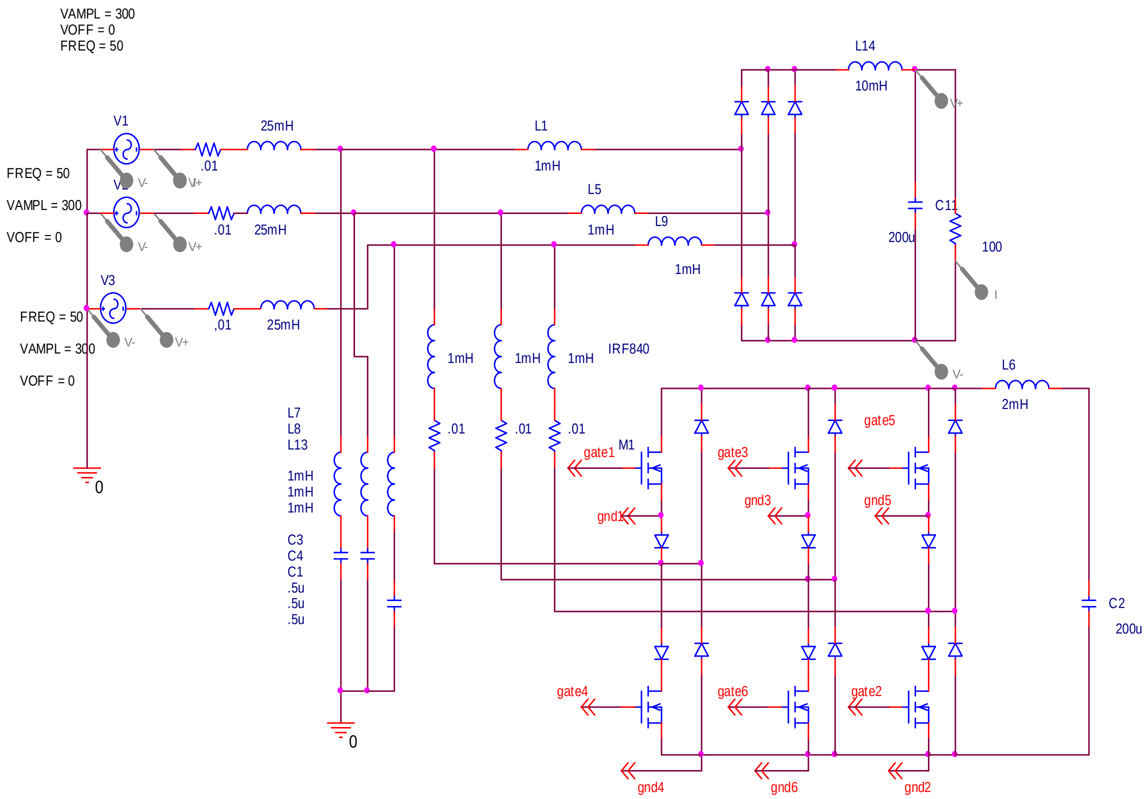


Figure 2.18: The overall proposed circuit (load is resistive)

