Input Power Factor Improvement of a Three Phase Rectifier by Harmonic Current Injection

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

Master of Science in Engineering

By

Hafiza Sultana

Department of Electrical and Electronic Engineering
BANGLADESH UNIVERSITY OF ENGINEERING AND TECHNOLOGY

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The thesis titled "Input Power factor Improvement of A Three Phase Rectifier by Harmonic Current Injection" Submitted by Hafiza Sultana, Student No. 100506107F session October, 2005 has been accepted as satisfactory in partial fulfillment of the requirement for the degree of Masters of Science in Engineering.

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ABSTRACT

A scheme for improving the input current wave shape of three phase bridge rectifier is proposed and analyzed in this thesis. Generally, to convert line frequency from ac to dc, a diode bridge rectifier is used. To reduce the ripple in the dc output voltage, a large filter is used at the output of a single-phase rectifier and a small output filter is used in a three phase rectifier. The capacitor used as filter causes the current drawn by converters to become non-sinusoidal in single-phase rectifiers. In three phase rectifiers input current takes the shape of periodic rectangular wave which is nonsinusoidal and discontinuous in nature. Due to the presence of low order harmonics, the total harmonic distortion of the current in lines become high and the input power factor in many cases become poor. The parallel active filter (PAF) is one of the solutions for harmonic current mitigation and reactive power compensation of nonlinear loads like rectifiers. This thesis analyzes design and control of a PAF for a 3-phase 3-wire rectifier load. A fifth-order harmonic injection PWM concept is developed for the harmonic reduction of the input current of a three-phase diode rectifier. The approach employs a direct selection of harmonic current. The fifth-order harmonic has been selected to be modulated by Pulse Width Modulator to suppress the dominant (fifth-order) harmonic in the input currents. To achieve THD less than 10% requirement of IEEE 519-1992, PAF technique has been introduced. The total scheme has been simulated by PSpice. The simulation result shows three phase rectifier’s input current becomes sinusoidal with less than ten percent THD. The scheme requires smaller input filter than passive filter method of input current shaping and it maintains high efficiency and maintains good input power factor at the same time.

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CHAPTER 1
Introduction

1.1 Background

In the modern day, utilization of electrical energy involves power electronic and microelectronics technologies. These technologies have improved the quality of life by allowing the introduction of controllable energy efficient equipment in industries and in domestic applications. Examples of such applications are Adjustable Speed Drives, Uninterruptible Power Supplies, computers and their peripherals, consumer electronic appliances, etc. Although the power electronics technology provides efficiency enhancement in energy utilization, it results in economical losses by creating power quality issues. A conflict exists as parts of industrial and domestic loads fed from AC utility present nonlinear characteristics and draw non-sinusoidal currents from the AC utility. The input current harmonic becomes the main polluter of the power system and results in power quality problems in the grid, distribution lines and transformers. The harmonics injected to the power system cause the line voltage distortions at the point of common coupling (PCC), where, the linear and nonlinear loads are connected. Voltage distortions at the PCC caused by harmonic currents of nonlinear load may result in malfunctioning or failure of voltage sensitive loads connected at the same PCC.

Harmonic currents result not only voltage distortions at the PCC, but also increase the RMS and peak-value of the line current causing additional losses, overheating, overloading and sometimes failure of power system equipments like capacitors, transformers and motors. Frequent tripping of circuit breakers and blowing of the fuses may also occur. They can also cause interferences with communication lines, errors in metering and resonances in distribution system [1], [2]. To alleviate harmonic related problems, recommended harmonic standards like EN61000-3-4 by IEC and IEEE 519-1992 by IEEE have been introduced and these standards have been regarded as a guideline for harmonic mitigation.

To define the harmonic content of a waveform (or distortion level of a waveform), the term ‘Total Harmonic Distortion (THD)’ is used and can be applied to either voltage or current. The THD of current is defined as,

$$\text{THD}=\frac{\sqrt{\sum_{n=2}^{\infty} i_n}}{i_1} \ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (1.1)$$

where, i_n is the rms value of the current harmonic component and i_1 is the rms value of the fundamental current component.

A harmonic injection technique which reduces the line frequency harmonics of the three phase rectifier has been implemented in this thesis. The proposed scheme deals with the fifth harmonic current injection technique using a shunt active power filter topology, which acts as a source of harmonic current that can be injected into the rectifier input. Its main component is a Current Source Inverter (CSI) that includes a DC link. The CSI is connected to the point of common coupling (PCC) via an inductance. The main purpose of an active power filter is to compensate distorted currents so that the fundamental frequency component dominates in the line current.

The work involved in the design of input filters which is significantly different from those involved in the design of input filters for DC-DC power converters. In many cases, the EMI and power factor requirements are impossible to meet using the existing filtering technology. This thesis will eliminate the need for the use of high-order filters to achieve the required EMI attenuation and attain desired level of power factor. The input filter provides a significant filter size reduction over the standard filter designs, minimizes the filter-power converter interaction and maintains good converter power efficiency.

1.2 Literature review

It is been continuous interest of researchers to meet a cost effective and economical solution to mitigate harmonics generated by rectifiers. A number of passive and active current wave shaping techniques [3-14] have been suggested in the past. One approach is to use three single phase power factor corrected rectifier in cascade [12]. The main advantage of this configuration is that well-known single phase power factor correction techniques can be used in three phase applications. However, the 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 processing to lower the cost.

Amongst the three phase ac-dc rectifiers, boost type topology is frequently used because of continuous input current and high output voltage. Basically, two topologies are popular:

1. A six switch full bridge boost rectifier
2. 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 current rating of switches used [13-15]. However, this circuit is complicated in power stage and control, making it expensive for medium and high power levels (5-10 kilowatts and above). The second one uses six diodes and one switch to control input currents and output power [4, 16]. 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 efficiency because the reverse recovery related losses of the boost diodes are eliminated. In a Discontinuous Conduction Mode (DCM) PWM boost rectifier is implemented with the conventional constant frequency low bandwidth output voltage feedback 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 720V and the input phase voltage is 230V, the maximum power of the converter is limited to 4.5KW 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.

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 [17-18]. To do this, the power switch must be turned on at the instant at which the boost diode 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 of the boost diode. In order to keep the average current [15] 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. In high power applications the switching loss of this scheme is high.

A simple technique that can be used to reduce the harmonic distortion of the input current is the harmonic injection method. The principles for achieving harmonic injection are described in [19-20]. The injected signal modifies the duty cycle of the rectifier switch so that the third order harmonic of the input current and the overall THD are reduced to meet the IEC 1000-3 requirement. However, from the afterward simulation and analysis it would be shown that Third order harmonic has a little effect on the THD of the input current. Hence injection of third harmonic current is not the appropriate method.

A low cost harmonic injection method for single switch three phase DCM boost rectifier and it’s implementation are presented in [22]. To reduce the fifth order harmonic and improve THD 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 the line cycle. The injected voltage signal is proportional to the ac component of the rectified three phase line to line input voltage. As a result, the injected signal is naturally synchronized with the three phase line to neutral input voltage. 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:

A three phase rectifier circuit with resistive load has been investigated for power factor improvement by harmonic current injection by a static VAR compensator type rectifier-inverter connected capacitor. Previous works have used third harmonic injection and the source was converted to a current source. In the present investigation rectifier inverter circuit has been used for charging a capacitor taking VAR from the source in the rectifier mode of the inverter and the stored charge has been used as a source of the inverter to inject required harmonic current to shape the input current of the main rectifier to sinusoidal with good power factor. Instead of third harmonic, the dominant 5th harmonic of the rectifier input current has been taken to produce the reference wave of the sine pulse width modulated (PWM) inverter to inject the harmonic current.

The outcome of the investigation includes the following,

1. A scheme based on VAR compensation method Current injection scheme,
2. A PWM modulator circuit for inverter switching,
3. A low pass filter for inverter input, with lower THD,
4. A scheme of rectifier with lower THD input current maintaining good power factor and efficiency, and
5. Simulation results.

1.4 Thesis Outline:

The organization of this thesis is as follows. The second chapter involves a system level study of Active Shunt Filter. It describes the operation principle of the APF implementation as a current source inverter, provides the theoretical analysis of the filter performance, and based on harmonic analysis, it is found that dominant harmonic in the three phase rectified load is the fifth order harmonic. The input and output voltage and current waveform of the non linear rectifier circuit with and without passive filter are studied and analyzed by a software simulation.

Current control method, which is more critical part of PAF is also described in this chapter. The modulator applicable in practice and its design issue and implementation are investigated. A PWM Modulator is presented to modulate the fifth harmonic frequency and inject the same to the input. A switching ripple filter (SRF) topology is analyzed to sink the high frequency switching harmonics created by the CSI. SRF is mandatory in this application since the PAF is directly connected to the utility grid and high frequency voltage pulses created by CSI result in high frequency distortion on the PCC voltage [23], [24], [25]. Spice based computer simulation of the total scheme is discussed and analyzed in the third chapter. The final chapter summarizes the contributions of the thesis and provides the concluding remarks and recommends for possible future work.

CHAPTER 2
The Parallel Active Filter System

2.1 Introduction

Tuned LC and high pass shunt passive filters were adopted as a viable harmonics cancellation solution [26] for a long time. Insufficient passive filter characteristics and resonant amplification of harmonics due to mistuned components and the use of power electronic devices increased the popularity of multilevel parallel, series and hybrid active power filters (APF) [27-32]. One of the mostly used active filters is the Parallel Active Filter (PAF).

2.2 Characteristics Analysis and Application consideration of the Parallel Active Filter

2.2.1 Harmonic producing Nonlinear loads

In order to understand the characteristics and application consideration of the Parallel Active Filter, it is important to discuss the general characteristics of nonlinear three phase rectifier loads. Since many industrial loads with high VA ratings are fed from 3-phase 3 wire AC utility grid and 3-phase diode rectifiers, the discussion will be on the characteristics of 3-phase diode rectifiers as nonlinear loads. These loads are sources of harmonic currents. Figure 2.1 illustrates a typical 3-phase diode rectifier with a resistive load on the DC side. The harmonic current content of the rectifier input current (load current) is less dependent on the AC side with a typical THD value of 25-30%. Therefore, this type of load behaves like a current source and called as harmonic current source type nonlinear load.

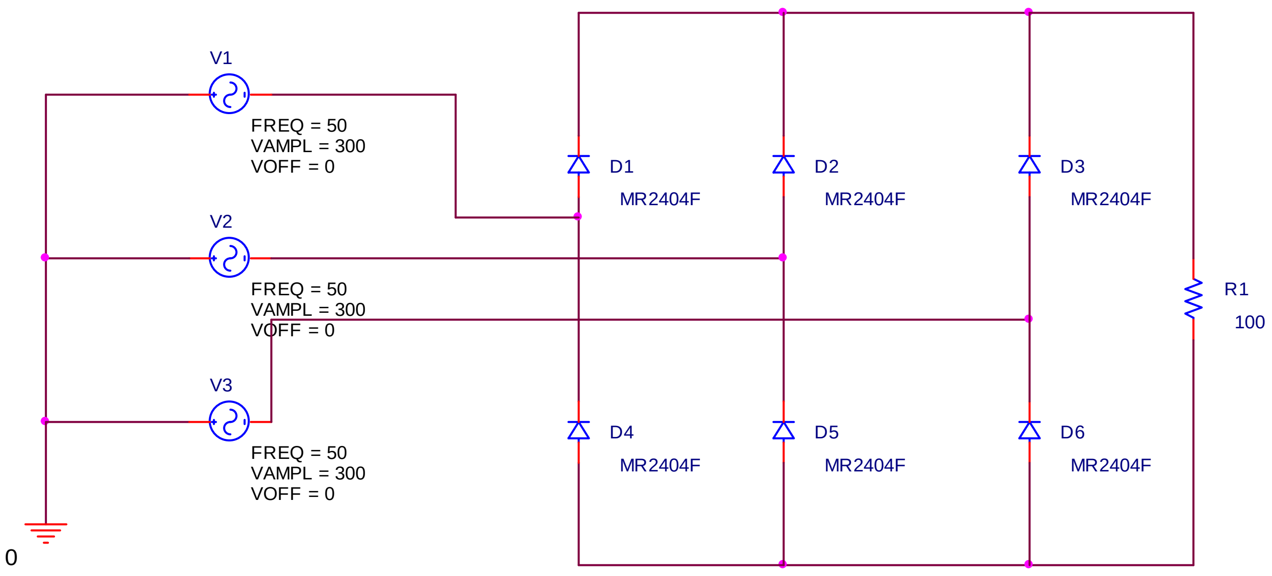
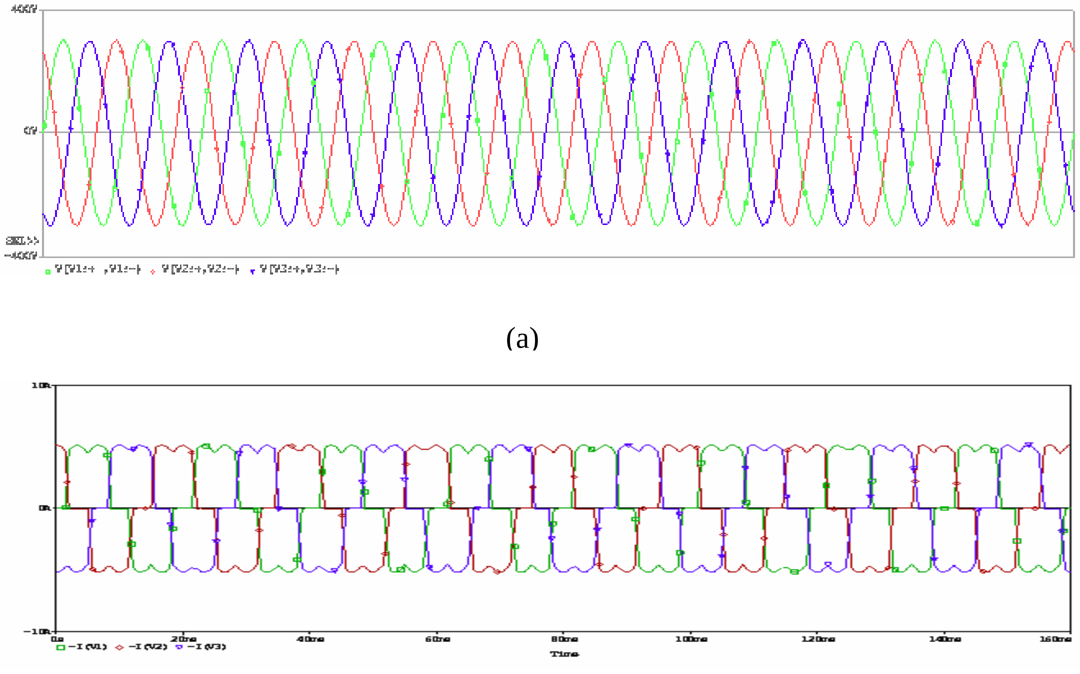


Figure 2.1: A three phase Full Wave Rectifier with resistive load

In figure 2.2 the PSpice simulation results of a nonlinear rectified load are presented, where the input voltage and the current waveform are shown.



