INVESTIGATION OF A THREE PHASE SWITCH MODE SINGLE ENDED PRIMARY INDUCTOR CONVERTER POWER FACTOR CORRECTED RECTIFIER

A Thesis

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Master of Science in Electrical and Electronic Engineering

by

Khandaker Lubaba Bashar

Bangladesh University of Engineering and Technology (BUET)

Dhaka, Bangladesh

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Certification of Approval

The thesis titled **"Investigation of a Three Phase Switch Mode Single Ended Primary Inductor Converter (SEPIC) Power Factor Corrected Rectifier"**, submitted by Khandaker Lubaba Bashar, Student Number 1014062208P, session October/2014 has been accepted as satisfactory in partial fulfilment of the requirement for the degree of Master of Science in Electrical and Electronic Engineering on July 23, 2017

Board of Examiners:

23/7/2017

Dr. Mohammad Ali Choudhury — Chairman (Supervisor)
Professor
Department of Electrical and Electronic Engineering
Bangladesh University of Engineering and Technology
Dhaka-1205, Bangladesh

Dr. Pran Kanai Saha — Member (Ex-0fficio)
Professor and Head
Department of Electrical and Electronic Engineering
Bangladesh University of Engineering and Technology
Dhaka-1205, Bangladesh

Dr. Mohammad Jahangir Alam — Member
Professor
Department of Electrical and Electronic Engineering
Bangladesh University of Engineering and Technology
Dhaka-1205, Bangladesh

Dr. Md. Ashraful Hoque — Member (External)
Professor
Department of Electrical and Electronic Engineering
Islamic University of Technology (IUT)
Boardbazar, Gazipur, Bangladesh

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Lubaba Bashar

Khandaker Lubaba Bashar

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ABSTRACT

Input switched SEPIC topology based output voltage regulated 3-phase 3-switch modular rectifier circuit is proposed and developed in this thesis. Fully controlled three phase converters consisting of six controlled switches are ideal methods for bidirectional AC-DC conversion. Complexity of control, requirement of protection against devices failure and costs limit their applications. In large rectifiers, harmonic current injection technique is used for PFC, THD and efficiency improvement but this technique requires separate dc sources for generating harmonic current to be injected.

Three phase AC-DC converters may use uncontrolled bridge rectifiers followed by DC-DC converters. These provide input current shaping with low THD. Large filters at their inputs degrade the conversion efficiency. Modular three phase rectifiers are composed of three single phase PFC rectifiers, where, input current waveforms are controlled by three switches and the output is taken from a DC rail. They are capable of being controlled like single phase boost PFC rectifiers. In this work, a modular three-phase power factor corrected (PFC) single ended primary inductor converter (SEPIC) rectifier is investigated. The advantage of the circuit is its ability to rectify individual voltage of three phases separately and superimpose them at the load. Per phase rectification allows sinusoidal input current shaping in the circuit by standard feedback control. Also boost topology at the input stage with series inductor allows easy reduction of input current total harmonic distortion (THD) and improvement of input power factor.

The proposed rectifier is a high performance controlled rectifier compared to traditional ones in terms of power factor, input current THD and conversion efficiency. The SEPIC topology retains benefits of buck/boost gain facility and provides capacitor isolated output. The performance results have been compared for the open and closed loop voltage regulations. In open loop system, the output voltage of the rectifier has been controlled by standard duty cycle control technique. To ensure high performance feedback control circuits have been employed with current and voltage controller loops. The performance of the proposed circuit has been found to be satisfactory in simulation and experimental results. Typical dynamic responses of the circuit are included to demonstrate its effectiveness to regulate output voltage during load changes with the performance remaining almost the same.

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List of Symbols and Abbreviations

AC	Alternating Current
DC	Direct Current
HVDC	High Voltage Direct Current
THD	Total Harmonic Distortion
SCR	Silicon Controlled Rectifier
EMI	Electromagnetic Induction
DPT	Direct Power Transfer
SEPIC	Single Ended Primary Inductor Converter
PWM	Pulse Width Modulation
APC	Active Power Filter
PCC	Point of Common Coupling
LED	Light Emitting Diode
UPS	Uninterruptable Power Supply
CCM	Continuous Conduction Mode
DCC	Discontinuous Current Mode
IC	Integrated Circuit
IGBT	Insulated Gate Bipolar Transistor
MOSFET	Metal Oxide Semiconductor Field Effect Transistor

Chapter 1

Introduction

Three phase rectifier circuits are the norm for a large number of industrial, telecom, computing equipment and high-power applications. Controlled and uncontrolled three phase AC-DC rectifiers have distorted input currents. Reduction of input current distortion and improvement of input power factor of three phase rectifiers at satisfactory power conversion efficiency is yet a complicated task.

1.1 Background and present status of the problem

Conventionally AC–DC converters which are also called rectifiers are developed using diodes and thyristors to provide uncontrolled and controlled DC power with unidirectional and bidirectional power flow. They have the demerits of poor power quality in terms of high input current harmonic distortion and low power factor at input AC mains, slow varying rippled DC output at the load end and low efficiency. These rectifiers need large size filters at input and output ends. In Fig. 1.1 and Fig. 1.2 input current waveforms and spectrum of input currents of single phase full bridge and three phase full bridge uncontrolled rectifiers with output filter are shown.

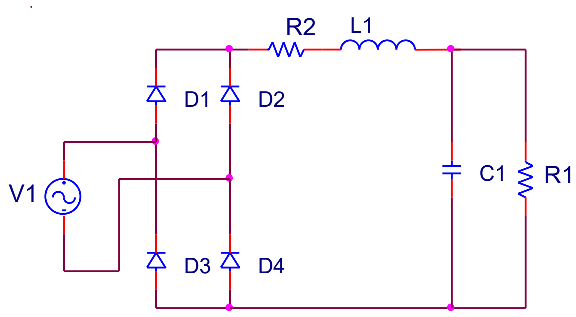


Fig. 1.1 (a)

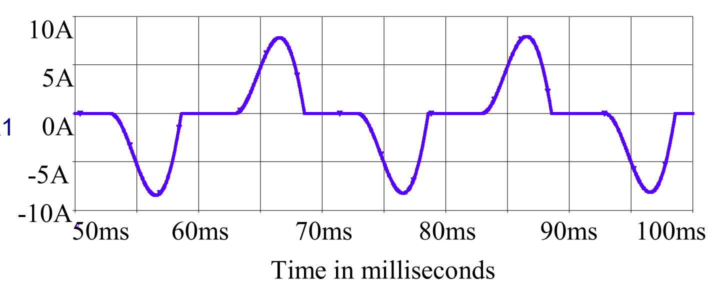


Fig. 1.1 (b)

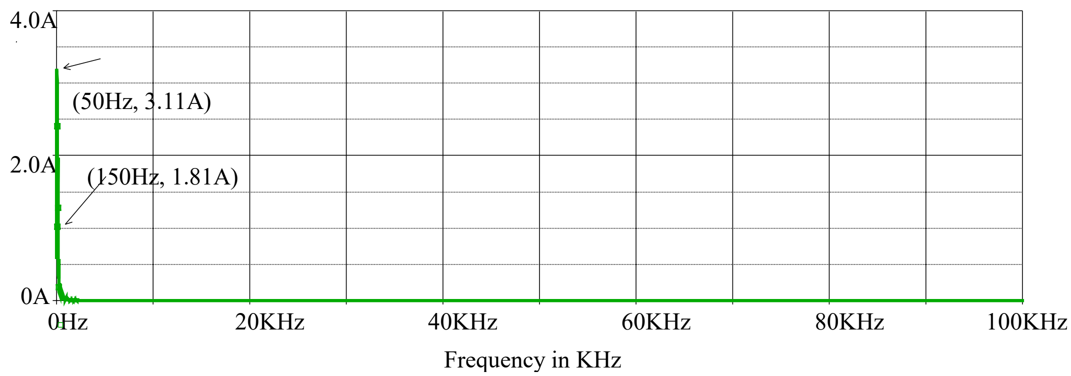


Fig. 1.1 (c)

Fig. 1.1 Current quality of single phase uncontrolled rectifier with output filter (input current THD = 60.12%)

(a) Single phase uncontrolled full bridge rectifier with output filter (Resistive load)