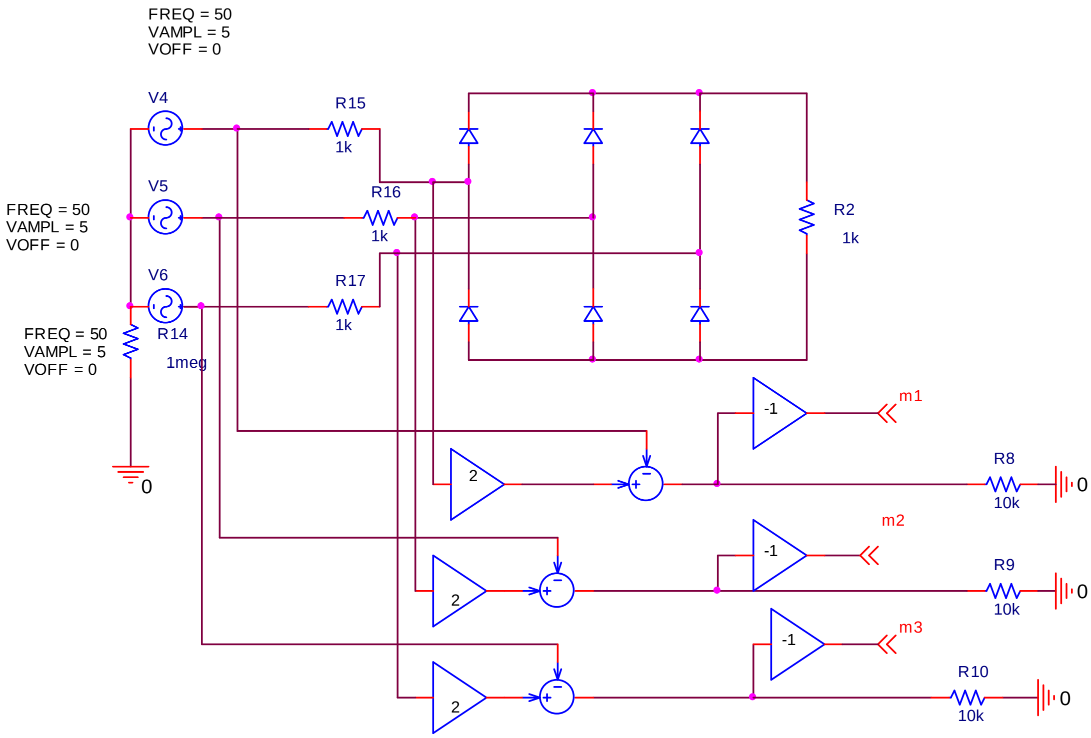


Figure 2.19: The circuit for extracting modulating signals

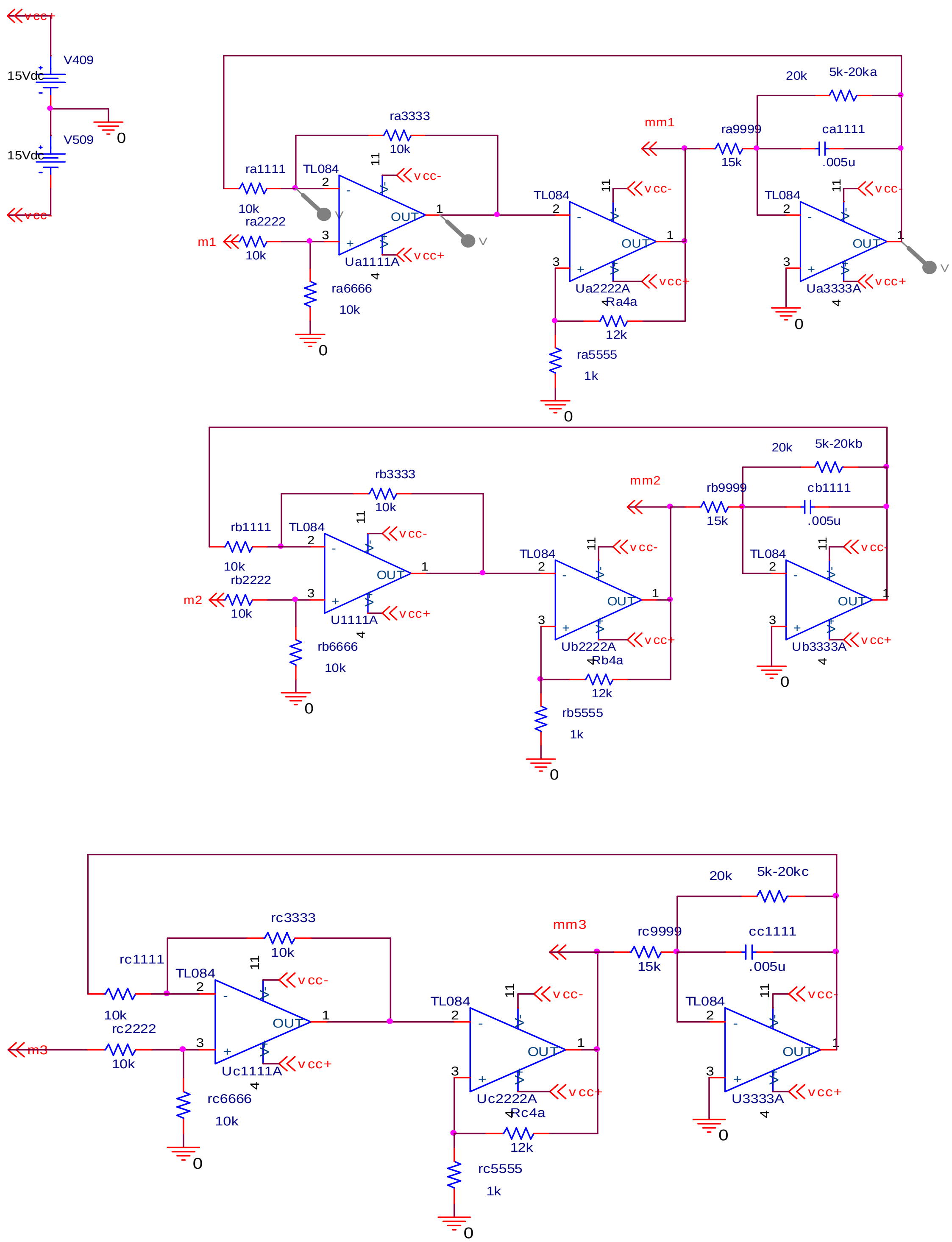