(a)

(b)

Figure 2.2: (a) Input line voltages of three phases (b) Input line currents of three phases of the rectifier with resistive load.

The output voltage and the load current are showed in figure 2.3

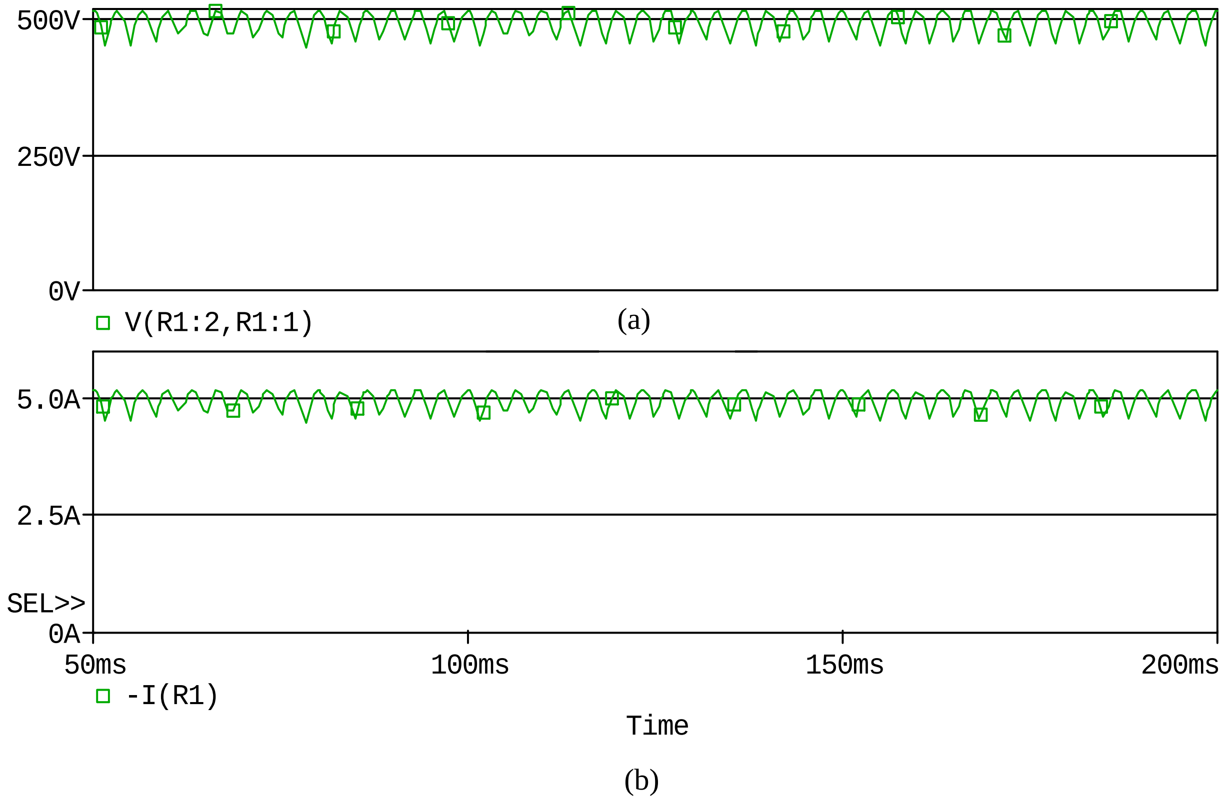


Figure 2.3: (a) Output Voltage (b) Output current of the three phase rectifier with resistive load

The expression for the Fourier series of the input current of a three phase rectifier with resistive load is,

i(t)= $\frac{2\sqrt{3}}{\pi} I_0 (Cos\omega_0 t - \frac{1}{5}Cos5\omega_0 t + \frac{1}{7}Cos7\omega_0 t - \frac{1}{11}Cos11\omega_0 t + \frac{1}{13}Cos13\omega_0 t - ....)$ (2.1)

The Fourier series indicates that the dominant harmonics are 5^{th} and 7^{th} and not the 3^{rd} as mentioned by many researchers [33].

Table 2.1: Table of Fourier components of the three phase input currents of rectifier load:

Frequency (Hz)	I(V1)	I(V2)	I(V3)
100	.2662	.07877	.3339
150	.3215	.269	.07985
200	.2727	.06458	.3163
250	1.187	1.002	1.089
300	.2748	.1148	.1618
350	.3229	.6625	.4873
400	.1849	.08583	.2547
450	.2411	.219	.1451
500	.1966	.0566	.2155
THD %	27.82	24.15	25.86

From Fourier analysis of simulation output file the percentage of Total Harmonic Distortion has been found to be 27.82 %. Table 2.1 provides the components of input current of 3phase rectifier and it is very clear that the fifth harmonic is the dominant harmonic. From the Fourier series expression and simulated harmonic of 3-phase rectifier input current third harmonic current is definitively concluded to be absent.

Power factor and Efficiency can be calculated from the following procedure:

P_{in} = AVG (VI)…………………….. (2.2)

P_{in} = 850W (derived from the simulation)

P_{out} = AVG (V (R1:2, R1:1)*-I(R1)) ……………… (2.3)

= 2450W (derived from the simulation)

$$V_{irms} = \frac{300}{\sqrt{2}} = 212.132\text{V}$$

I_{inrms} = RMS (I(V_1))………….. …………………. (2.4)

= 4.1amps (derived from the simulation)

$$\text{Input pf} = \frac{P_{in/phase}}{V_{irms/phase} \times I_{irms/phase}} \quad \text{………………………} \quad (2.5)$$

$$= \frac{850}{212.132 \times 4.1}$$

= .98

$$\eta = \frac{P_{out}}{P_{in}} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (2.6)$$

$$= \frac{2450}{850 \times 3}$$

$$= .96$$

$$= 96\%$$

2.2.2 Three phase rectifier load with conventional passive filters

In order to correct the power factor, passive filter method is studied first for later comparison with the results of proposed scheme. An example of the use of passive filter is shown in the Figure 2.4. Inductors of value of 30mH and delta connected three capacitors of the value of 20uF are connected at the input side of the three phase rectifier. From the PSpice simulation result the waveform of the input voltage, output voltage, input current and the output current are obtained and presented in the Figures 2.5 and 2.6,

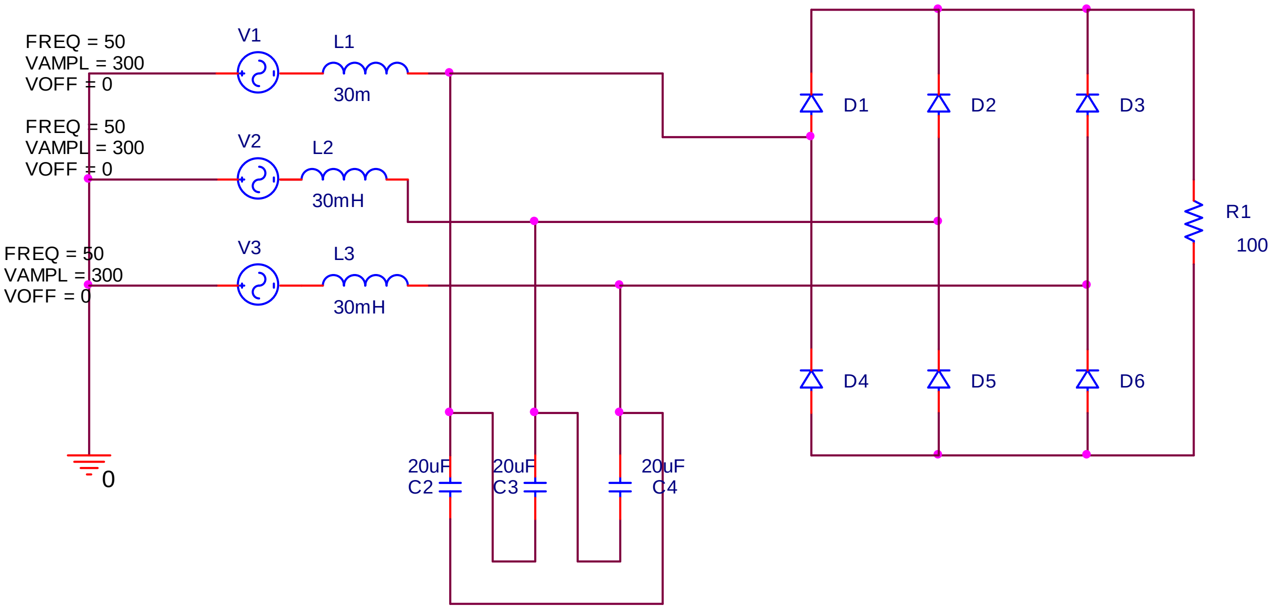
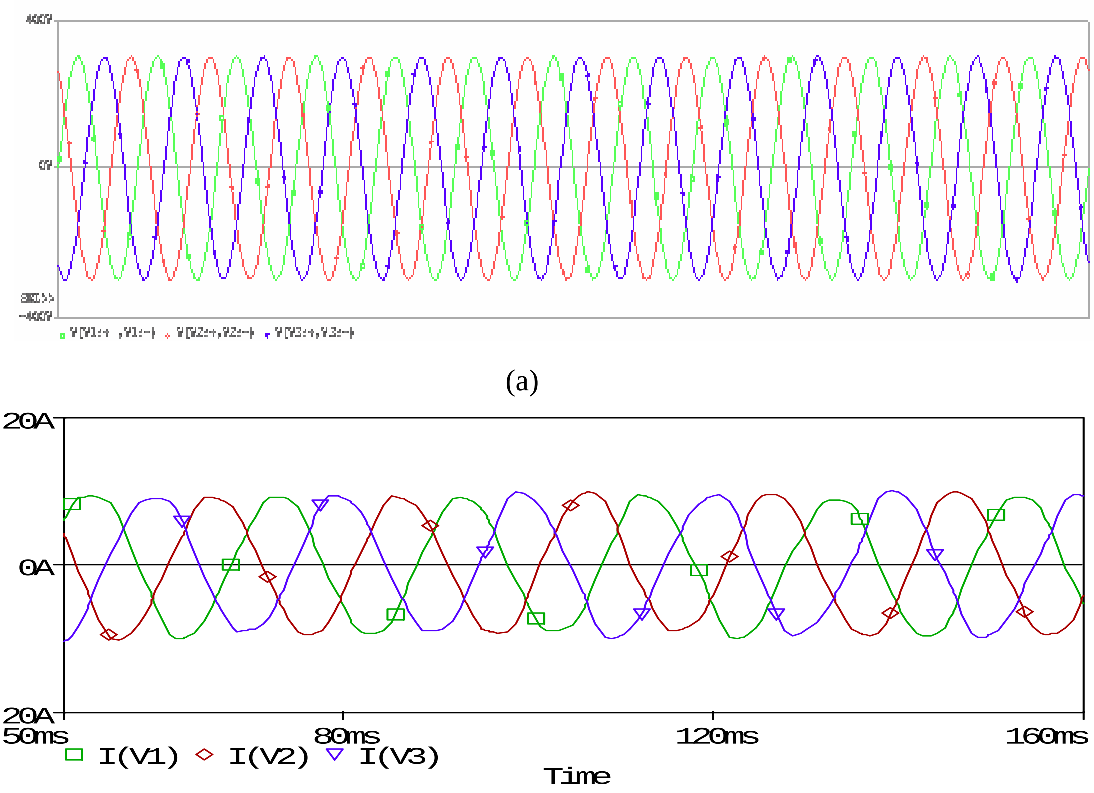


Figure 2.4: A three phase rectifier load with passive input filter (resistive load).



(a)

(b)

Figure 2.5: (a) Input line voltages of three phases (b) Input line currents of three phases of the rectifier with passive filter

The waveform shows that the harmonic nature of the input current has improved because of the addition of the input filter. To achieve this result a large filter is used. This large filter at the input would affect voltage magnitude considerably due to their high impedance. One of the objectives of this research is to minimize the value of the filter keeping the THD at the IEEE standard. The power factor and the efficiency can be calculated as,

P_{in} = AVG (VI) …………… (2.7)

P_{in} = 1200W (derived from the simulation)

P_{out} = AVG(V(R1:2,R1:1)*-I(R1)) ……………. (2.8)

= 3550 W (derived from the simulation)

$$V_{irms} = \frac{300}{\sqrt{2}} = 212.132V$$

I_{inrms} = RMS ($I(V_1)$)…………… (2.9)

= 6.9amps (derived from the simulation)

Input pf $= \dfrac{P_{in/phase}}{V_{irms/phase} \times I_{irms/phase}}$ ………. (2.10)

$$= \frac{1200}{212.132 \times 6.9}$$

= .81

$\eta = \dfrac{P_{out}}{P_{in}}$ ……………….. (2.11)

$$= \frac{3550}{1200 \times 3}$$

= .986

Table 2.2: Table of major Fourier components of input current of three phase rectifier with passive filter:

Frequency (Hz)	I(V1)	I(V2)	I(V3)
100	.2771	1.972E-01	1.118E-01
150	2.167E-02	1.636E-01	1.582E-01
200	2.323E-02	1.022E-01	1.092E-01
250	2.161E-01	2.753E-01	2.914E-01
300	4.685E-02	1.544E-02	6.155E-02
350	1.280E-02	3.198E-02	3.916E-02
400	4.456E-02	1.821E-02	6.272E-02
450	3.482E-02	1.728E-02	3.783E-02
500	2.929E-02	9.662E-03	2.901E-02
THD%	3.71	3.96	3.88

From the tabulated values it is shown that THD is reduced to 3.71%. From the earlier calculation the power factor is decreased compared to that of the three phase rectifier circuit without input filter. This is also evident from the shift of input voltage and input current of Fig 2.5.

2.2.3 Harmonic Injected Three phase rectifier Load without passive input filter:

2.2.3.1 Three phase rectifier load with 5th and 7th harmonics:

In the input current of a three phase diode rectifier the dominant Harmonics are the 5th and 7th harmonics. The THD can be improved by injecting them directly in opposition in the input line. The three phase rectifier circuit and the current sources circuit of 5th and 7th harmonic injection are shown in the Figure 2.7.