(b) Input current waveform

(c) Spectrum of input current waveform

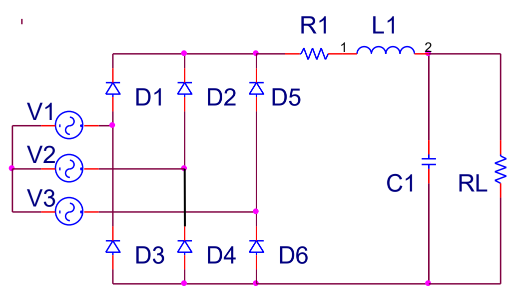


Fig. 1.2 (a)

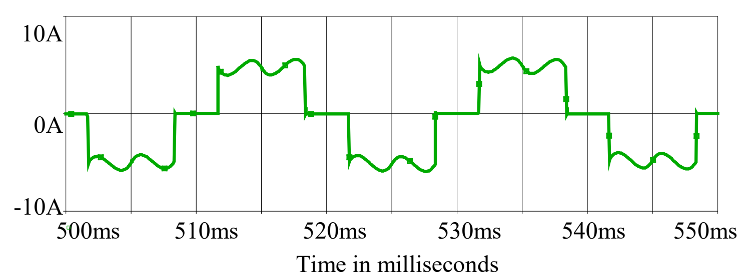


Fig. 1.2 (b)

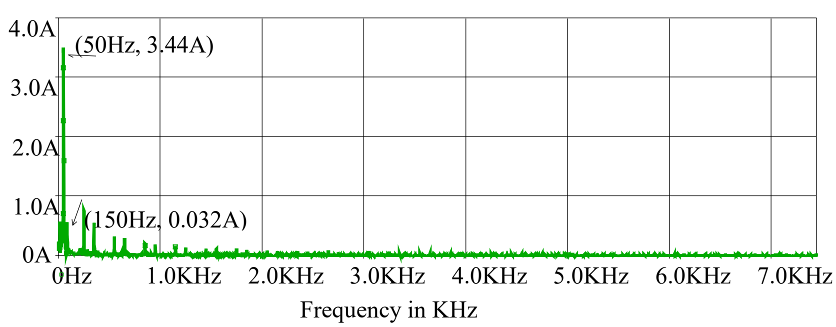


Fig. 1.2 (c)

Fig. 1.2 Current quality of three phase uncontrolled rectifier with output filter (input current THD= 36.32%)

(a) Three phase uncontrolled full bridge rectifier with output filter (Resistive load)

(b) Input current waveform of phase-I

(c) Spectrum of input current waveform of phase-I

The input currents are non-sinusoidal and have large harmonic distortions. Harmonics of input current causes,

- Overheating of transformers, power cables, AC machines and switchgear, leading to premature aging and failure,
- Inadvertent tripping of protective devices,
- Incorrect measurement of voltage and current by meters,
- Reduced power factor due to non-linear loads, hence less active power available from a wall outlet having a certain apparent power rating,
- Increased iron losses in transformers,
- Motors to heat up and produce pulsating torque,
- Electrical resonance in the power system, leading to excessive peak voltages and RMS currents, and causing premature aging and failure of capacitors and insulation,
- Telephone interference,
- Errors in metering equipment and
- Increased audio noise etc.

Buildings with large number of computers and data processing equipment use AC-DC conversion for their supply. Applications requiring AC-DC conversion include electrolysis, electroplating, induction heating, welding, arc furnaces and ovens, electrochemical processing, battery chargers and UPS etc. AC-DC converters draw harmonic current which cause neutral current. Besides power quality problems at user end and utility harmonics also cause problems on other users. Power quality problem for single phase and three phase controlled rectifiers are illustrated by typical waveforms in Table 1.1 and 1.2. The waveforms are shown for rectifier with pure resistive load with no output filter. The power factor and THD of the input current will further deteriorate with output filter.

Table 1.1 Single Phase Thyristor Controlled Rectifiers

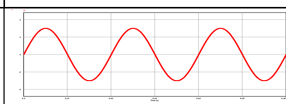
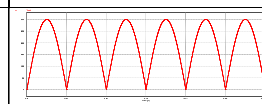
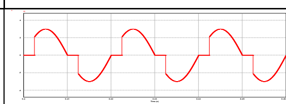
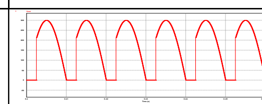
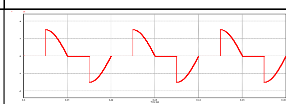
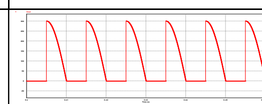
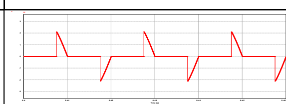
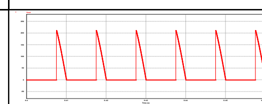
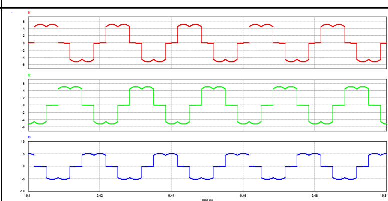
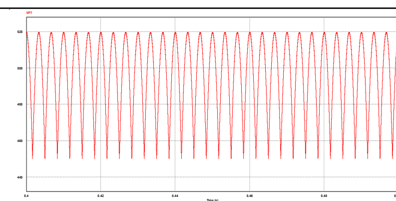
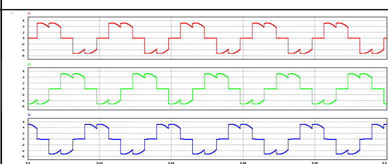
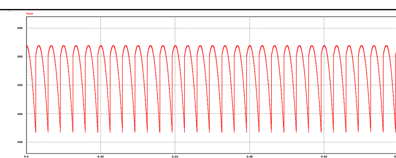
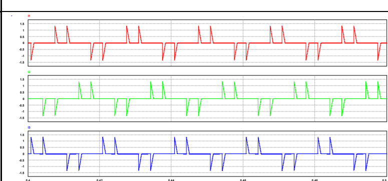
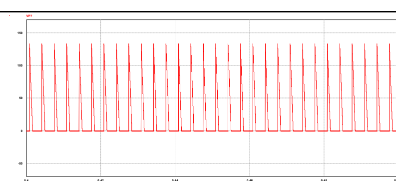
Deg.	THD (%)	PF	Input Current	Output Voltage
0	0.24	0.9999		
45	25.98	0.9533		
90	65.12	0.7067		
135	130.66	0.3010		

Table 1.2 Three Phase Thyristor Controlled Rectifiers

Deg.	THD (%)	PF	Input Current	Output Voltage
0	30.80	0.95		
45	31.89	0.92		
135	208.6	0.07		

The design of input stage of such rectifiers should focus on two aspects. One is the input power factor correction (PFC) and the other is the input current THD reduction [1]. Design issues compromise PFC and THD improvements to maintain desired step-up/step-down voltage/current regulation at high conversion efficiency. There are different approaches of PFC rectifier design, fabrication and operations for both single and three phase rectifiers.

1.2 Single Phase AC-DC PFC topologies

Regarding the power factor correction stage and input current shaping, some of the techniques used in applications of single phase AC-DC converters are stated below:

a) Passive Filter Technique,
b) Active Filter Technique and
c) Hybrid Filter Technique.

(a) Passive Filter Technique:

Passive PFC methods use passive components with the diode bridge rectifier. This method is the simplest solution if output voltage control is not required. These have been investigated in references [1-4], where, line frequency reactive elements are connected at input and output sides of rectifiers. The advantages of passive filter include simplicity, reliability, ruggedness, insensitivity to noise and surges, absence of high frequency electromagnetic interference (EMI) and switching loss. The drawbacks that limit use of passive filter is size, poor dynamic response, difficulty of tuning, lack of voltage regulation facility, load dependent input current, poor power factor and degradation of conversion efficiency.

(b) Active filter technique

For active PFC, controlled switches are used in conjunction with reactive elements in order to increase the effectiveness of the line current shaping and to obtain controllable output voltage. There are two methods of controlling these switches: Phase control and Pulse width modulation control method. In most cases, these rectifiers are operated by Pulse Width Modulation (PWM) control method. The PWM converter can achieve high power quality at high cost and with complex control mechanism. [1-6].