Figure 2.20: The three phase delta modulator circuit

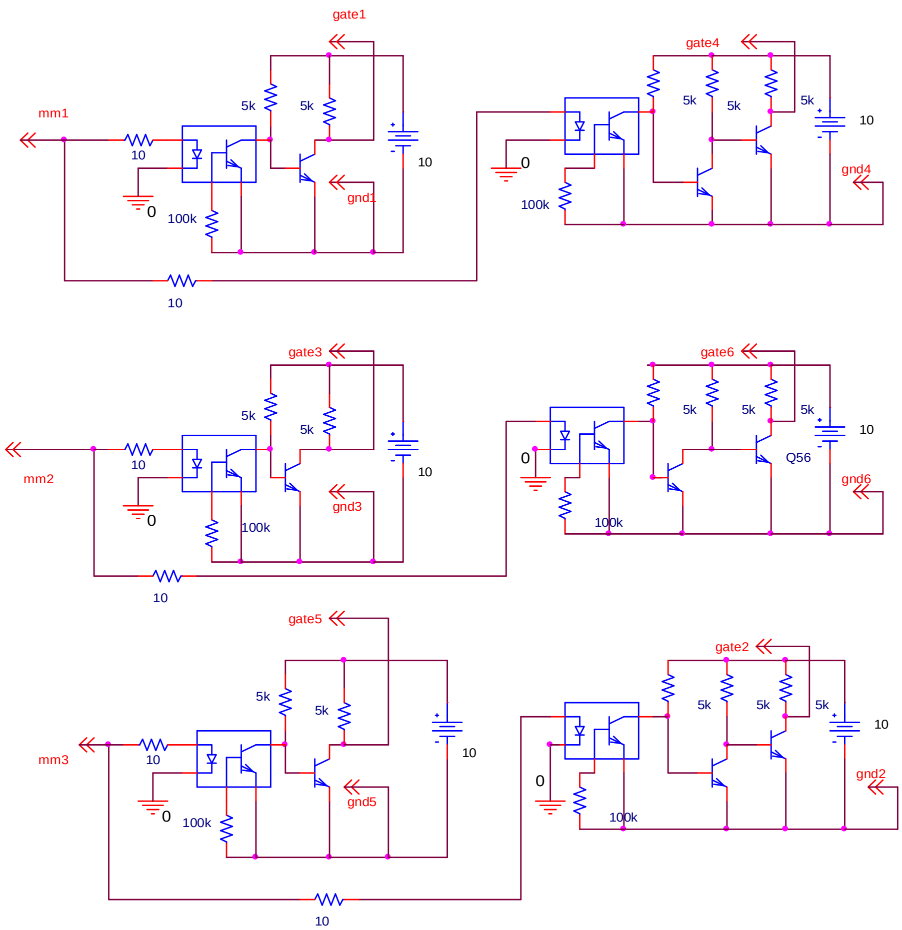


Figure 2.21: Opto coupler isolation circuits