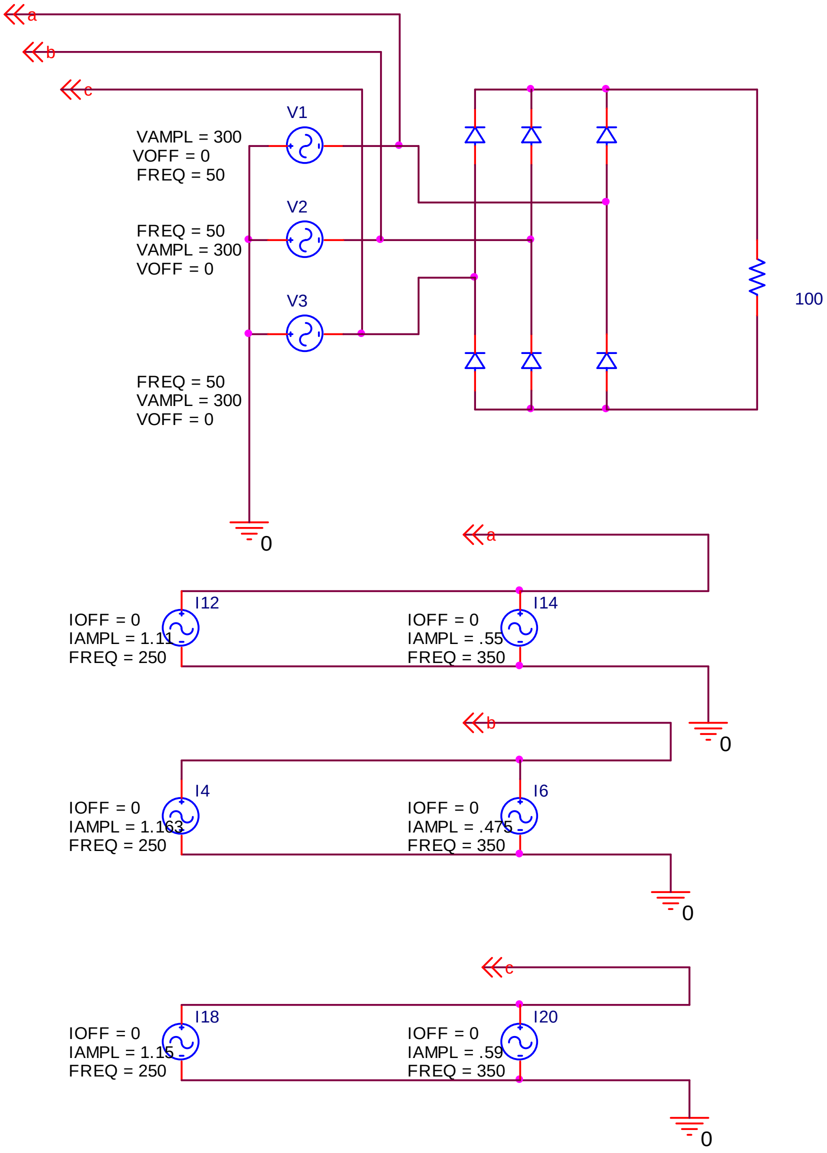
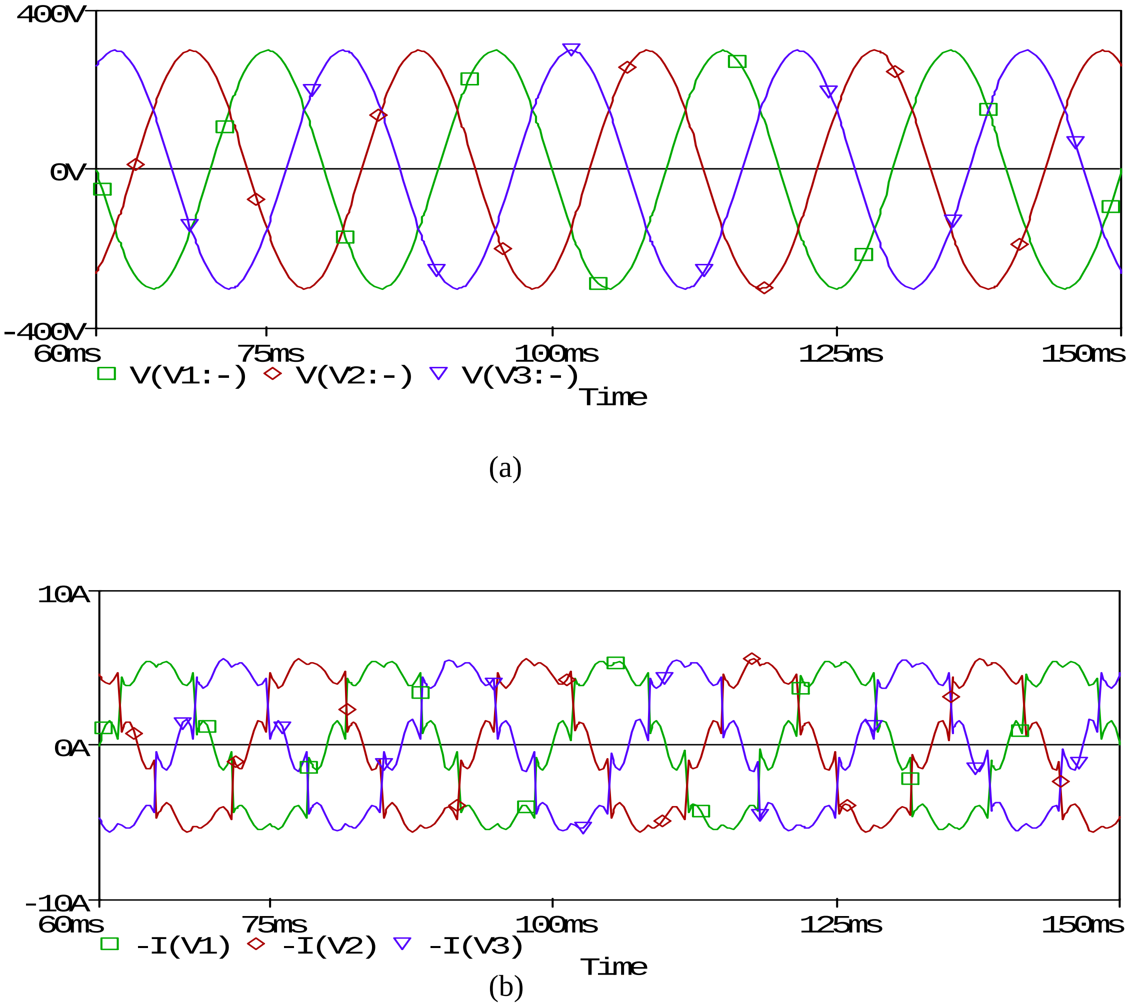


Figure 2.7: Three phase rectifier circuit with injection of 5th & 7th Harmonics.

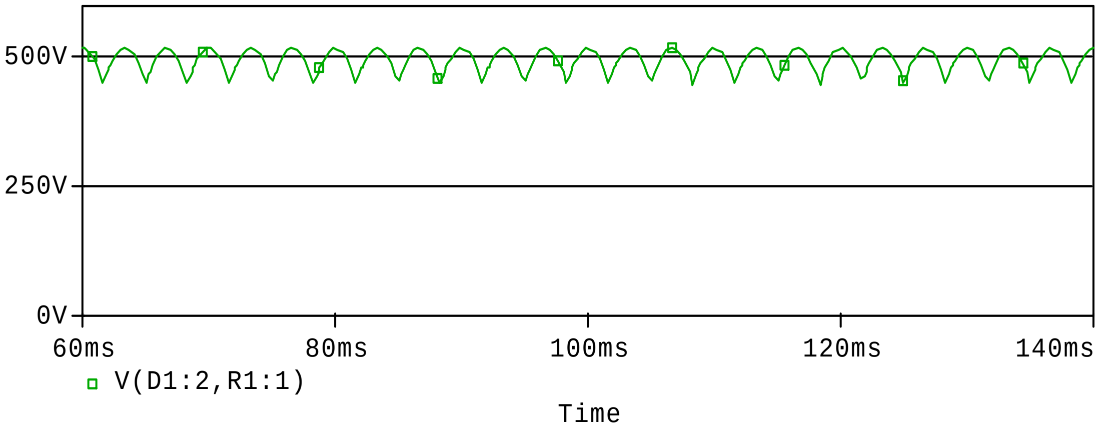
From the simulation of PSpice the input Voltage, Input Current, Output Voltage and Output Current can be obtained and shown in Figure 2.8 and 2.9:



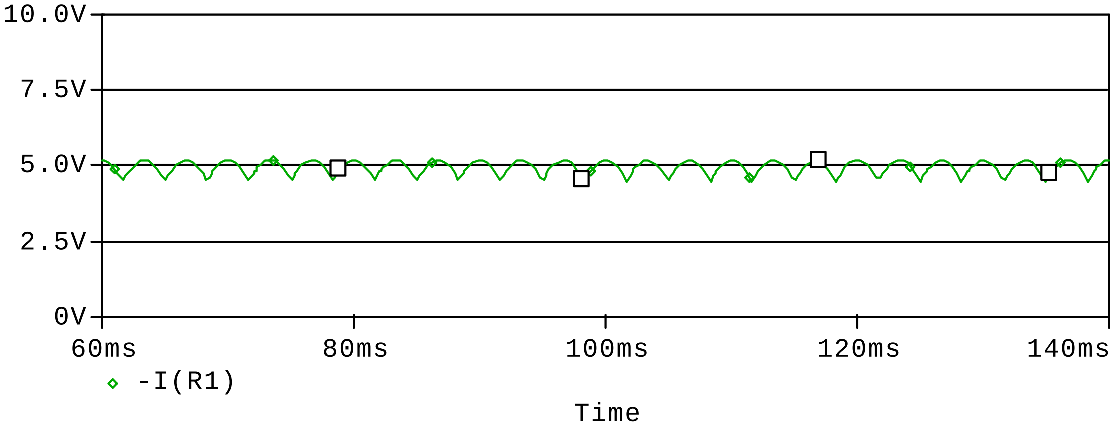
(a)

(b)

Figure 2.8: (a) Input line voltages of three phases (b) Input line currents of three phases of the rectifier with 5th & 7th harmonic current injection.



(a)



(b)

Figure 2.9: (a) Output voltage (b) Output current of three phase rectifier with 5th & 7th harmonic current injection

2.2.3.2 Three phase rectifier load with injection of 5th harmonic current:

Though in a three phase nonlinear load like diode rectifier, the dominant Harmonics are the 5th & 7th harmonics, it is found by PSpice simulation, that the 5th harmonic has significant affect in improving the THD. The three phase rectifier circuit and the current sources circuit of 5th harmonic injection are shown in the Figure 2.10:

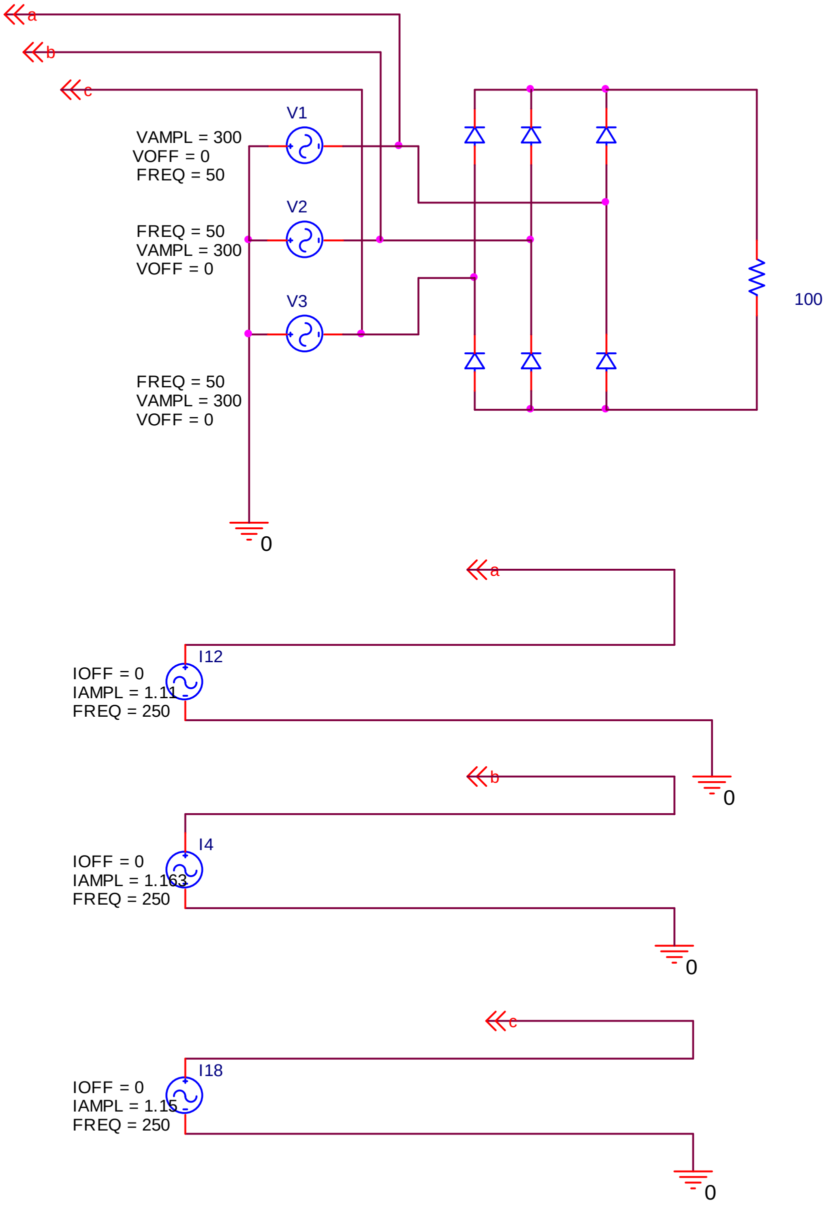
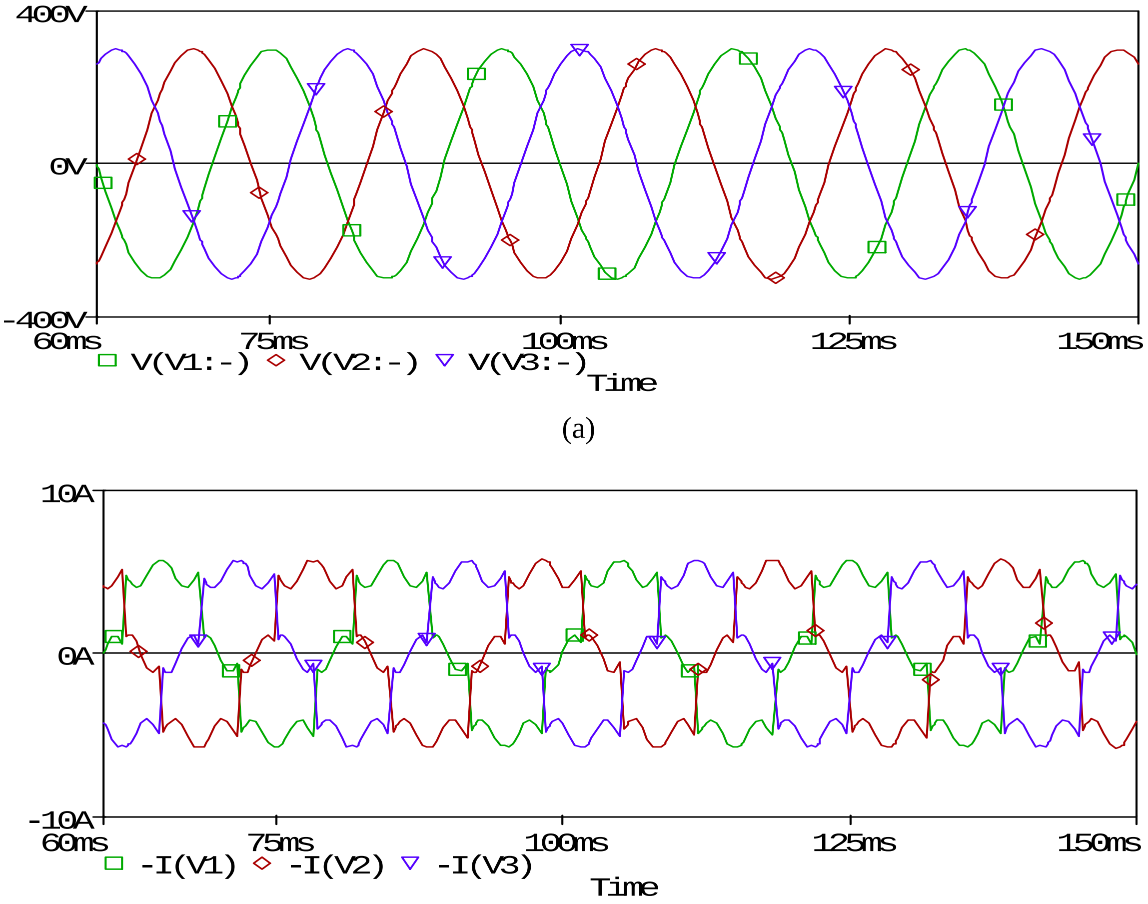


Figure 2.10: Three phase rectifier circuit with injection of 5th harmonics.