(c) Hybrid Filter Technique

In hybrid filter technique semiconductor switches are integrated with the diode bridge for output voltage regulation, input current shaping and input power factor correction. Three different approaches are used; two stages for high power application, single stage for low power application and direct power transfer (DPT) for improved efficiency [7-12]. For any of these three approaches, a DC-DC converter cell with step-up, step-down or step-up/down capability is connected with the diode bridge in one of the two different ways;

- DC-DC converter between load and rectifier
- Input switching between supply and rectifier.

The step-up boost converter (in either continuous or in discontinuous conduction mode) is the most common topology used for power factor correction of single phase rectifiers. The Buck converter has a step-down conversion ratio and can operate only when the instantaneous input voltage is higher than the output voltage [12-14]. The Buck-Boost converter can operate either as a step-down or a step-up converter which gives freedom in specifying the output voltage.

1.3 Three Phase AC-DC PFC topologies

In high power applications where three-phase systems are required to avoid the system load unbalance, the search for three-phase PFC rectifier topologies with high efficiency, high reliability, simple control scheme and high-quality input currents has increased in the last decade. Three-phase diode bridge rectifiers are commonly used as front-end converters due their simplicity, reliability and low cost.

As THD of the input currents of three phase rectifiers are high, several techniques are used to meet the harmonic specification and power quality standards. Preference of one technique over the other depends on the application, nature of the load and system parameters to make use of the advantages and avoid the disadvantageous. An overview of existing three phase PFC and harmonic filtering schemes is [15]:

i. **Multi-pulse rectifiers**

Multi-pulse rectifiers are made by combining 6-pulse rectifier to form 12-pulse, 18-pulse, 24-pulse etc. by shifting each 6-pulse with angle of (360/number of pulse) from each other.

In multi-pulse rectifiers phase shifting transformers are used to create the phase shift between the pulses and to provide electric isolation between the load and the supply. Several designs and methods are used to adjust the transformer size and power rating. Main advantages of multi-pulse rectifiers are:

- Transformers provide electric isolation between the load and the supply,
- No control circuit is required which make the system simple,
- Robust and need less maintenance activity,
- The absence of high switching frequency eliminates the EMI noise and
- Transformers turn ratios could be adjusted to have low DC link voltage.

However, low frequency transformers (60/50 Hz) connected in series between the supply and the load yield in the following disadvantages:

- Need large space and has greater weight compared to other active technique based rectifiers,
- Magnetic component used in the transformers core has high cost,
- In some topologies zero sequence block transformer is required which increase the size, weight and cost and
- Designed for specific system parameter.

The technique is suitable in high power application with an environment that does not limit the size and weight.

ii. **Phase modular rectifiers**

Single phase boost PFC rectifiers have high power density and fulfill the harmonic standard requirement and is easy to control compared to the PWM rectifiers [16]. Modular single-phase PFC rectifiers can be connected to form three phase PFC rectifier system. Modular single-phase PFC rectifiers can be connected in Y or delta to form three phase PFC rectifiers. Using modular single-phase PFC rectifiers to form three phase PFC rectifiers must balance the load among the modules. This is vital to keep the system working properly. The advantages of modular methods are:

- Easy to implement,
- Can be operated for wide input range,
- High input current quality and
- More loads can be added by adding more modules.

And the disadvantages of the modular method are:

- Load balance between the modules is required to achieve symmetrical loading,
- Additional DC/DC converter is required to provide the electrical isolation,
- Each module has individual DC link and DC capacitor filter [17],
- Neutral current may exist and
- Relatively high number of circuit elements are used.

iii. Use of Active filters

Harmonics can be filtered with passive filter design for each harmonic order. Active Power Filter (APF) topologies are designed to eliminate several low order harmonics using less passive element and more active element. APF can be classified as shunt active power filter, series active power filter and hybrid power filter. An APF is a compensation of active and passive filters to improve the performance with lower rating. For low to medium power application the APF is suitable and cost effective. Unlike the multi-pulse rectifier, APF can be used to compensate several nonlinear loads connected to the same point of common coupling (PCC) and can be used to eliminate neutrals' current [18, 19]. Moreover, APF is smaller in size and lower in cost compared with multi-pulse rectifiers. But, the APF requires complex control circuit.

iv. Harmonic Current Injection technique

Harmonic current injection is a solution for improvement of power quality of three phase rectifiers [20-22]. If the difference of positive and negative line bridge current can be fed back by current injection network to the mains, a sinusoidal current shape can be obtained. To provide proper current injection a part of the input power has to be transmitted to the current injection network which may be as high as 8.57%. One example of passive injection network is Minnesota rectifier. However, passive injection networks show relatively large volume and weight. Considering the high-power density demand in industry active current injection is preferable.

v. Boost rectifier in DCM

The three-phase boost rectifier operating in discontinuous current mode (DCM) is kind of direct three phase rectifiers that utilize single active switch. The system was first proposed in reference [23]. The circuit topology is shown in Fig.1.3. Its main principle is to shape the inductor discontinuous current by the input voltage so that the input current has a fundamental sinusoidal modulated wave form along with high frequency carrier wave.

The main advantages of this topology are:

- Single active switch,
- Small reactive component,
- High power factor and low harmonics,
- Simple control circuit, similar to dc-dc converter and
- Zero current switching for the diode bridge which reduce the switching loss in the bridge.

The scheme is similar to single phase boost PFC rectifier. But the scheme's effective power factor and input current improvement in three phase case was not proven.

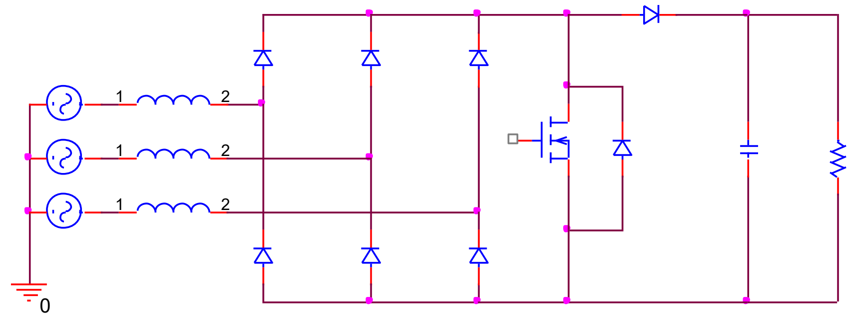


Fig. 1.3 DCM Boost Rectifier

vi. Direct three phase PWM rectifiers

The PWM rectifiers use the pulse width modulation technique to control 3-leg 6-switch to have sinusoidal input current. As the circuit shown in Fig.1.4 PWM rectifiers are classified as current source rectifier or voltage source rectifier based on DC link type.

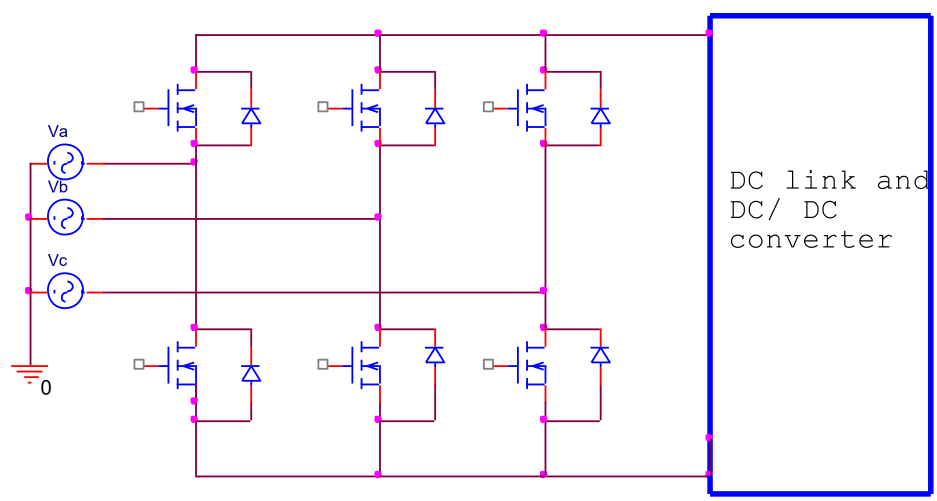


Fig. 1.4 PWM Rectifier

The current source rectifier has more component and lower performance. The direct three phase PWM rectifiers overcome the drawbacks of modular rectifiers made from single phase rectifiers. They require additional DC/DC converter to provide the electrical isolation. PWM three phase rectifiers have six active switches which can be further reduced in other techniques.

vii. VIENNA Rectifier

The drawback of the low order harmonics in the system presented in boost three phase rectifier in DCM mode is overcome with multi-level PWM rectifiers by adding four-quadrant switches in symmetrical three phase shape to balance the input current path such as in Delta switch and VIENNA rectifiers. VIENNA rectifier circuit is shown in Fig.1.5. It has high power density and it is usually designed for telecom applications.