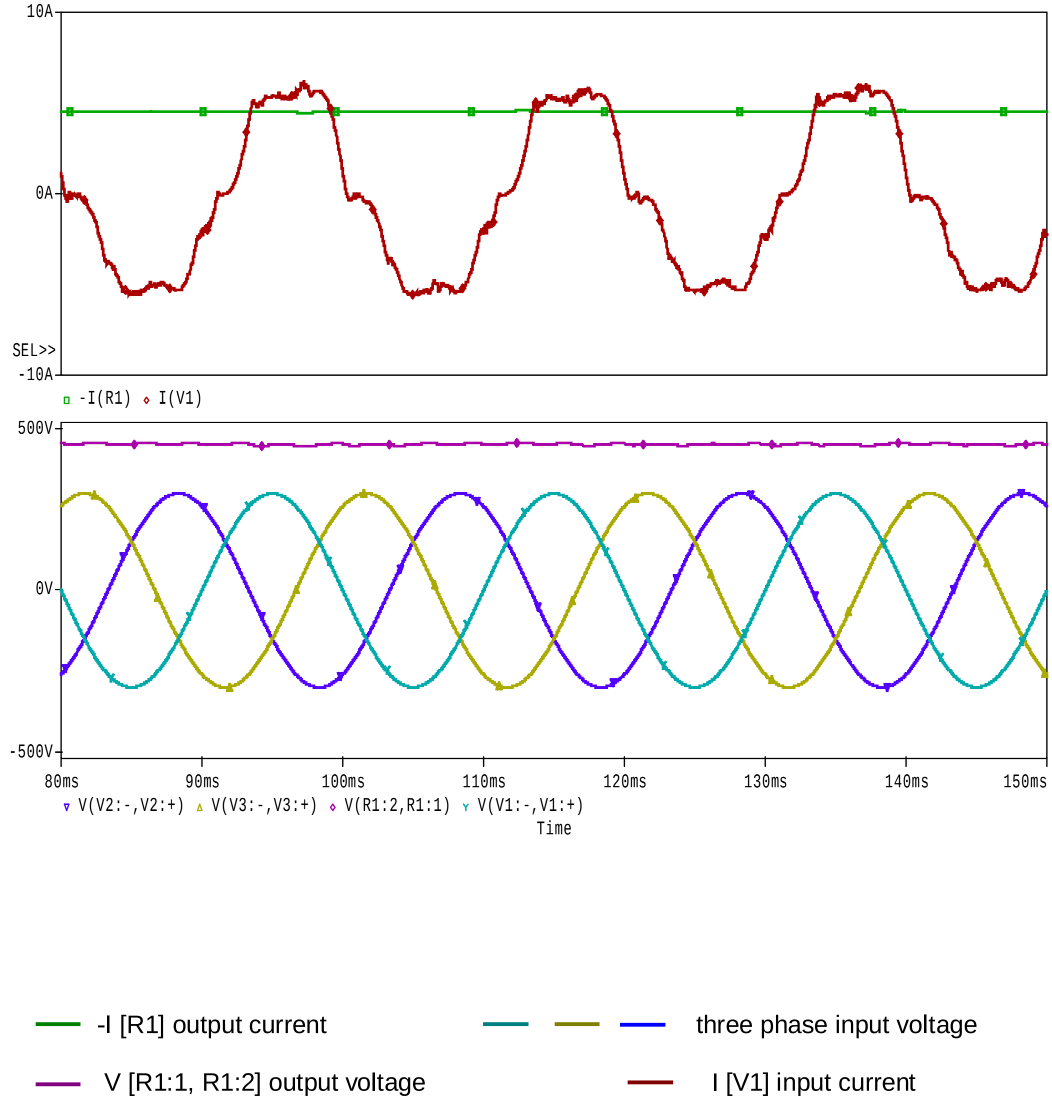


Figure 2.22: Input and output voltage and current of the proposed rectifier (load is resistive)