From the simulation of PSpice the input voltage, input current, output voltage and output current can be obtained and shown in Figure 2.11 and 2.12:



(a)

(b)

Figure 2.11: (a) Input line voltages of three phases (b) Input line currents of three phases of the rectifier with 5th harmonic current injection.

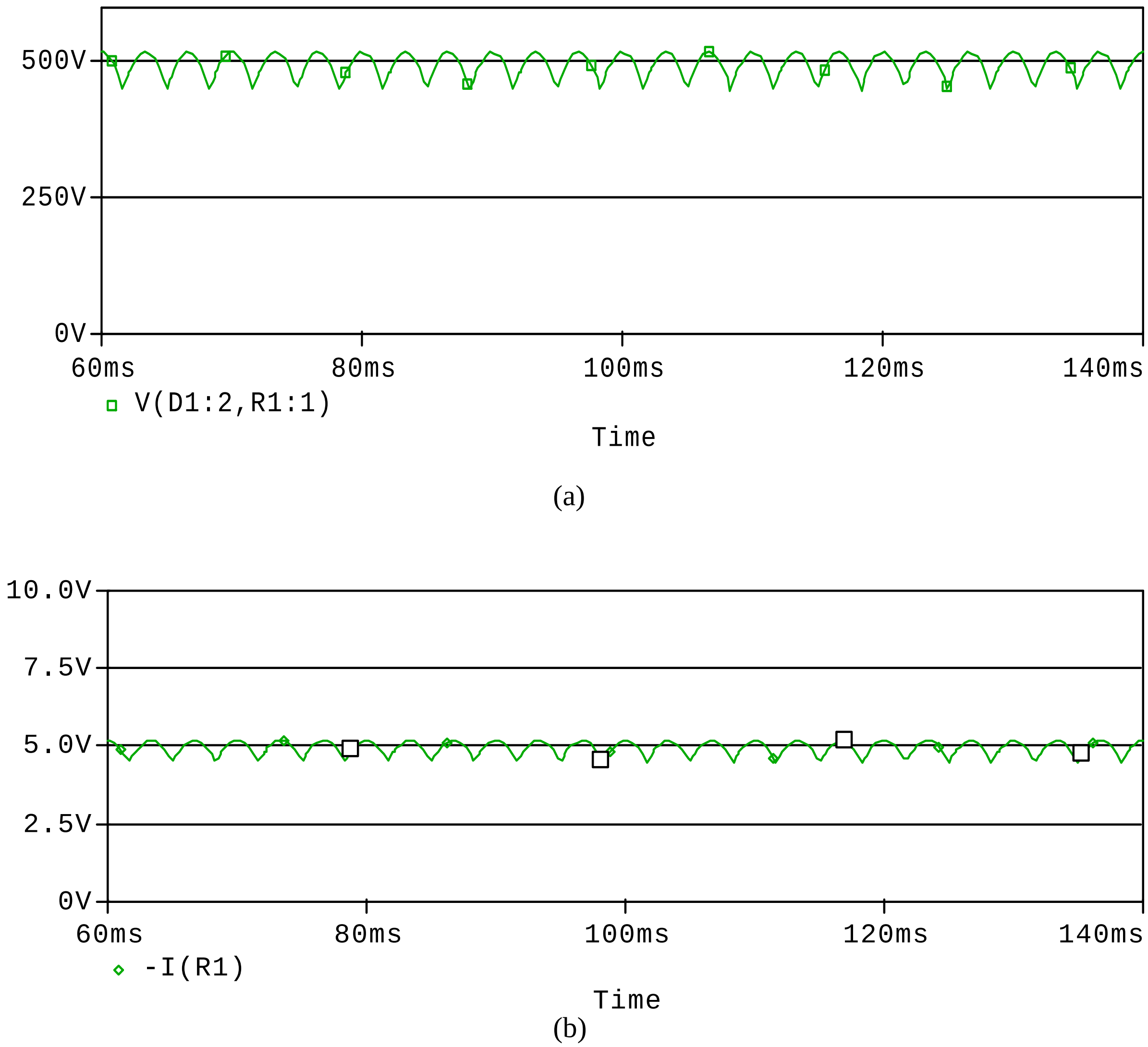


Figure 2.12: (a) Output voltage (b) Output current of three phase rectifier with 5th harmonic current injection

At this point, the power factor and efficiency for the three phase rectifier with the injection of 5th and 7th Harmonic current and the power factor Efficiency for three phase rectifier with the injection of only 5th harmonic can be calculated by equation no. 2.4 and 2.5 and a comparative evaluation is given in Table 2.3.

Table 2.3: Comparison of the circuit parameters between three phase rectifier with 5th & 7th harmonic injected circuit and with 5th harmonic injected circuit:

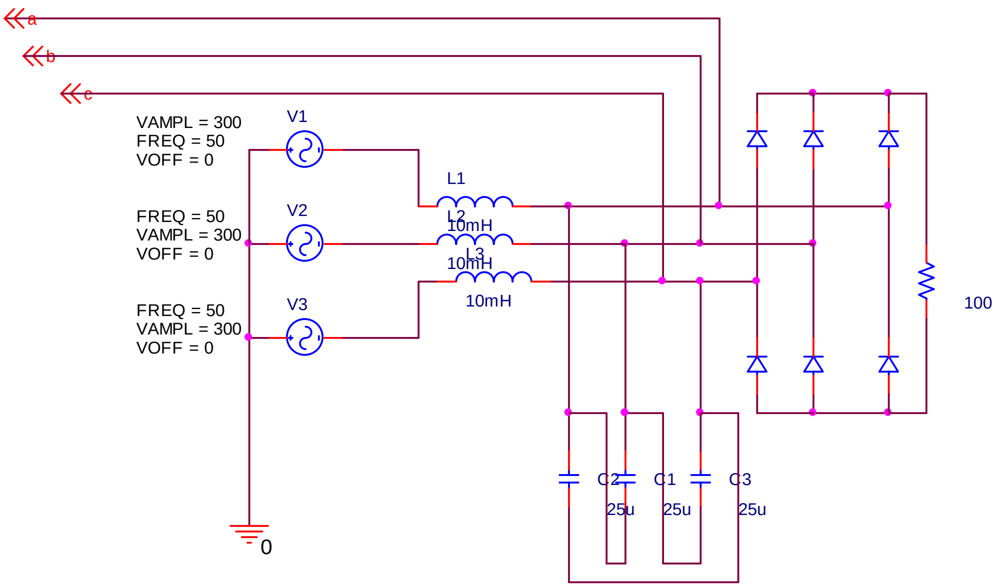
Parameters	three phase rectifier with 5th & 7th harmonic injection without input filter	three phase rectifier with 5th harmonic injection without input filter
L_{in}	-	-
C_{in}	-	-
V_{inrms}	212.132 V	212.132 V
I_{inrms}	4.0 A	4.0 A
V_{out}	510V	520V
I_{out}	5.1A	5.2A
THD%	15.2	17.71
η	98.8%	99.4%
Pf	.972	.97

From the tabulated figures it can be seen that the injection of 7th harmonic has a little affect on the THD improvement and the power factor and efficiency is quite same. Although only the injection of harmonic current is not enough to keep the THD below 10%, which is the IEEE 519-1992 standard of THD for nonlinear loads.

2.2.4 Harmonic injected three phase rectifier Load with passive input filter:

2.2.4.1 Three phase rectifier load with 5th and 7th harmonics injection and input passive filter:

The THD can be improved by injecting the dominant harmonic currents directly in the input line as it was found in the earlier results. To reduce the problem of efficiency and pf degradation, the three phase rectifier circuit with the injection of 5th and 7th harmonic current is investigated with the passive filter. The circuit is shown in the Figure 2.13. The harmonic current generator circuit is shown in figure 2.14.



2.13: Three phase rectifier with 5th &7th harmonic current injection and input passive filter

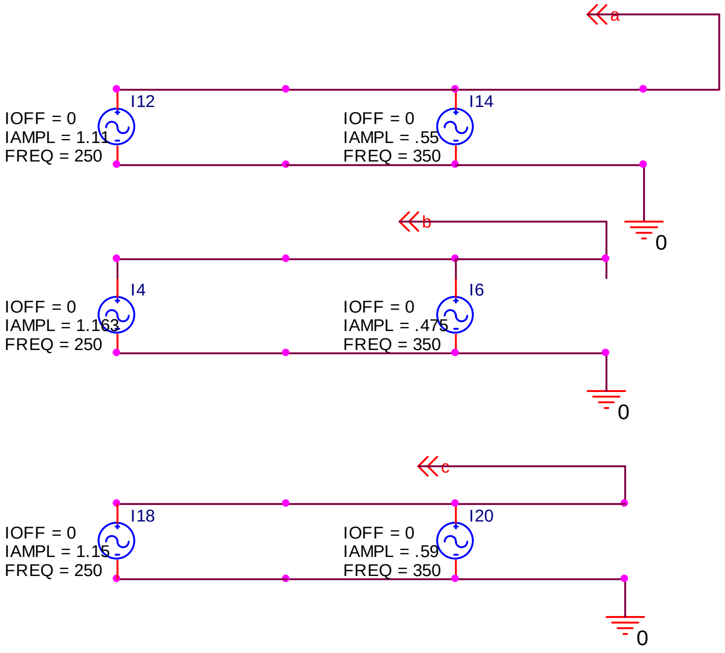
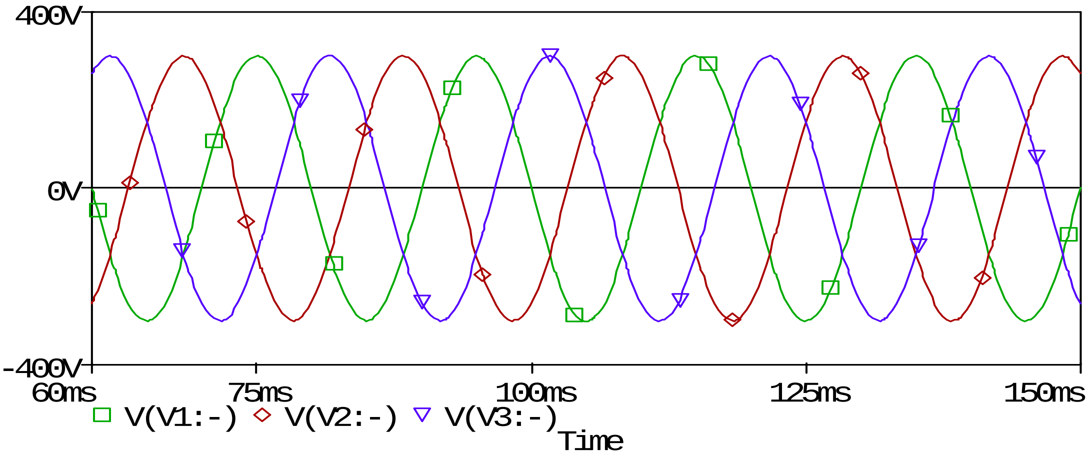
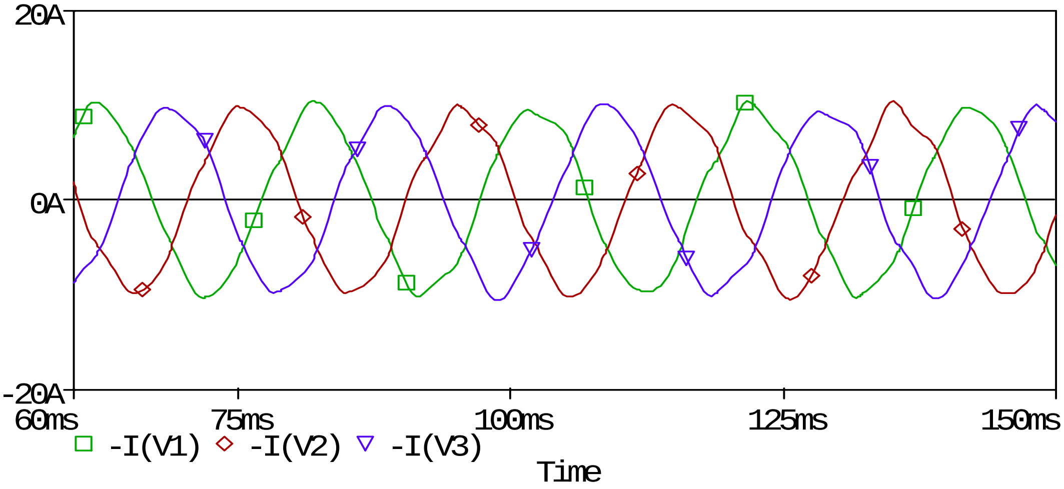


Figure 2.14: The of 5th & 7th harmonics injection circuit.