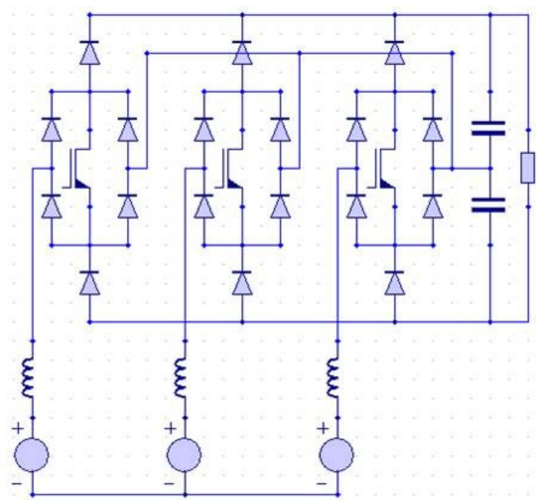


Fig. 1.5 Vienna Rectifier

The main advantages of VIENNA rectifiers are [24-27]:

- Lower input current harmonics as output DC voltage has a mid-point to form virtual neutral,
- Less device voltage stresses compared to devices of PWM and Delta switch rectifiers,
- High power density,
- Load power can be distributed over the negative and positive output partial voltage and
- Phase shift between the input current and input voltage is possible.

In single phase unidirectional AC-DC conversions, input power factor improvement and input current shaping is done by using high frequency DC-DC converters between uncontrolled rectifiers and the loads. The method could not be effectively used in three phase unidirectional regulated AC-DC converters. In three-phase diode bridge uncontrolled rectifiers input and output currents are not converted on phase to output basis. Input currents of switched controlled three phase rectifiers exhibit shapes of switched three-phase bridge rectifier. As a result, attempts of output switching between rectifier and the load did not become popular. In applications, where, unidirectional power flow from ac side to dc load is adequate, modular rectifiers consisting of 3-single phase rectifiers having one controlled switch in each phase have been used to operate in cascade. Three phase Vienna rectifiers are examples of such modular rectifiers. Survey of three phase conventional and switch mode controlled rectifiers are available in references [7-16].

A three-phase 3-switch modular rectifier circuit with SEPIC topology based input switching is proposed and developed in this research work. The advantage of the circuit is its ability to rectify individual voltage of three phases separately and superimpose them at the load. Per phase rectification allows sinusoidal input current shaping in the circuit by standard feedback control. The performance results of the proposed rectifier have been studied and compared for open and closed loop voltage regulations. In open loop system, the output voltage of the projected rectifier has been controlled by standard duty cycle control technique. To ensure power factor improvement, improved input current THD and high conversion efficiency, standard feedback control circuits is employed having current and voltage controller loops respectively.

The SEPIC topology of switching AC-DC three phase converters is not common in PFC rectifiers. This topology has advantages of input boost topology stage, boost-buck gain characteristics and single ended capacitively isolated positive output.

1.4 Objective of the present thesis work

The aim and objective of this thesis work is to,

- Investigate a 3-phase 3-switch modular rectifier using input SEPIC topology based switching to improve its input current shape, THD and the input power factor,
- Design and study the appropriate power and feedback control circuits for an input switched SEPIC topology based 3-phase 3-switch PFC rectifier and
- Study the performances of proposed modular three-phase three switch input switched and output regulated half bridge SEPIC rectifiers and compare their results.

Possible outcome of the research:

In this thesis, a new 3-switch 3-phase SEPIC rectifier similar to the modular boost and Vienna rectifier is proposed which has both step up and step-down voltage gain characteristics. The input stage of the proposed rectifier being that of boost configuration allows average inductor current tracking to improve input current and the input power factor of the circuit. The circuit is also able to rectify individual voltage of three phases separately and superimpose them at the load. Thus, an improved 3-phase modular SEPIC rectifier with low input current THD, near sinusoidal input current with near unity power factor and high conversion efficiency can be achieved. This is a robust AC-DC converter in terms of operation, maintenance, control and has satisfactory efficiency of conversion compared to traditional controlled three phase rectifiers. The proposed rectifier will also be capacitively input/output isolated with single ended positive output.

1.5 Organization of the Thesis

New topology of a three phase three switch SEPIC AC-DC converter operated along with a properly designed PFC feedback controller is proposed and developed in this thesis. The operation and performance of the circuit is illustrated by simulation and practical results.

Chapter-1 is the introductory chapter with brief review of the status of the three phase PFC rectifiers. This chapter's summary gives the motivation, aim and objective and objective of the thesis.

Chapter-2 contains the introduction of single phase version of the proposed SEPIC rectifier. Basic working principle and ideal voltage gain expression of the 1-phase SEPIC input switched rectifier with split output capacitors are derived. The ideal and simulated voltage gains are compared in tabular and graphical forms.

In chapter-3 a new topology of the three-phase three-switch modular SEPIC rectifier is proposed with description of its basic operation and derivation of the voltage gain expression. Performance of the circuit with feedback and without feedback control are presented in tabular and graphical forms. Typical dynamic responses of the circuit are included to demonstrate the effectiveness of the proposed circuit to regulate output voltage during load changes.

Chapter-4 deals with the design and working procedure of the feedback control circuit of proposed AC-DC converter. Typical simulated waveforms of the controller at different points of operation are included in this chapter.

Chapter-5 describes the practical implementation of the proposed SEPIC topologies without feedback and contains the justification of the practically measured results with the theoretically shown results of the proposed topology.

Chapter-6 concludes the thesis with conclusion, summary and suggestion on future works followed by references.

Chapter 2

Single Phase Version of the Proposed SEPIC Rectifier

2.1 Conventional Single-Phase Output Switched Boost AC-DC Converter

The conventional practice is to use output switched boost PFC circuit for active power factor correction (PFC) and input current improvement of a single-phase diode bridge rectifier. It uses a diode bridge to rectify the AC input voltage to DC, which is then followed by the boost DC-DC converter section. To control the input current within a narrow window around sinusoidal reference current either the input inductor should have a high value or the switching frequency of the device is kept high. To reduce the size of the rectifier the second method is usually followed. With higher switching frequency, the switching power loss increases [28-30]. This increased power loss brings down the efficiency of the rectifier.

2.2 New Single-Phase input switched SEPIC Rectifier

Input current shaping and power factor improvement of single phase diode rectifier may also be accomplished by input switching at high frequency. High frequency input switched current provides better opportunity of obtaining near sinusoidal current of the rectifier. The duty cycle control of the switch provides means of regulating the output voltage of the rectifier. The input current of the rectifier may also be controlled to follow the input voltage by techniques like average inductor current control to improve the input power factor of the rectifier. Input switching of single phase rectifier can be implemented by any of the DC-DC topologies similar to DC-DC converters [28-31].

The single-phase version of the proposed SEPIC AC-DC converter shown in Figs. 2.1 (a)-(e) is input switched and output voltage regulated. This configuration uses a bidirectional switch and provides step-up and step-down output dc voltage.

2.3 Working Principle

The basic working mechanism of the single-phase input switched SEPIC half bridge AC-DC converter of Fig. 2.1 (a) is illustrated for switch ON and OFF conditions during positive and negative half cycles of the supply in Figs. 2.1 (b) - (e).

Fig. 2.1 (b) shows the path of inductor L_1 charging during switch ON period (in positive supply cycle). The input positive voltage charges the input inductor L_1 and the current flows in a clockwise direction from V_{in} to R_1, L_1, switch M_1 back to V_{in}. Simultaneously the capacitor C_1 which was charged during switch OFF period of positive supply cycle starts discharging in an anti-clockwise direction through switch M_1, R_2 and L_2. But it cannot discharge completely due to the inductor L_2.