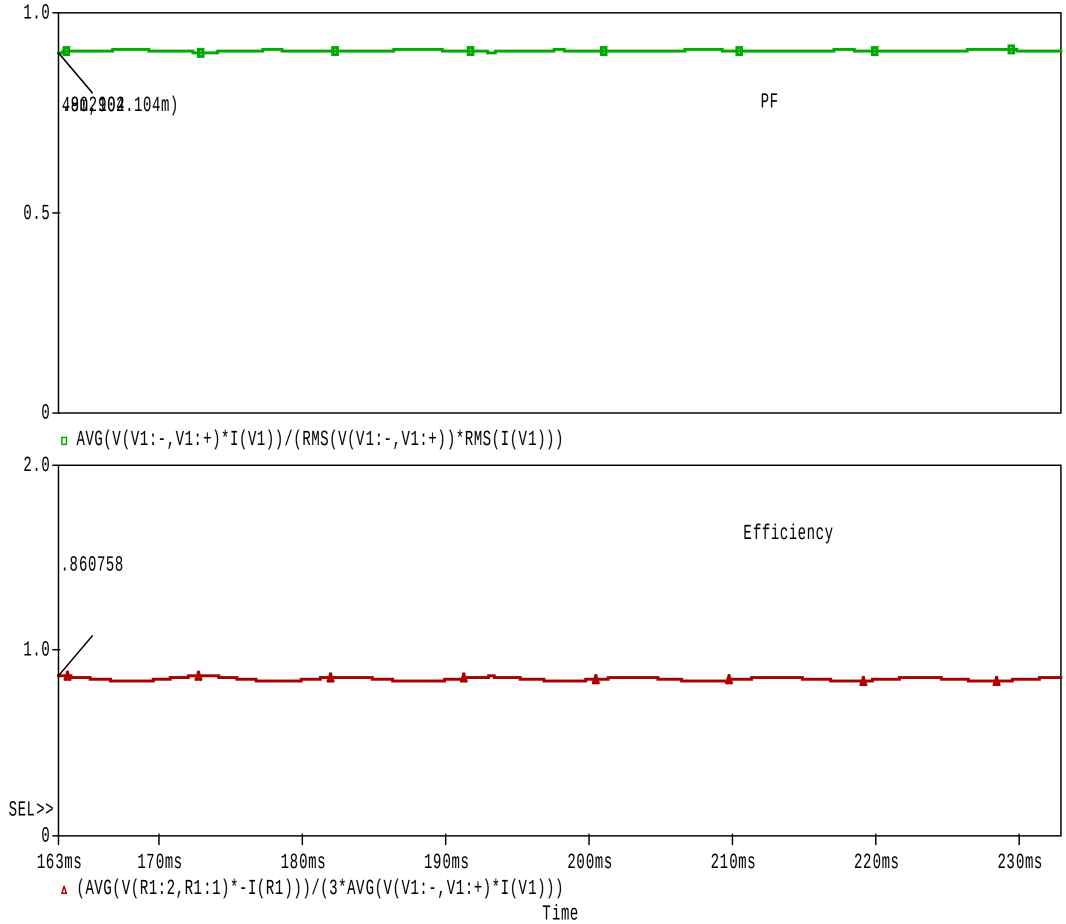


Figure 2.23: The power factor and the efficiency of the proposed rectifier (load is resistive)

Table 2.4: Table of significant Fourier transforms coefficients of input current of the proposed three phase rectifier (load is resistive)