From the simulation of PSpice the input Voltage, Input Current, Output Voltage and Output Current are obtained and are shown in Figure 2.15 and Figure 2.16:

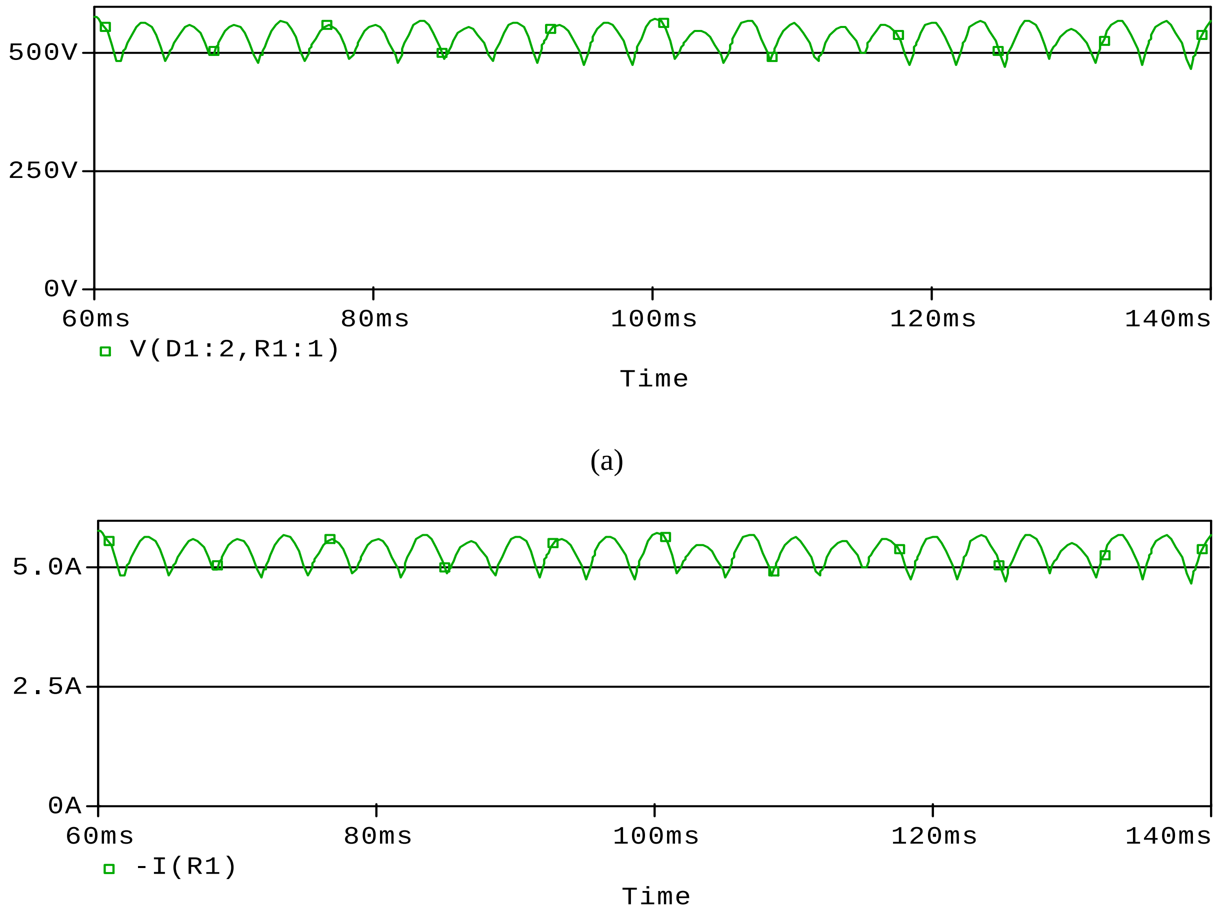


(a)



(b)

Figure 2.15: (a) Input line voltages of three phases (b) Input line currents of three phases of the rectifier with 5^{th} & 7^{th} harmonic current injection and input passive filter.



(a)

(b)

Figure 2.16: (a) Output voltage (b) Output current of three phase rectifier with 5th & 7th harmonic current injection and input passive filter.

2.2.4.2 Three phase rectifier load with injection of 5th harmonic current and Input passive filter:

Though in a three phase diode rectifier, the dominant Harmonics are the 5th & 7th harmonics, it is found by PSpice simulation, that the 5th harmonic has significant affect in improving the THD by injecting directly in opposite in the input line. The three phase rectifier circuit and the 5th harmonic generating current source circuit for injection is shown in Figure 2.17.

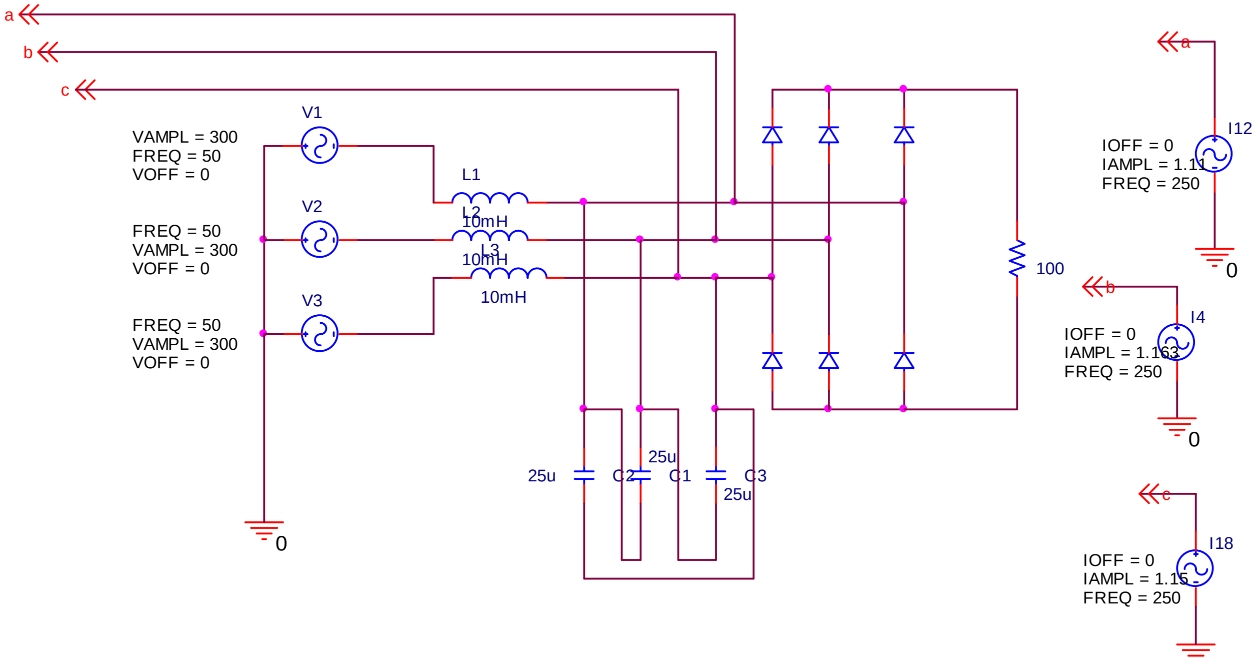
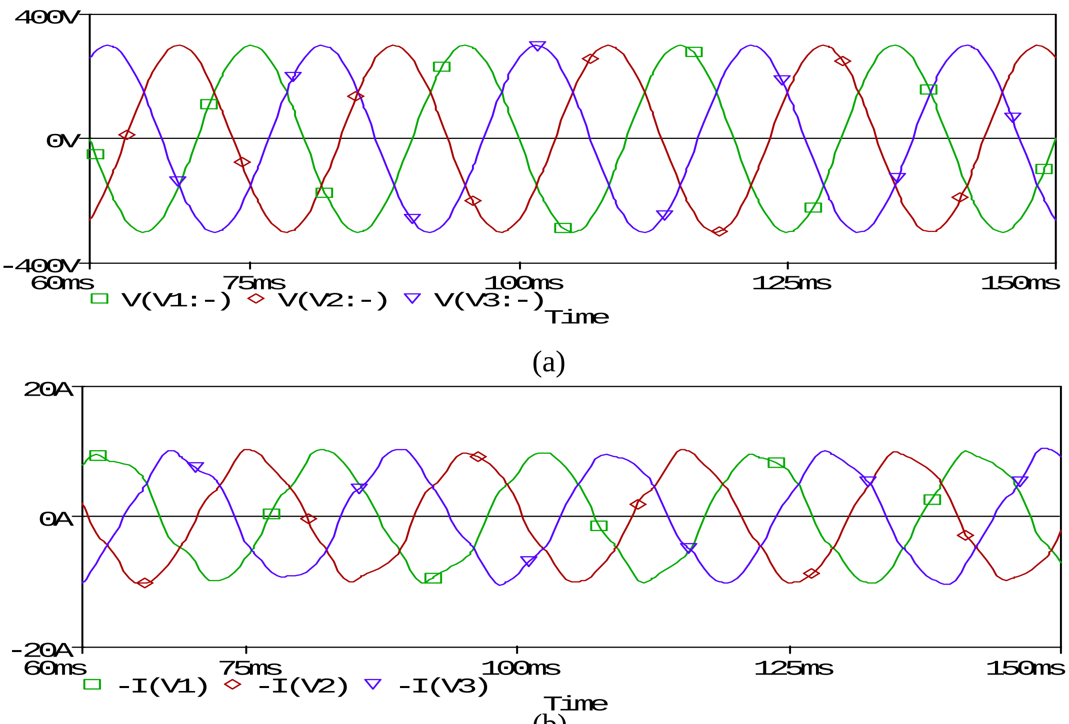


Figure 2.17: Three phase rectifier with 5th harmonic current injection and input passive filter and 5th harmonics current generator circuit.

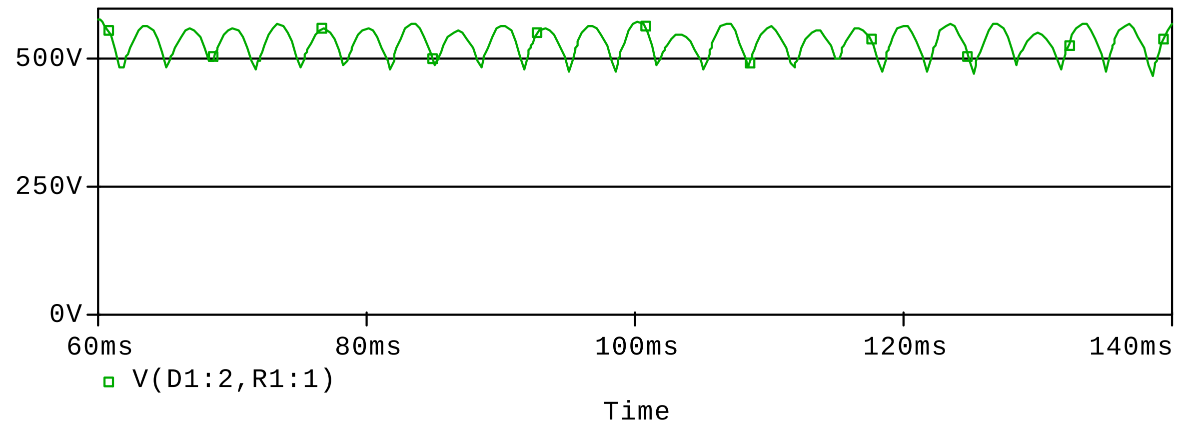
From the simulation of PSpice the input Voltage, Input Current, Output Voltage and Output Current are obtained and are shown in Figure 2.18 and 2.19:



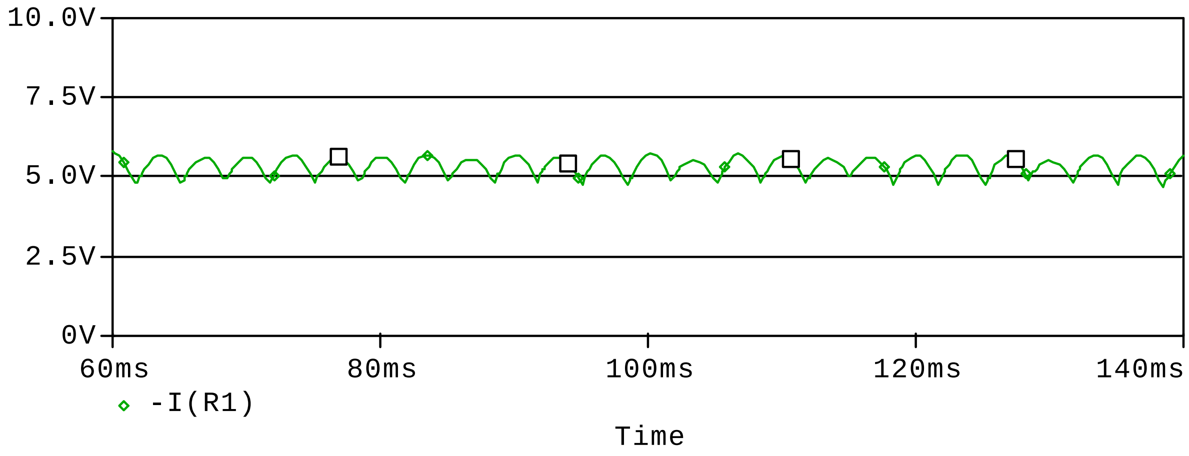
(a)

(b)

Figure 2.18: (a) Input line voltages of three phases (b) Input line currents of three phases of the rectifier with 5th harmonic current injection and input passive filter.



(a)



(b)

Figure 2.19: (a) Output voltage (b) Output current of three phase rectifier with 5th harmonic current injection and input passive filter

The power factor and efficiency for the three phase rectifier with the injection of 5th Harmonic current including Input passive filter and the power factor and Efficiency for 5th harmonic current injected three phase rectifier with input passive filter is calculated by the equations no. 2.5 and 2.6 and a comparative evaluation is placed in the Table 2.4.

Table 2.4: Comparison of the circuit parameters between three phase rectifier with 5th harmonic injection without input filter and three phase rectifier with 5th harmonic injection without input filter

Parameters	three phase rectifier with 5th & 7th harmonic injection		three phase rectifier with 5th harmonic injection	
	without input filter	with input filter	without input filter	with input filter
L_{in}	-	10mH	-	10mH
C_{in}	-	25uF	-	25uF
V_{inrms}	212.132	212.132V	212.132V	212.132 V
I_{inrms}	4.0A	7A	4.0A	5.5 A
V_{out}	510V	550V	520V	560V
I_{out}	5.1A	5.5A	5.2A	5.6A
THD %	15.2	7.59	17.71	5.354
η	98.8%	96.66%	99.4%	98.3%
Pf	.972	.6734	.97	.857

2.3 Topology description of The Parallel Active Filter:

The basic principle of active filters was established around 1970s [34], [35]. However, the idea could not become technologically and economically feasible until the last two decades when fast and cost effective semiconductor devices such as Insulated Gate Bipolar Transistors (IGBTs) and MOSFETs became available. Moreover, the advances in control theory and application of modern control methods in power electronics have played a significant role in the practical realization and commercial success of active filters. Modern active filters are superior in filtering performance since the basic principle of the active filter is to precisely inject to the system voltage/current harmonics of nonlinear loads with same magnitude and opposite sign so they cancel each other and clean waveforms are obtained at the power line. Active filters are also smaller in physical size and unlike traditional passive filters they have additional functions to harmonic filtering. They form effective solutions to many power quality problems. Depending on the active filter type, controllable reactive power compensation for power factor correction, voltage regulation, load balancing, voltage-flicker reduction, harmonic damping, harmonic isolation and/or their combinations could be provided.

Hybrid filters combine passive and active filters in various configurations in order to reduce initial cost and increase the efficiency of the filter structure. The basic principle of hybrid filtering is to improve the filtering capacity of a passive filter and to damp series and parallel resonances with a small rated active filter. In this proposed scheme, combination of a passive filter and active filter has been designed to compensate the Total harmonic distortion as recommended in IEEE standards.

To realize a current source for three-phase three-wire PAF, a Pulse Width Modulation (PWM) Current Source Inverter (CSI) with a dc link inductor is shown in Figure 2.20, where, CSI utilizes IGBTs with series connected diodes for reverse-blocking capability.