When the switch is OFF, the input voltage and the boost inductor L_1 charges the capacitor C_1 and upper output capacitor C_{ou}. The same output capacitor C_{ou} is simultaneously charged by the output inductor current as shown in the Fig. 2.1 (c).

Fig. 2.1 (d) shows the path of the inductor L_1 charging in the negative supply cycle during switch ON period. The input negative voltage charges the input inductor L_1 in an anti-clockwise direction, whereas, the capacitor C_1 charges the inductor L_2 in a clockwise direction.

When the Switch is OFF, the input voltage and boost inductor voltage charge the lower output capacitor C_{od} and the capacitor C_1. The lower output capacitor is also charged by the inductor L_2 in an anti-clockwise direction as shown in Fig. 2.1 (e).

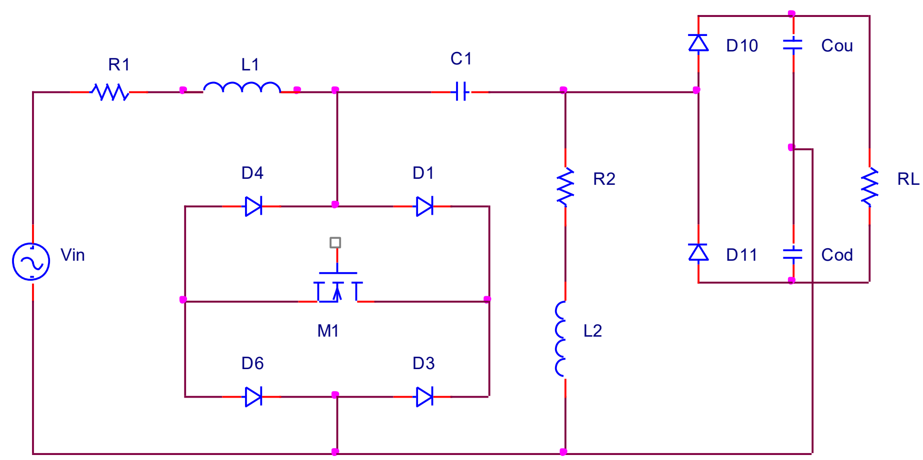


Fig. 2.1 (a) Input switched Single phase SEPIC AC-DC converter (output is half bridge)

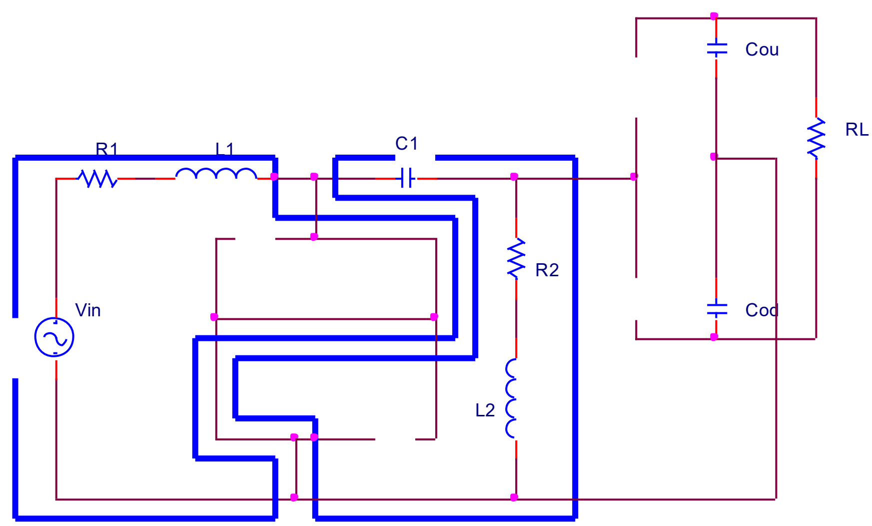


Fig. 2.1 (b) Switch ON of circuit of Fig. 2.1 (a) during positive supply cycle

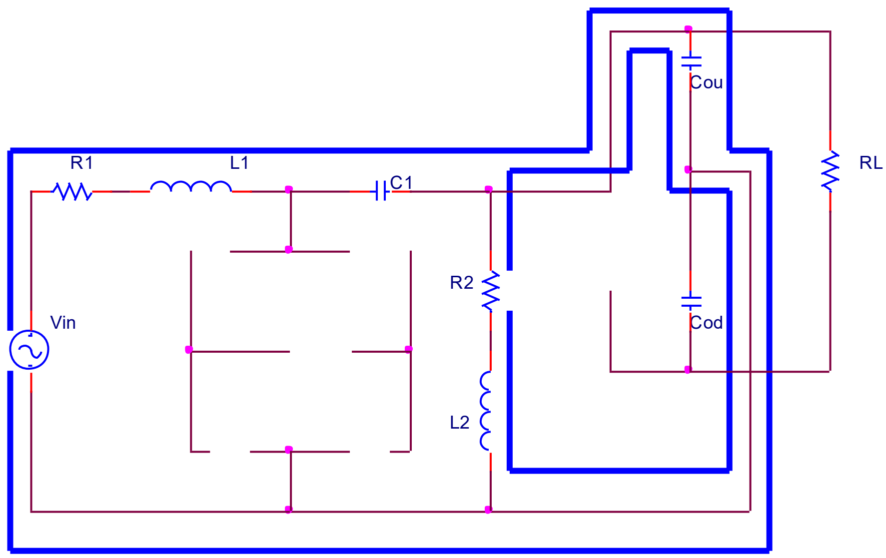


Fig. 2.1 (c) Switch OFF of circuit of Fig. 2.1 (a) during positive supply cycle

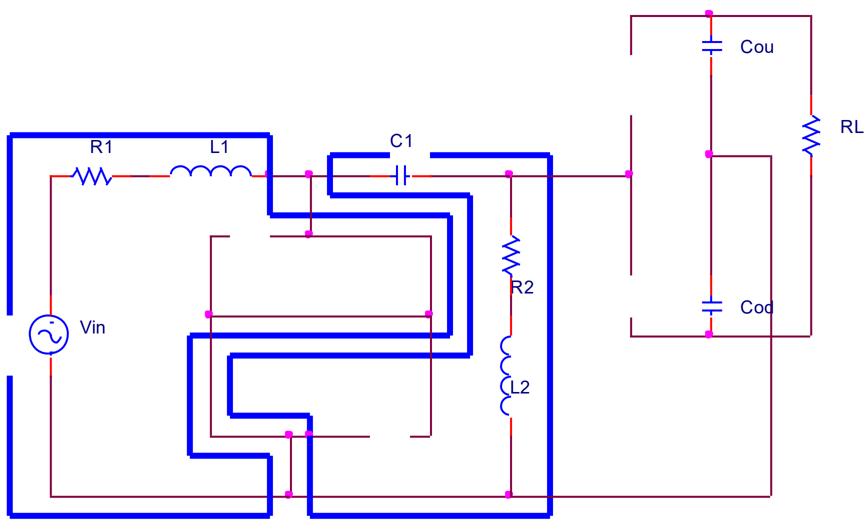


Fig. 2.1 (d) Switch ON of circuit of Fig. 2.1 (a) during negative supply cycle

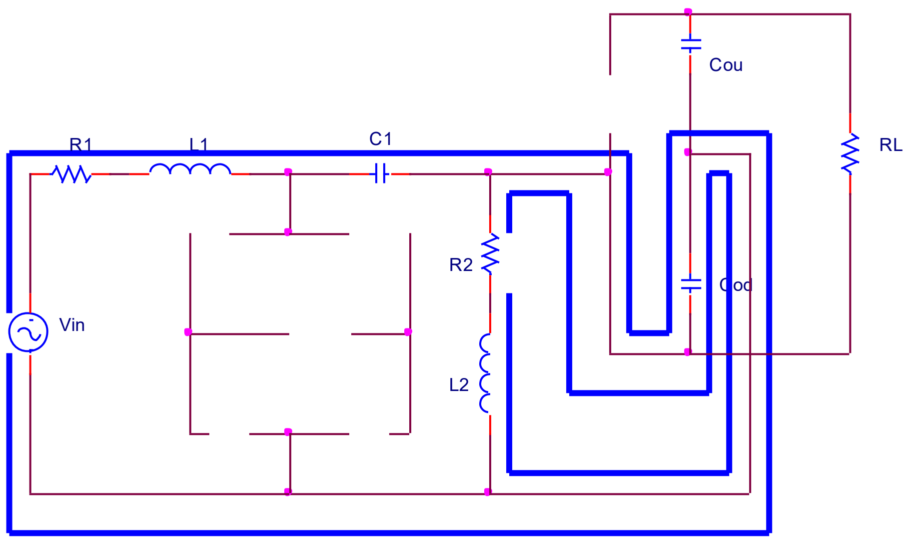


Fig. 2.1 (e) Switch OFF of circuit of Fig. 2.1 (a) during negative supply cycle

Simulated waveforms of the proposed single-phase version of SEPIC rectifier are shown in Figs. 2.2 for small output capacitor values [C_{ou} = 10 µF and C_{od} = 10 µF] and for large output capacitor values [C_{ou} = 1000 µF and C_{od} = 1000 µF] respectively.