HARMONIC NO	FREQUENCY (HZ)	FOURIER COMPONENT	NORMALIZED COMPONENT	PHASE (DEG)	NORMALIZED PHASE (DEG)
1	5.000E+01	6.229E+00	1.000E+00	1.536E+02	0.000E+00
2	1.000E+02	5.589E-01	8.972E-02	-1.075E+02	-4.147E+02
3	1.500E+02	1.121E-01	1.799E-02	1.248E+02	-3.361E+02
4	2.000E+02	2.661E-01	4.271E-02	-1.288E+02	-7.433E+02
5	2.500E+02	5.581E-01	8.959E-02	-1.192E+02	-8.874E+02
6	3.000E+02	7.991E-02	1.283E-02	-1.177E+02	-1.040E+03
7	3.500E+02	1.861E-01	2.988E-02	1.600E+02	-9.155E+02
8	4.000E+02	3.473E-01	5.576E-02	-1.314E+02	-1.361E+03
9	4.500E+02	7.260E-02	1.165E-02	6.174E+01	-1.321E+03
10	5.000E+02	2.041E-01	3.277E-02	-1.784E+02	-1.715E+03
11	5.500E+02	1.900E-01	3.050E-02	-1.557E+01	-1.706E+03
12	6.000E+02	6.043E-02	9.702E-03	1.699E+02	-1.674E+03
13	6.500E+02	4.688E-02	7.525E-03	5.260E+01	-1.945E+03
14	7.000E+02	1.212E-01	1.946E-02	-1.462E+02	-2.297E+03
15	7.500E+02	2.933E-02	4.708E-03	1.830E+01	-2.286E+03
16	8.000E+02	7.389E-02	1.186E-02	1.355E+02	-2.323E+03
17	8.500E+02	4.958E-02	7.960E-03	-1.106E+02	-2.722E+03
18	9.000E+02	3.621E-02	5.813E-03	2.544E+01	-2.740E+03
19	9.500E+02	4.604E-02	7.391E-03	9.630E+01	-2.823E+03
20	1.000E+03	7.300E-02	1.172E-02	-9.544E+01	-3.168E+03
21	1.050E+03	3.577E-02	5.743E-03	9.547E+01	-3.131E+03
22	1.100E+03	3.892E-02	6.248E-03	-1.253E+01	-3.393E+03
23	1.150E+03	2.779E-02	4.462E-03	1.218E+02	-3.412E+03
24	1.200E+03	2.498E-02	4.010E-03	-3.673E+01	-3.724E+03
25	1.250E+03	6.327E-02	1.016E-02	6.605E+01	-3.775E+03
26	1.300E+03	8.484E-02	1.362E-02	-1.192E+02	-4.114E+03
27	1.350E+03	3.675E-02	5.900E-03	-4.599E+00	-4.153E+03
28	1.400E+03	2.734E-02	4.390E-03	8.340E+00	-4.294E+03
29	1.450E+03	1.235E-02	1.983E-03	-1.282E+01	-4.468E+03
30	1.500E+03	2.480E-02	3.981E-03	-1.314E+02	-4.741E+03
31	1.550E+03	4.485E-02	7.201E-03	-1.045E+01	-4.773E+03
32	1.600E+03	2.780E-02	4.462E-03	-1.546E+02	-5.071E+03
33	1.650E+03	1.782E-02	2.861E-03	-1.571E+02	-5.227E+03
34	1.700E+03	1.519E-02	2.439E-03	2.787E+01	-5.196E+03
35	1.750E+03	4.270E-02	6.855E-03	1.714E+02	-5.206E+03
36	1.800E+03	3.015E-02	4.840E-03	-5.416E+01	-5.585E+03
37	1.850E+03	1.813E-02	2.911E-03	-1.393E+02	-5.824E+03
38	1.900E+03	2.860E-02	4.591E-03	7.121E+01	-5.767E+03
39	1.950E+03	2.038E-02	3.272E-03	1.611E+02	-5.831E+03
40	2.000E+03	2.189E-02	3.513E-03	-2.014E+01	-6.166E+03

TOTAL HARMONIC DISTORTION = 16.18%

2.6 Results

The simulation results of the final rectifier circuit are shown in Fig 2.22 and 2.23. The efficiency is found 86.07% and the power factor is .908. From Table 2.3 the THD is found to be 16.18%. With acceptable efficiency and power factor this circuit provides lower THD of input current than previously described three phase rectifier with passive filters. Hence this can be inferred that since this circuit fulfills all three requirements in a single scheme which was not possible in the passive filtering technique.