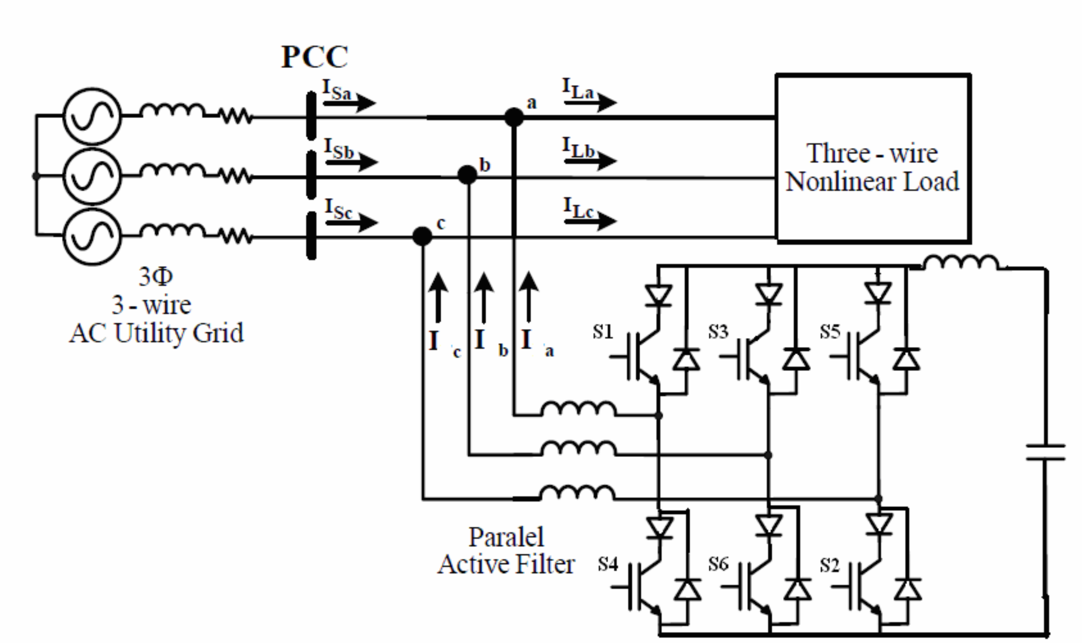


Figure 2.20: The power electronic circuit topology for 3-phase 3-wire PAF: PWM current source inverter.

A CSI filter generates current in the point of common connection (PCC) in order to cancel the harmonic current in the AC system, to correct the power factor and to balance the load. So, the AC distribution system only carries the active fundamental component of the load current. The main advantage of the current source inverter is that it increases the voltage towards the mains itself, so additional ac/dc and dc/dc converters may not be necessary. This results in less complexity of the system and it's control. In order to properly gate the power switches of a three-phase CSI topology, two main constraints should be met: 1) the ac side is mainly capacitive, thus, it must not be short circuited; this implies that, at most one top switch (S_1, S_3 or S_5) and one bottom switch (S_2, S_4 or S_6) should be closed at any time and 2) the dc bus is of the current-source type and, thus, it cannot be opened; therefore, there must be at least one top switch and one bottom switch closed at all times (Fig. 2.20). Both constraints can be summarized by stating that at any time, only one top switch and one bottom switch must be closed. The constraints are reduced to nine valid states in three-phase CSIs, where states 7–9 (Table 2.5) produce zero ac line currents. In this case, the dc-link current freewheels through either the switches S_1 and S_4, S_3 and S_6, or S_5 and S_2.

Table 2.5: Valid switch states for three CSI:

State	**State**	I_a	I_b	I_c
S_1, S_2 on ; S_3, S_4,S_5, S_6 off	1	i_{dc}	0	$-i_{dc}$
S_2, S_3 on ; S_4,S_5, S_6, S_1 off	2	0	i_{dc}	$-i_{dc}$
S_3, S_4 on ; S_2, S_5, S_6, S_1 off	3	$-i_{dc}$	i_{dc}	0
S_4, S_5 on ; S_6, S_1, S_2, S_3 off	4	$-i_{dc}$	0	i_{dc}
S_5, S_6 on ; S_1, S_2, S_3, S_4 off	5	0	$-i_{dc}$	i_{dc}
S_6, S_1 on ; S_2, S_3, S_4, S_5 off	6	i_{dc}	$-i_{dc}$	0
S_1, S_4 on ; S_2, S_3, S_5, S_6 off	7	0	0	0
S_3, S_6 on ; S_1, S_2, S_4, S_5 off	8	0	0	0
S_5, S_2 on ; S_6, S_1, S_3, S_4 off	9	0	0	0

CHAPTER 3
Fifth Harmonic Current Injection by Active Power Filter

3.1 Introduction:

This chapter describes a fifth harmonic current injection technique to control a three phase diode bridge rectifier input current by a Active Power Filter. The Active Power Filter is controlled by Pulse Width Modulation of pre-determined non sinusoidal fifth order harmonic current with a triangular wave. This process allows the compensation for current harmonics and maintains good input power factor of the rectifier and operates at satisfactory efficiency.

3.2 DC source for the inverter:

The average value of direct current of the inverter must be kept constant in order to ensure that the active filter provides the necessary reactive power emulating a resistive load for the AC mains. Some active power shall flow in the active filter in order to compensate for the switches and conduction losses in the switches and other parasitic losses. It is proposed that a combination of series inductor of 20mH and a capacitor of 100uF in each be used at the rectifier output to act as a CSI. The system has been developed based on static VAR compensation technique.

3.3 Pulse Width Modulator:

In the PAF application, a controllable AC voltage is required at the output terminals of the CSI to create voltage difference across the filter inductor and hence, to achieve a controllable current. The AC voltage reference (inverter voltage reference) is synthesized by carrier based PWM modulator that employs the per-carrier cycle volt-second balance principle to generate rectangular output voltage pulses that meet the output voltage requirement. Given the reference voltage, the inverter switches should be manipulated such that the reference volt seconds and output volt-seconds must be equal over each PWM cycle. PWM method to generate the switching signals for the inverter switches operate based on this principle. In the scalar PWM method, the voltage reference wave (modulation wave) is compared with a triangular carrier wave and the intersections define the switching instants for the switches of CSI. Here Selective Harmonic Elimination (SHE) technique has been used. This technique deals directly with the gating patterns of the CSI. It defines the gating signals in order to eliminate some predefined harmonics and control the fundamental amplitude of input current. In this scheme, only fifth harmonic frequency is directly modulated with a triangular carrier wave is proposed to eliminate a given number of harmonics. Waveform of The Pulse Width Modulator technique found by PSpice simulation is shown in Figure 3.1 and Figure 3.2.

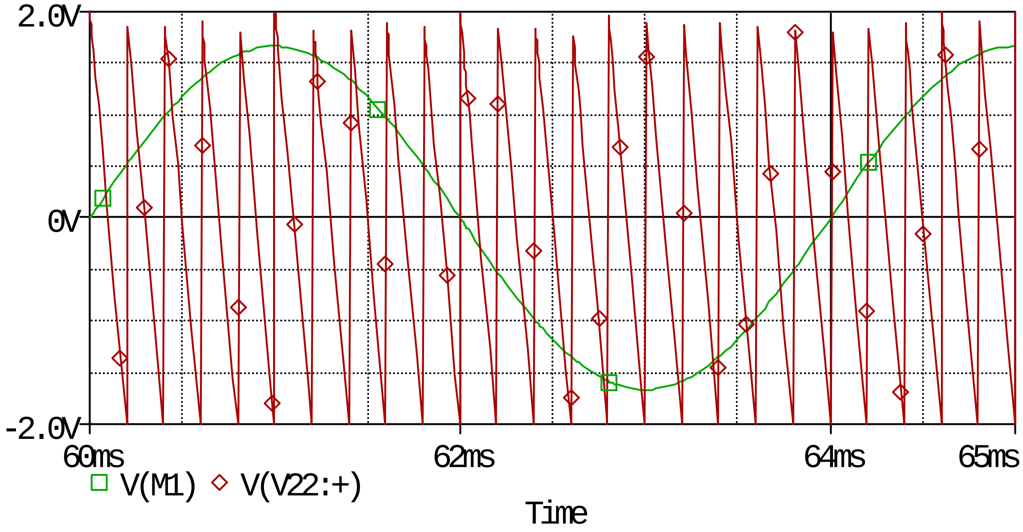


Figure 3.1: Pulse Width Modulation of fifth harmonic current and Triangular carrier Wave.

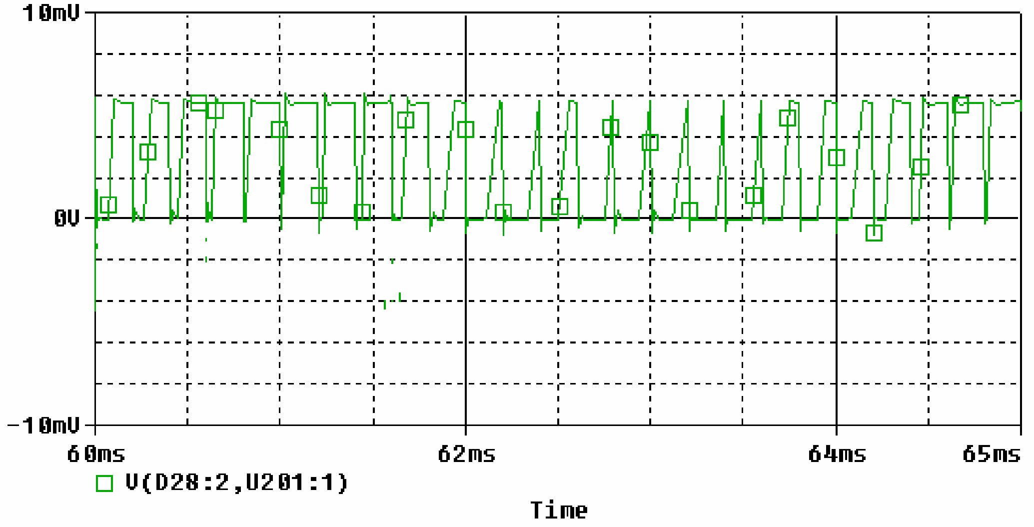


Figure 3.2: Switching Pulses for one switch of the Current Source Inverter.

3.4 Switching Ripple Filter Topology

The PWM voltage and current ripple generated by the CSI of the PAF power circuitry can spread to the power line through the PCC where the PAF system is coupled to the power system. High frequency switching harmonics create noise problems for other loads connected to the same PCC. Figure 3.3 illustrates a typical source current harmonic spectrum of a line current with f_{sw} of 5 kHz in a PAF application. The most dominant switching ripple currents appear at 5 kHz other than 250Hz (fifth harmonic to be injected).

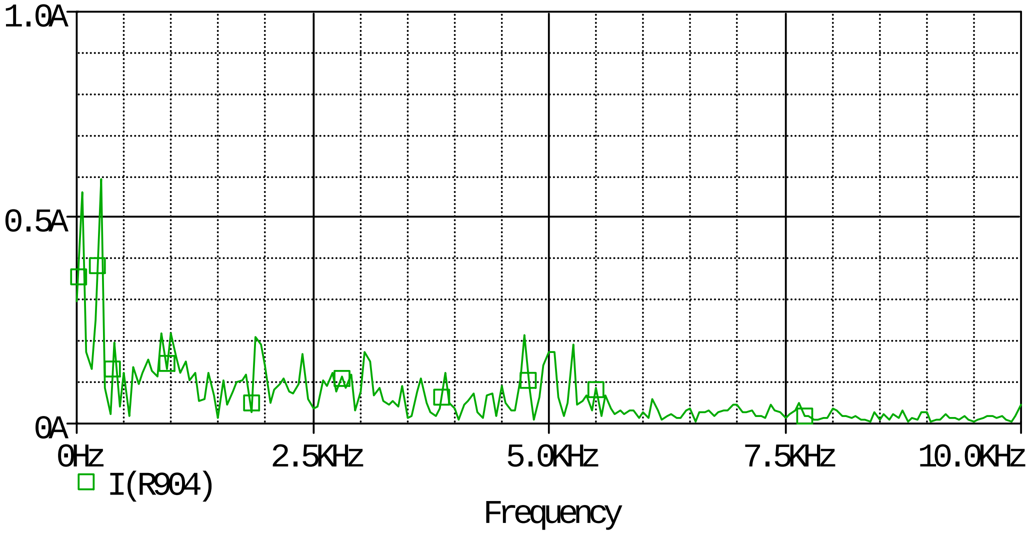


Figure 3.3 Typical line current harmonic spectrum in a PAF application

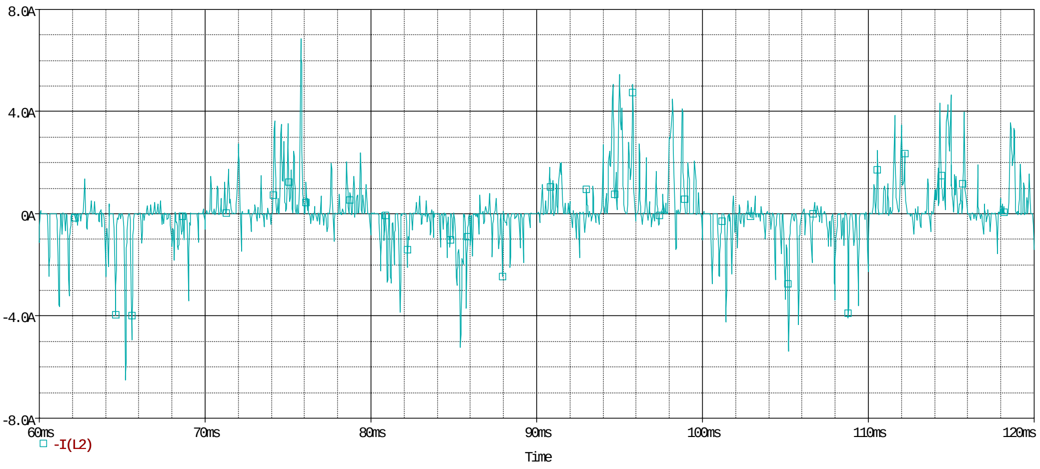


Figure 3.4: The output current of the CSI with inductor filter

In APF application that is proposed in this thesis, the tuned LCR type SRF illustrated in Figure 3.5 has been utilized for a switching ripple current free AC utility grid line (source) current.