In Figs. 2.2, output voltage, input voltage and input current waveforms are shown for open loop operation of the circuit without any feedback control.

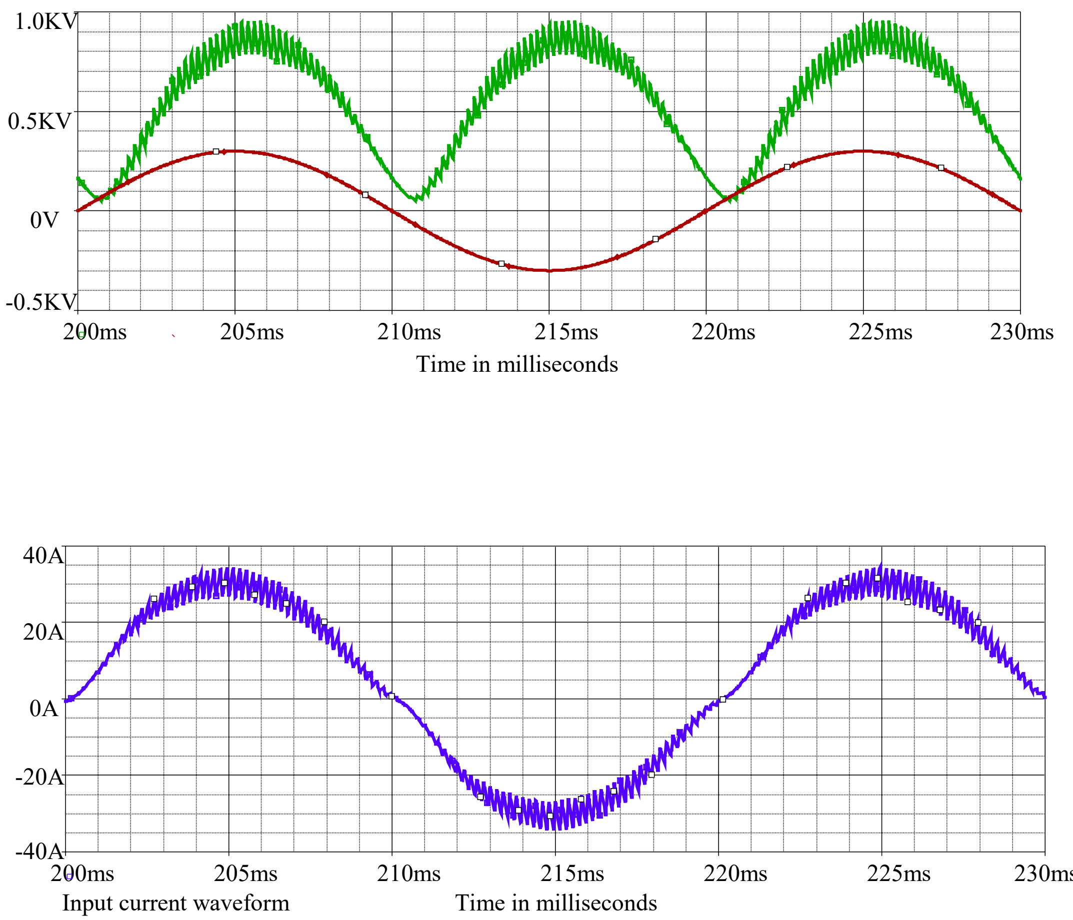
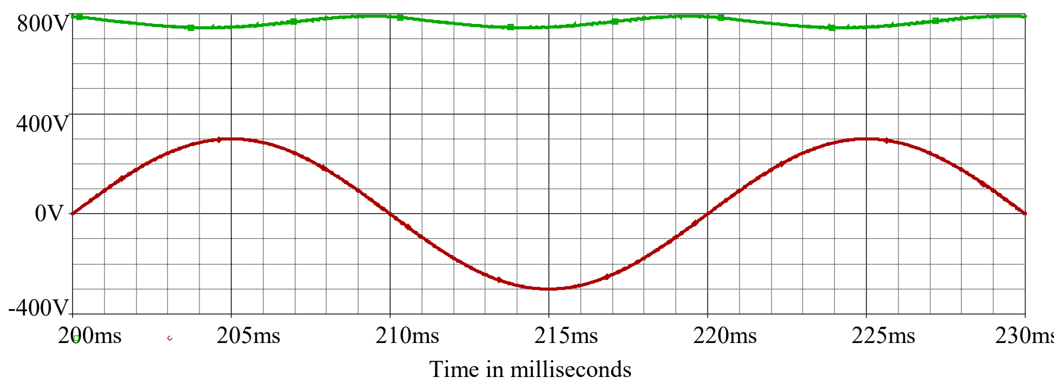


Fig.2.2 (a) (C_{ou} = 10 μF and C_{od} = 10 μF)



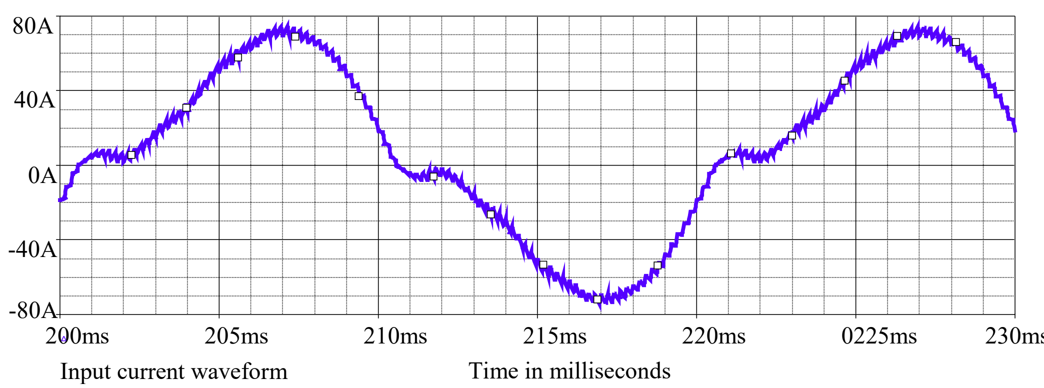


Fig. 2.2 (b) (C_{ou} = 1000 µF and C_{od} = 1000 µF)

Fig. 2.2 Simulated waveforms of the circuit 2.1 (a)

(a) output voltage, input voltage and input current for C_{ou} = 10 µF and C_{od} = 10 µF.

(b) output voltage, input voltage and input current for C_{ou} = 1000 µF and C_{od} = 1000 µF.

From the waveforms of Fig. 2.2 it can be observed that while using large capacitors though the output voltage waveform approximately becomes closer to DC but the input current waveform distorts significantly.

2.4 Ideal Voltage Gain of 1-φ SEPIC Input Switched Rectifier with Half Bridge Output

Ideal voltage gain relationship of the proposed single phase version of SEPIC rectifier can be obtained by equating the volt.-sec. balance of inductors of the convertor over a complete supply cycle (50/60 Hz). In dc-dc switch mode converter the volt.-sec. balance is equated for a switching cycle, whereas in this case the balance is equated for the supply ac cycle having N switching in one cycle. If,

$$v_{in} = \text{ Input voltage} = V_{inmax} \sin \omega t$$

$$v_C = \text{Differential Capacitor Voltage} = V_{Cmax} \sin \omega t$$

Output, $v_0 = |v_0|$ where, $v_0 = V_{0max} \sin \omega t$

(Assuming no phase shift between v_{in}, v_C *and* $v_0 -$ even with phase shift result will approximately be same.)