Table 2.5: Comparison of performance of three phase rectifier with / without passive input filter with proposed scheme.

Performance Parameter	Three phase rectifier without input Filter	Three Phase Rectifier With Passive input Filter	Proposed three Phase rectifier with Current Injection
Power factor	.955	.945	.908
Efficiency	98.54%	99%	86.07%
THD	25.88%	23.54%	16.18%.
Input Filter size	None	L=25mH C=2uF , L=2mH	L=25mH C=0.5uF, L=1mH
Input voltage	300 v pp(L-N)	300 v pp(L-N)	300 v pp(L-N)
Output voltage	450 V DC	450 V DC	450 V DC

In the proposed scheme though the power factor and efficiency has degraded to some extent the THD has reduced significantly. In the proposed scheme input filter used has smaller values of inductance and capacitance in the shunt arm of the input filter.

Chapter 3
Conclusions and Recommendation for Future Work

3.1 Conclusions

Input power factor improvement of a three phase diode bridge rectifier is an important part of power system and in modern power systems harmonic suppression to prescribed levels is mandatory. Since both power factor improvement and harmonic suppression with better efficiency can be performed by one stage as proposed in this research, this can be a desirable method acceptable in practical applications. The existing methods of power factor correction such as capacitors, synchronous condensers and static VAR compensators are capable of only VAR compensation. Addition of input and output filter can reduce harmonics to some extent but it will require large size of capacitor and these methods reduce the efficiency of rectifier. Besides, capacitors are subject to harmonic problems and resonance. In this dissertation a technique of current injection based on static VAR compensation technique has been developed which has many advantages including direct control of injection current, short-circuit protection and improved high reliability. An active switching technique has been developed which significantly reduce the harmonics. The proposed system has been designed and investigated using spice simulation software.

3.2 Contribution Of The Work

A current injector based input current waveform improvement technique of a three phase rectifier is proposed and investigated in this thesis. The current source required for the injection is derived from the three phase source itself by connecting a rectifier inverter circuit and inductor/capacitor. The capacitor gets charged by the rectifier formed by antiparallel diodes of the inverter switches, and then it functions as a current source in conjunction with the large inductor.

The inverter injects the difference of reference sine wave (desired input current shape) and the rectifier current (extracted by a template of low voltage rectifier and logic circuits). Inverter produces the desired ac injection current wave by modulating the dc current to pulsed waveform when switched by proper gate pulses generated by a delta modulation circuit with the difference signal extracted by the template as modulating signal. Since the reported switch mode regulated rectifiers are not suitable for high power (above 2kw) rectifiers for input current improvement, the proposed method implemented with the VAR compensation technique would provide a means for the purpose without the requirement of a separate current source.

3.3 Future Work

The present work demonstrated the successful input current waveform improvement of a three phase rectifier to a significant level. However, complete unity power factor operation with THD within prescribed level is yet to be achieved by this method. For this feedback control technique and proper filter design is necessary. These may be incorporated in future work. The study and results reported in the thesis is based primarily on the basis of simulation of proposed technique. Any conclusive remarks may be made after the implementation of the technique practically. The modulation technique used in the present study is the dual slope delta modulator for future possibility of making the rectifier a controlled one with input current improvement. In this thesis controlled output voltage operation of the rectifier is not investigated. The switching regulator based rectifier input current shaper performs voltage regulation. Hence the same objective should be investigated with proposed technique in future.

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