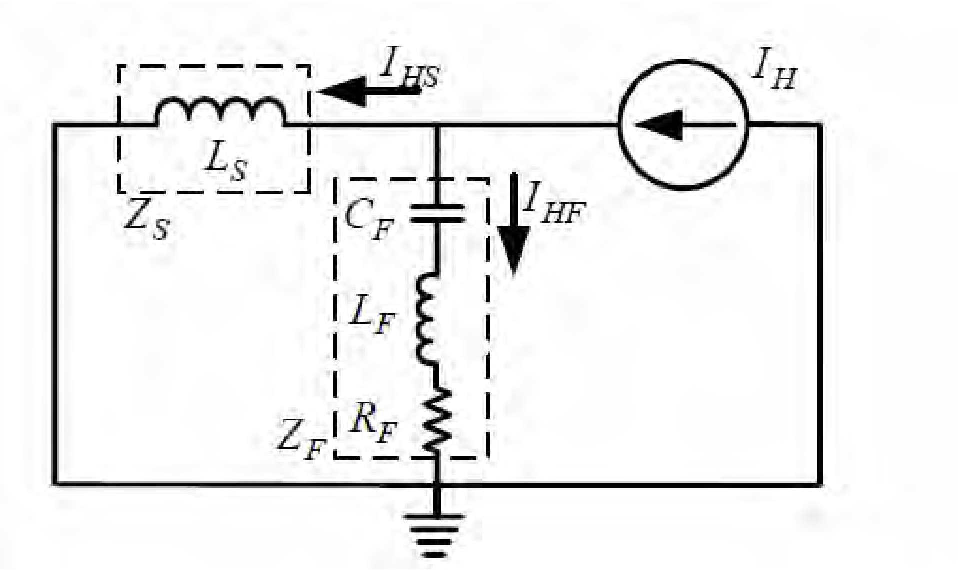


Figure 3.5: Equivalent circuit model of the load, PAF, tuned LCR type SRF, and AC utility grid at harmonic frequencies.

The series resonant frequency (f_s) of the filter is defined as

$$f_s = \frac{1}{2\pi\sqrt{L_f C_f}} \text{ ……….} \qquad (3.1)$$

where, L_f is the filter inductance and C_f is the filter capacitance. The impedances of C_f and L_f are equal in magnitude with opposite signs at f_s. Therefore they cancel each other and the total impedance of filter is equal to filter resistance R_f at f_s. Since the aim of the filter is to sink the switching ripple currents through its path by providing low impedance, the value of R_f should be low. Hence, the internal resistance of L_f typically constitutes the R_f value. By tuning f_s of the LCR filter to f_{sw}, the most dominant switching ripple currents at f_{sw} are filtered through the low impedance path.

When a tuned LCR filter is designed to sink the low frequency harmonics of the load current (conventional approach), the filter capacitor C_f is sized according to the reactive power demand of the load at the fundamental frequency. However, when it is utilized as

SRF, C_f is sized according to the attenuation of the second dominant switching ripple currents at $2f_{sw}$. The utilized R_f value for the filter is 1mΩ, Since the filter is tuned to 5 kHz, the impedance of the filter at 5 kHz is low. However, as the filter capacitor size decreases, the sharpness of the filter increases. This results in poor filtering of switching ripple currents at the sidebands of f_{sw}. As filter capacitor size decreases, the filter impedance at $2f_{sw}$ (10 kHz) increases, which means that the attenuation of the second dominant switching ripple currents at $2f_{sw}$ will be poor. Therefore, the capacitor size should be kept as high as possible for a better attenuation of the switching ripple currents.

As the capacitor size increases, the parallel resonant frequency (f_p) in (3.2), that occurs between the filter components and the line inductance (L_s) decreases. A low f_p value is undesired since it increases the possibility of the oscillations at this frequency, which is explained in the following. The f_p restricts the C_f size in tuned LCR type SRF design.

$$f_p = \frac{1}{2\pi\sqrt{(L_s + L_f)C_f}} \quad \ldots\ldots\ldots\ldots\ldots\ldots \qquad (3.2)$$

The parallel resonance condition can be explained by examining Figure 3.5 illustrating the equivalent circuit model of the load, PAF, SRF and AC utility grid (source) at harmonic frequencies. In Figure 3.5, the load and the PAF are modeled as a current source of I_H at harmonic frequencies. This current source of I_H models the uncompensated current harmonics at the range of the PAF bandwidth, the load current harmonics above the PAF bandwidth and the switching ripple currents of linear current regulators at f_{sw} and its multiples. By neglecting the AC utility grid voltage harmonics, the AC utility grid is modeled by the line inductance L_s at harmonic frequencies. Since the aim of SRF is to filter the switching ripple currents, the SRF current I_{HF} is desired to be switching ripple currents, which are the components of I_H. The line current I_{HS} is then desired to be the sum of the uncompensated current harmonics at the range of the PAF bandwidth and the load current harmonics above PAF bandwidth.

When f_p in (3.2) is chosen as 5 kHz for large C_f size and f_s in (3.1) is chosen as 10 kHz, two unknown circuit parameters C_f and L_f are found from two equations as

C_f = 25uF

L_f = 5 mH

for L_s value of 12 mH. Therefore, the design values of L_f and C_f are determined for the

PAF with f_{sw} of 5 kHz.

3.5 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 optocoupler circuit. Necessary circuits used for this purpose is shown in Figure 3.6, where gnd 4 and gnd 1 are separate grounds and gate pulses are connected to switches 1 and 4 of the power circuit. Similar arrangements are used for switches 3-6 and 5-2 pairs of the H bridge of the inverter.

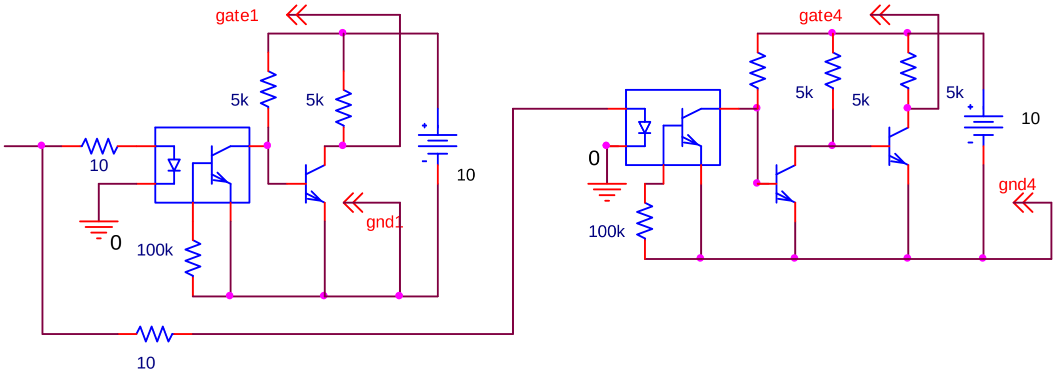


Figure 3.6: Circuit diagram of optocoupler for isolating gate signals.

3.6 The power circuitry of the overall system and result

The PAF performance is investigated by simulations. At first, the PAF computer simulation model is constructed. The nonlinear load connected to the AC utility grid for the PAF application is modeled. The performance criteria and system parameters of the PAF system are given. Once the whole system is modeled in the computer simulation environment, the performance of the CSI circuit as PAF is studied.

3.6.1 The complete circuit of proposed three phase rectifier compensated by Active CSI filter

The complete circuit of the proposed scheme is presented in this section. Figure 3.7 shows the main circuit with the Input voltage. The power circuitry consists of a rectifier with resistive load, SRF system and the CSI. For simulation purpose the following parameters are used:

Line voltage V_s = 300Volts

Line frequency f = 50Hz

Load Resistance R_l = 100 Ω

The modulating signal generator circuit is shown in Figure 3.8 and the Pulse width Modulator and Optocoupler circuit to isolate the switching circuit is shown in Figure 3.9.

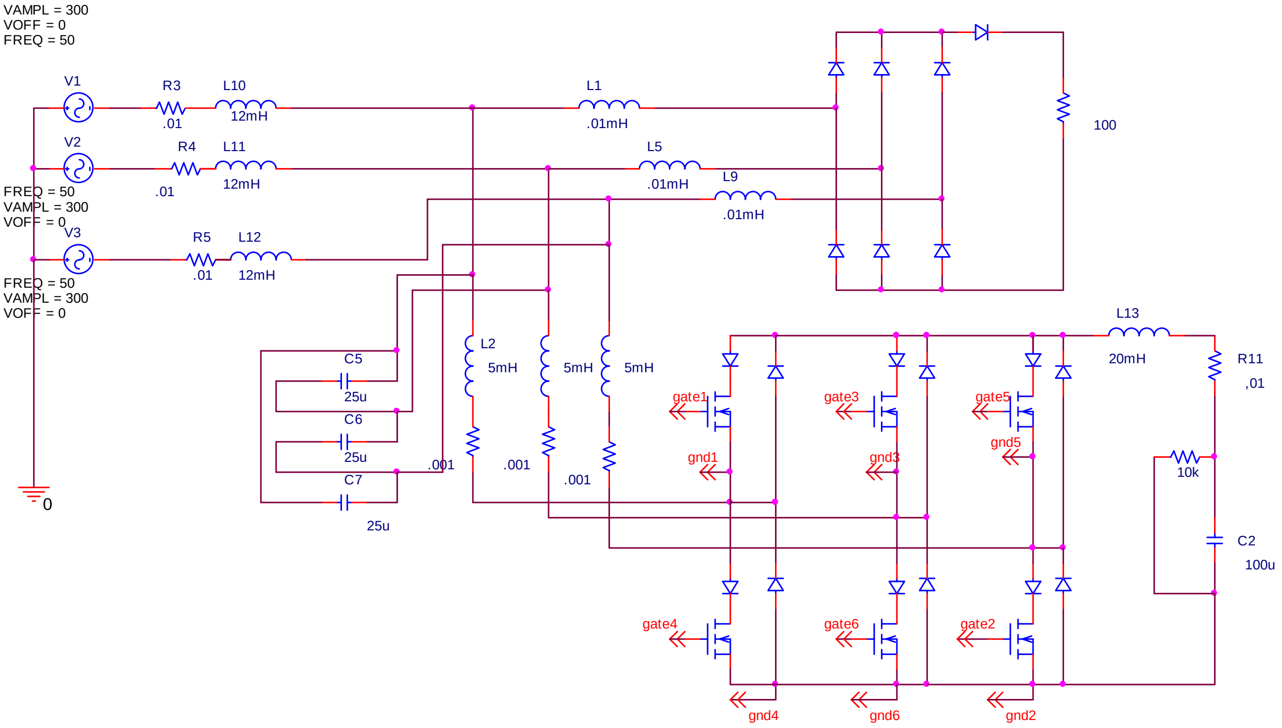


Figure 3.7: The electrical power circuitry of the overall system

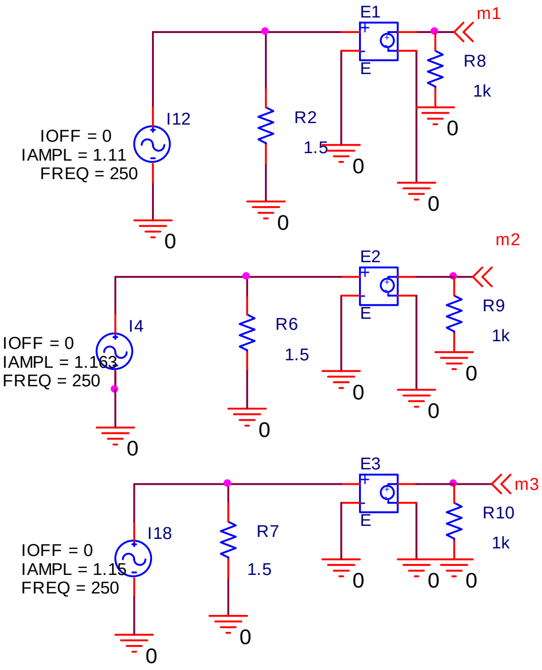


Figure 3.8 Modulating signal generator circuit

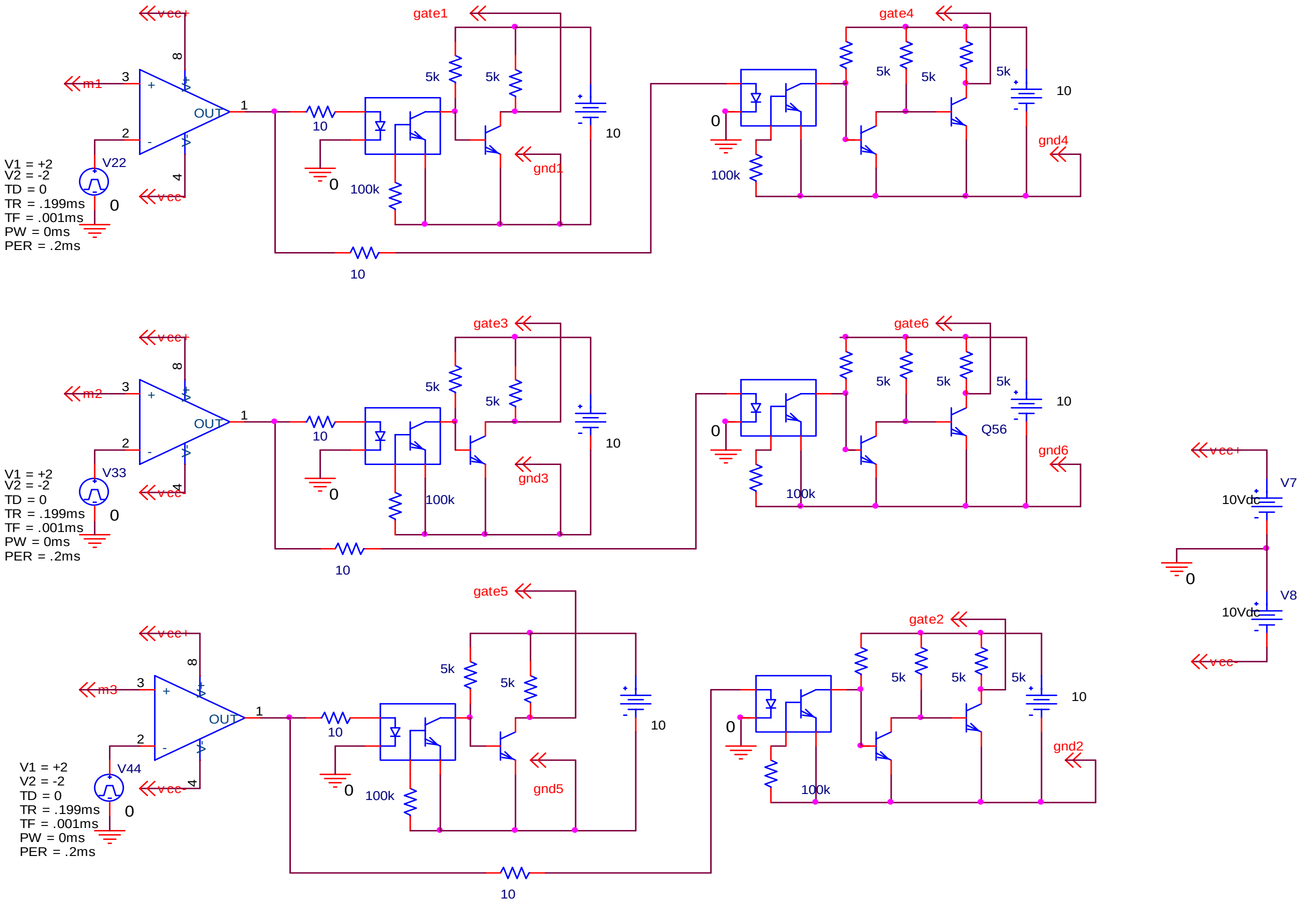
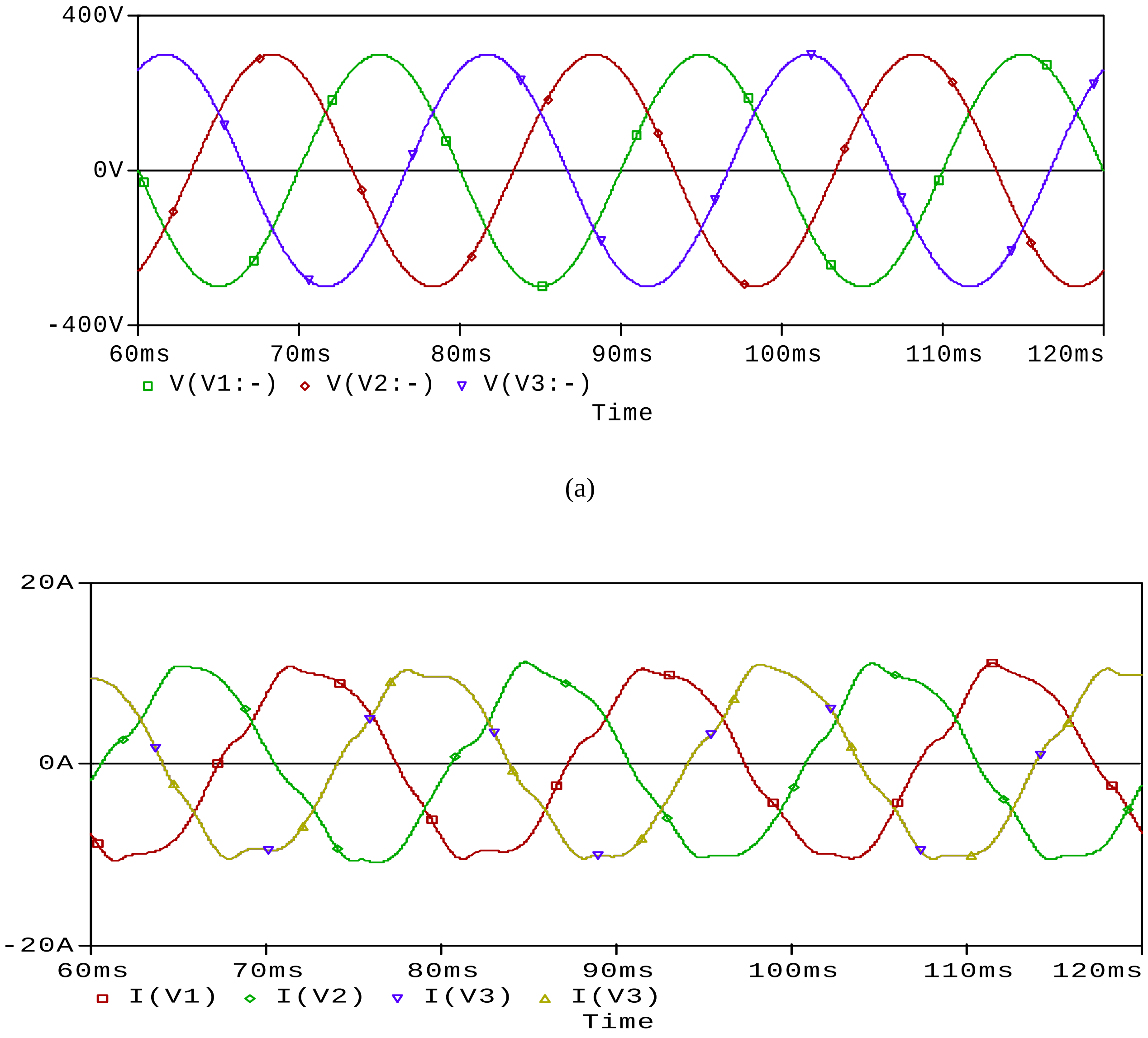