T_S = Switching cycle

D= Duty Cycle = $\frac{T_{ON}}{T}$

T= Supply frequency period

$DT_S = T_{ON}$= On time

(1-D) $T_S = T_{OFF}$ =Off time

T_S is very small.

For Inductor L_1:

During positive half cycle of the ac input, in one generalized switching cycle from t_i *to* $t_i + T_s$

$$v_{L1} = v_{in} - 0 \text{ for } t = t_i \text{ to } t_i + DT_S$$

$$v_{L1} = v_{in} - v_C - v_{0up} \text{ for } t = t_i + DT_S \text{ to } t_i + T_S$$

If there are $N = \frac{T_S}{T}$ switching cycles over a full sinusoidal AC supply cycle, volt-sec of an inductor,

$$\sum_{i=1}^{N} \int_{t_i}^{t_i+DT_S} (v_{in} - 0)\, dt + \sum_{i=1}^{N} \int_{t_i+DT_S}^{t_i+T_S} (v_{in} - v_C - v_{0up})\, dt = 0$$

Or,

$$\sum_{i=1}^{N}\int_{t_i}^{t_i+DT_S} V_{inmax}\sin\omega t\ dt\ +\sum_{i=1}^{N}\int_{t_i+DT_S}^{t_i+T_S}(V_{inmax}-V_{Cmax}-V_{0upmax})\sin\omega t dt=0$$

Or,

$$\sum_{i=1}^{N} V_{inmax}[\cos(\omega t_i+\omega DT_S)-\cos\omega t_i]$$
$$+\sum_{i=1}^{N} V_{inmax}[\cos(\omega t_i+\omega T_S)-\cos(\omega t_i+\omega DT_S)]$$
$$-\sum_{i=1}^{N} V_{Cmax}[\cos(\omega t_i+\omega T_S)-\cos(\omega t_i+\omega DT_S)]$$
$$-\sum_{i=1}^{N} V_{0upmax}[\cos(\omega t_i+\omega T_S)-\cos(\omega t_i+\omega DT_S)]=0$$

Or,

$$\sum_{i=1}^{N} V_{inmax}[\cos(\omega t_i+\omega T_S)-\cos\omega t_i)]$$
$$-\sum_{i=1}^{N} V_{Cmax}[\cos(\omega t_i+\omega T_S)-\cos(\omega t_i+\omega DT_S)]$$
$$-\sum_{i=1}^{N} V_{0upmax}[\cos(\omega t_i+\omega T_S)-\cos(\omega t_i+\omega DT_S)]=0$$

Using trigonometric solution,

$$\cos A-\cos B=2\sin\frac{A+B}{2}\sin\frac{B-A}{2}$$

One obtains,

$$\sum_{i=1}^{N} 2V_{inmax}\left[\sin\left(\omega t_i + \frac{\omega T_S}{2}\right)(-\sin\frac{\omega T_S}{2})\right]$$
$$-\sum_{i=1}^{N} 2V_{Cmax}\left[\sin\left(\omega t_i + \frac{(1+D)\omega T_S}{2}\right)\sin\left(-(1-D)\frac{\omega T_S}{2}\right)\right]$$
$$-\sum_{i=1}^{N} 2V_{0upmax}\left[\sin\left(\omega t_i + \frac{(1+D)\omega T_S}{2}\right)\sin\left(-(1-D)\frac{\omega T_S}{2}\right)\right] = 0$$

Using relationship,

$\lim_{\theta\to 0}\frac{\sin\theta}{\theta} = 1$, as T_S is very small;

$$\sin\frac{\omega T_S}{2} = \left[\frac{\sin\frac{\omega T_S}{2}}{\frac{\omega T_S}{2}}\right]\frac{\omega T_S}{2} = 1.\frac{\omega T_S}{2}$$

$$\sin\frac{(1-D)\omega T_S}{2} = \frac{(1-D)\omega T_S}{2}$$

Hence, volt-sec balance approximates to,

$$-\frac{\omega T_S}{2}\sum_{i=1}^{N} V_{inmax}\left[\sin\left(\omega t_i + \frac{\omega T_S}{2}\right)\right]$$
$$+(1-D)\frac{\omega T_S}{2}\sum_{i=1}^{N} V_{Cmax}\left[\sin\left(\omega t_i + \frac{(1+D)\omega T_S}{2}\right)\right]$$
$$+(1-D)\frac{\omega T_S}{2}\sum_{i=1}^{N} V_{0upmax}\left[\sin\left(\omega t_i + \frac{(1+D)\omega T_S}{2}\right)\right] = 0$$

$$-\sum_{i=1}^{N} V_{inmax}\left[\sin\left(\omega t_i + \frac{\omega T_S}{2}\right)\right] + (1-D)\sum_{i=1}^{N} V_{Cmax}\left[\sin\left(\omega t_i + \frac{(1+D)\omega T_S}{2}\right)\right]$$
$$+(1-D)\sum_{i=1}^{N} V_{0upmax}\left[\sin\left(\omega t_i + \frac{(1+D)\omega T_S}{2}\right)\right] = 0$$

Consider $\frac{\omega T_S}{2}$ is very small as T_S is very small. So,

$$\lim_{T_S \to 0} \frac{\omega T_S}{2} = 0$$

$$-\sum_{i=1}^{N}[V_{inmax}\sin(\omega t_i)] + (1-D)\sum_{i=1}^{N}[V_{Cmax}\sin(\omega t_i)] + (1-D)\sum_{i=1}^{N}[V_{0upmax}\sin(\omega t_i)] = 0$$

Which leads to,

$$\sum_{i=1}^{N}[V_{inmax}\sin(\omega t_i)] = (1-D)\sum_{i=1}^{N}[V_{Cmax}\sin(\omega t_i)] + (1-D)\sum_{i=1}^{N}[V_{0upmax}\sin(\omega t_i)] = 0$$

$$V_{Cmax} = \frac{1}{(1-D)}V_{inmax} - V_{0upmax} \tag{2.1}$$

For inductor L_2

During positive half cycle of the ac input, in one generalized switching cycle from t_i *to* $t_i + T_s$

$$v_{L2} = -v_C - 0 \text{ for } t = t_i \text{ to } t_i + DT_S$$

$$v_{L2} = v_{0up} \text{ for } t = t_i + DT_S \text{ to } t_i + T_S$$

In general, for a switching cycle integration of volt-sec of L_2 is,

$$\int_{t_i}^{t_i+T_S} v_{L2}dt = \int_{t_i}^{t_i+DT_S} -v_c\, dt + \int_{t_i+DT_S}^{t_i+T_S} v_{0up}dt$$

For complete supply cycle, integration of volt-sec of L_2 is,

$$\sum_{i=1}^{N}\int_{t_i}^{t_i+T_S} v_{L_2}\, dt = \sum_{i=1}^{N}\int_{t_i}^{t_i+DT_S} -v_C\, dt + \sum_{i=1}^{N}\int_{t_i+DT_S}^{t_i+T_S} v_{oup}\, dt = 0$$

Or,

$$\sum_{i=1}^{N}\int_{t_i}^{t_i+DT_S} V_{Cmax}\sin\omega t\, dt = \sum_{i=1}^{N}\int_{t_i+DT_S}^{t_i+T_S} V_{oupmax}\sin\omega t\, dt$$

Which leads to,

$$V_{Cmax}\sum_{i=1}^{N}[\cos(\omega t_i + \omega DT_S) - \cos\omega t_i]$$
$$= V_{oupmax}\sum_{i=1}^{N}[\cos(\omega t_i + \omega T_S) - \cos(\omega t_i + \omega DT_S)]$$

Using trigonometric identity,

$$\cos A - \cos B = 2\sin\frac{A+B}{2}\sin\frac{B-A}{2}$$

We can write,

$$V_{Cmax}\sum_{i=1}^{N}\left[2\sin\frac{2\omega t_i + \omega DT_S}{2}\sin\left(-\frac{\omega DT_S}{2}\right)\right]$$
$$= V_{oupmax}\sum_{i=1}^{N}\left[2\sin\frac{2\omega t_i + (1+D)\omega T_S}{2}\sin\left(-\frac{(1-D)\omega T_S}{2}\right)\right]$$