Figure 3.9 PWM circuit and Optocoupler isolation circuit.

3.6.2 Simulation Result:

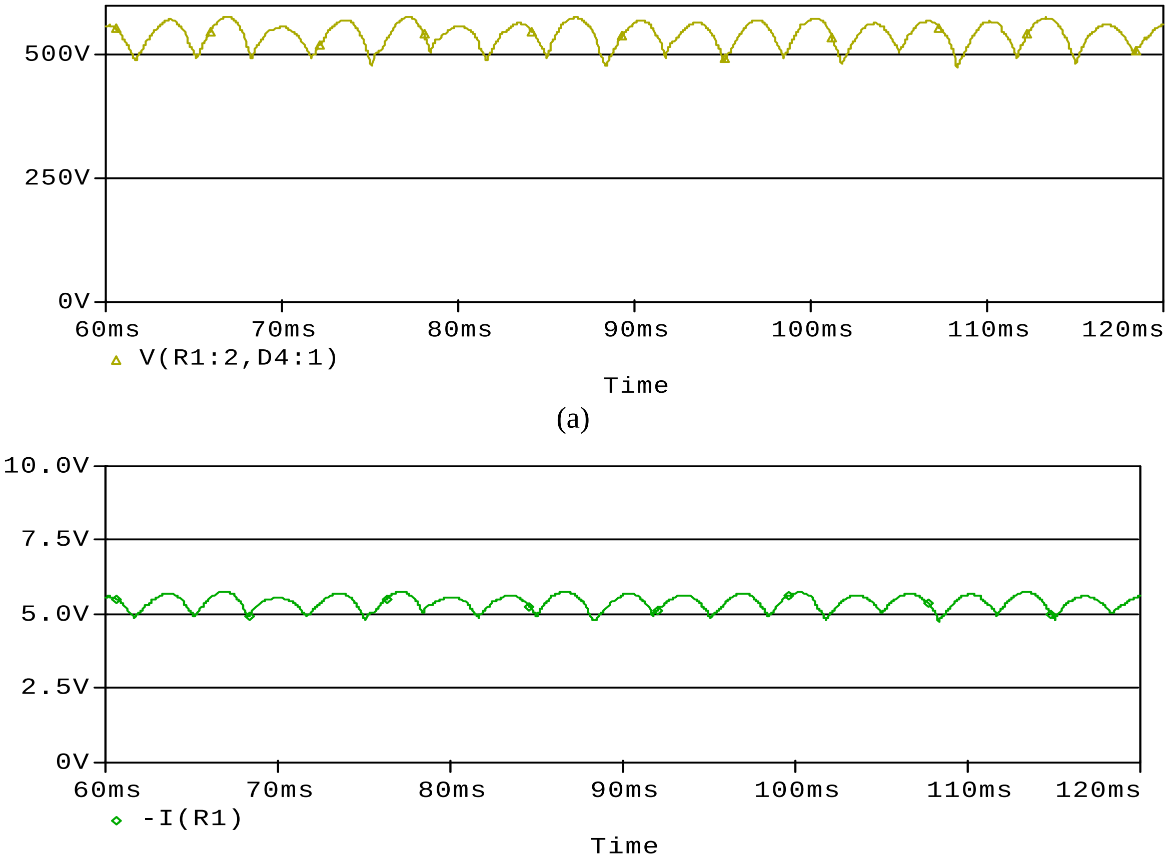
In order to verify the principle and the proposed control strategy the CSI scheme has been simulated. The OrCAD 9.1 Simulation software package has been used to design, simulate and test the filter control scheme. The simulation results of the overall system are shown in Figure 3.10 and Figure 3.11.



(a)

(b)

Figure 3.10: (a) Input line voltages of three phases (b) Input line currents of three phases of the rectifier with APF system.



(a)

(b)

Figure 3.11: (a) Output voltage (b) Output current of three phase rectifier with the proposed scheme

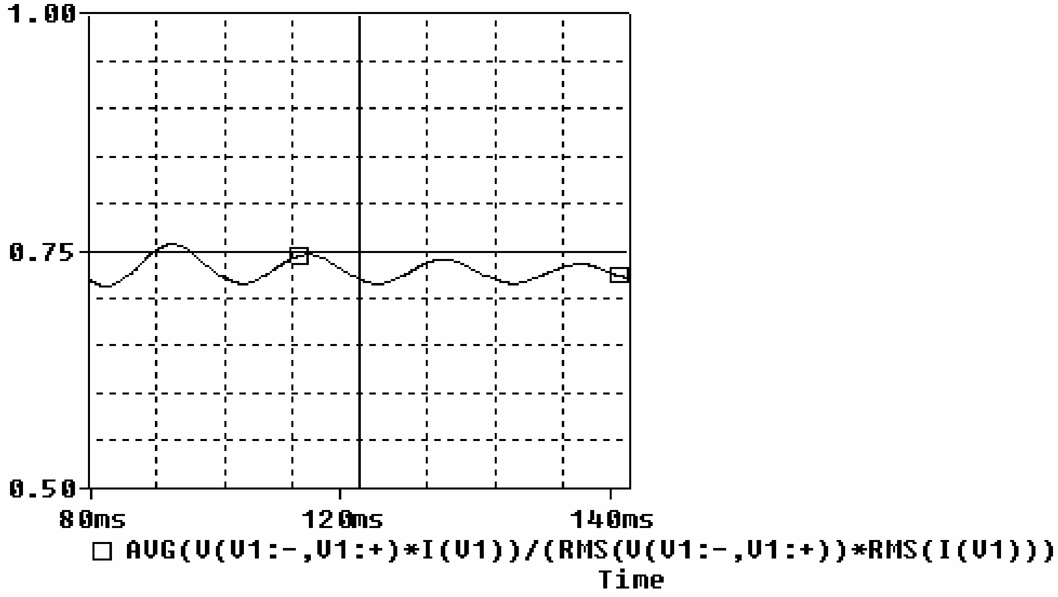


Figure 3.12: Input Power Factor of the proposed scheme

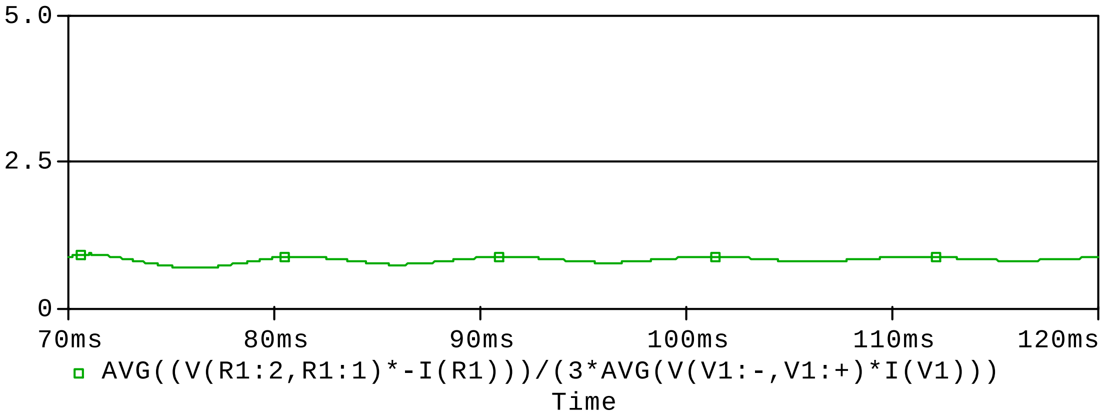


Figure 3.13: Efficiency of the proposed APF system

From the Figure 3.12 and the Figure 3.13 the power factor can be found .75 leading and The Efficiency is 90%. From the simulation output file table 3.1 can be made where The THD is 7.105%. As per the IEEE Standard the required THD is below 10%.

Table 3.1: Table of significant Fourier components of Input current

HARMONIC NO	FREQUENCY (HZ)	FOURIER COMPONENT	NORMALIZED COMPONENT	PHASE (DEG)	NORMALIZED PHASE (DEG)
1	5.000E+01	1.065E+01	1.000E+00	-1.335E+02	0.000E+00
2	1.000E+02	2.467E-01	2.316E-02	-4.774E+01	2.192E+02
3	1.500E+02	7.007E-02	6.579E-03	-1.659E+02	2.345E+02
4	2.000E+02	1.146E-01	1.076E-02	1.492E+01	5.489E+02
5	2.500E+02	6.409E-01	6.018E-02	1.763E+02	8.438E+02
6	3.000E+02	6.227E-02	5.846E-03	1.163E+02	9.172E+02
7	3.500E+02	2.682E-01	2.518E-02	-1.795E+02	7.549E+02
8	4.000E+02	7.592E-03	7.128E-04	9.030E+01	1.158E+03
9	4.500E+02	2.790E-02	2.619E-03	1.385E+02	1.340E+03
10	5.000E+02	4.660E-02	4.375E-03	-1.737E+02	1.161E+03

TOTAL HARMONIC DISTORTION = 7.105 %

In the proposed scheme input filter has been reduced significantly to get the required THD with acceptable power factor and efficiency. A comparison between a conventional harmonic reduction method using passive Filter and the proposed PAF scheme with fifth harmonic injection method is shown in Table 3.2.

Table 3.2: Comparison between three phase rectifier with passive filter and PAF based three phase rectifier

Performance Parameters	Normal three phase rectifier with input passive filter Filter used L=30mH, C=20uF	PAF based Proposed Scheme Filter used L=12mH, C=25uF
Power factor	.81	.75
Efficiency, η	98.6%	90%
THD%	3.71	7.105
Input Filter Size	L=30mh, C=20uF	L=12mH, C=25uF,
Input voltage	300V	300 V
Output voltage	600 V	512 V

CHAPTER 4
Conclusion and Recommendation for Future Works

4.1 Conclusion

The parallel active filter is the modern solution to eliminate the harmonic current and reactive power related power quality problems in power systems. It is suitable for current sink type loads and it is applicable for loads with power ratings up to MVA levels. Implemented as a controlled current source, the PAF injects a compensating current into the system so that it cancels the harmonic current, the reactive power current, and the unbalanced current components of a harmonic current generating nonlinear load. As a result, the current drawn form the AC utility grid becomes sinusoidal, in phase with the line voltage, and balanced. This thesis is concerned with the design, control, and the implementation of a PAF for 3-phase 3-wire rectifier load systems to comply with the harmonic standards of IEEE 519-1992.

The fifth order harmonic current reference signal is sent to the current regulator that generates the switching signals of the CSI which chops the DC bus voltage to obtain the desired AC current at the CSI output terminals for the creation of the PAF reference current through the filter inductors.

Since the CSI of the PAF operates at high switching frequencies in the range of kHz, high frequency switching ripple is generated at the PCC and power quality problems arise for the other loads connected to the same PCC. Therefore, adequate attenuation of the switching harmonics via a switching ripple filter (SRF) is mandatory from the point of power quality. In addition to the PAF study, this thesis also investigates the SRF topology and it’s design.

As 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 provide a means for the purpose without the requirement of a separate current source.

4.2 Future work

The present work demonstrated the successful input current waveform improvement of three phase nonlinear load to a significant level. However, complete unity power factor operation with THD within prescribed level is yet to be achieved by this method as the power factor has been leading. To achieve this feedback control technique and proper filter design is necessary. These maybe incorporated in future work. The result reported in this thesis is based primarily on the basis of simulation of proposed technique. The harmonic current used as the current reference, is been directly modulated by PWM modulator, which in future work can be derived from the load itself by using current reference generator. In this scheme only diode rectifier has been used. The switching regulator based rectifier should be investigated for achieving the same objective with proposed technique in future.

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