Or,

$$V_{Cmax}\sum_{i=1}^{N}\left[\sin(\omega t_i + \frac{\omega DT_S}{2})\sin\left(\frac{\omega DT_S}{2}\right)\right]$$
$$= V_{oupmax}\sum_{i=1}^{N}\left[\sin(\omega t_i + \frac{(1+D)\omega T_S}{2})\sin\left(\frac{(1-D)}{2}\omega T_S\right)\right]$$

Using relationship,

$\lim_{\theta\to 0}\sin\theta = \theta$,

We have,

$$V_{Cmax}\frac{\omega DT_S}{2}\sum_{i=1}^{N}\left[\sin(\omega t_i + \frac{\omega DT_S}{2})\right]$$
$$= V_{oupmax}\frac{(1-D)}{2}\omega T_S\sum_{i=1}^{N}\left[\sin(\omega t_i + \frac{(1+D)\omega T_S}{2})\right]$$

Or,

$$V_{Cmax} D \sum_{i=1}^{N} \left[\sin(\omega t_i + \frac{\omega D T_S}{2}) \right] = V_{oupmax}(1-D) \sum_{i=1}^{N} \left[\sin(\omega t_i + \frac{(1+D)\omega T_S}{2}) \right]$$

Or,

$$\frac{D}{1-D} V_{Cmax} \sum_{i=1}^{N} \left[\sin(\omega t_i + \frac{\omega D T_S}{2}) \right] = V_{oupmax} \sum_{i=1}^{N} \left[\sin(\omega t_i + \frac{(1+D)\omega T_S}{2}) \right]$$

As T_S is very small. So,

$$\lim_{T_S \to 0} \frac{\omega T_S}{2} = 0$$

So, we have

$$\frac{D}{1-D} V_{Cmax} \sum_{i=1}^{N} [\sin(\omega t_i)] = V_{oupmax} \sum_{i=1}^{N} [\sin(\omega t_i)]$$

Or,

$$V_{Cmax} = \frac{1-D}{D} V_{oupmax} \qquad (2.2)$$

From equation (A) and (B)

$$\frac{1}{1-D} V_{inmax} = \left[1 + \frac{(1-D)}{D} \right] V_{oupmax}$$

Or,

$$\frac{1}{1-D} V_{inmax} = \frac{1}{D} V_{oupmax}$$

Which leads to,

$$V_{0upmax} = \frac{D}{1-D} V_{inmax}$$

But upper output capacitor (of the split output capacitors) retains the change of positive half wave rectification.

V_{OAV} of the upper output capacitor is = $\frac{D}{1-D}\frac{V_{inmax}}{\pi}$ [Average output voltage of 1-φ Half wave rectifier is = $\frac{V_{max}}{\pi}$]

For negative half cycle, similar analysis will result in V_{OAV} across bottom output capacitor (of the split output capacitors) will have same V_{OAV} as the upper capacitor.

V_{OAV} of the bottom output capacitor is = $\frac{D}{1-D}\frac{V_{inmax}}{\pi}$

The total output average voltage is therefore,

$$V_{OAV} = \frac{D}{1-D}\left[\frac{V_{inmax}}{\pi} + \frac{V_{inmax}}{\pi}\right]$$

Or,

$$V_{OAV} = \frac{2D}{(1-D)\pi} V_{inmax} \qquad (2.3)$$

Ideal voltage gains obtained by simulation of the circuit of Fig. 2.1 (a) are compared with the calculated values as obtained from equation (2.3). The comparison results are shown in Table 2.2. Parameters used for the simulated circuit are given in Table 2.1. The voltage gains deviate significantly in low and high duty cycles of the switching signal. The deviation in the low and high duty cycle gains is expected due to non-ideal components (inductance with internal resistance, devices with internal ON resistances, switching losses etc.).

Table 2.1 Parameters of the proposed single phase SEPIC rectifier of Fig. 2.1 (a) as used for voltage gain calculations

Component	Value
L_1, L_2	5 mH
C_1	10 μF
C_{ou}, C_{od}	10 μF or 1000 μF
R_L	100 Ω
Internal R_s of inductances	0.001 Ω
Switching frequency	5 KHz.

Table 2.2 Comparison of the ideal and the simulated voltage gains of the proposed 1-phase SEPIC rectifier of Fig. 2.1 (a) [Input 212 V AC RMS]

Duty cycle D of switching signal	Theoretical Gain from the formula	Gain from simulation (Cou and Cod = 10 μF each)
0.2	0.225	0.98
0.3	0.385	1.13
0.4	0.6	1.34
0.5	0.9	1.59
0.6	1.35	2.02
0.7	2.1	2.2
0.8	3.6	3.2
0.9	8.1	3.6

The comparison between theoretical gain and simulation gain is also shown in graphical form in Fig. 2.3.

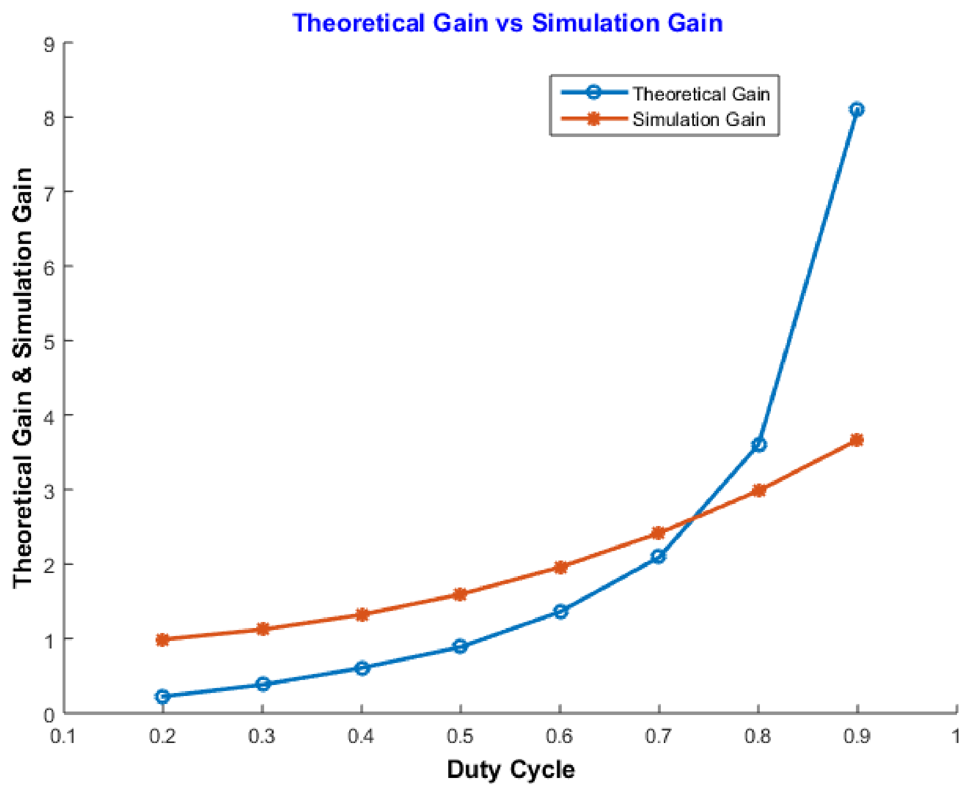


Fig. 2.3 Comparison between theoretical and simulation gain of the 1-phase version of the proposed converter.

Performance of the circuit of Fig. 2.1 (a) for open loop system under different duty cycle is shown in tabular form in Table 2.3 and in graphical form in Fig. 2.4 respectively.

Table 2.3 Performance of the proposed 1-phase SEPIC rectifier of Fig. 2.1 (a) for open loop configuration

Duty Cycle, $D = \frac{T_{ON}}{T_{OFF}}$	Voltage gain = $\frac{V_{out(Avg)}}{V_{in\ (RMS)}}$	Simulation Gain	Input Current THD (%)	Efficiency, $(\eta) = \frac{P_{out}}{P_{in}}$ (%)	Input Power factor = $\frac{P_{in}}{V_{in(RMS)} I_{in\ (RMS)}}$
0.2	0.225	0.98	13.23	77.45	0.93
0.3	0.385	1.13	14.41	75.42	0.90
0.4	0.6	1.34	13.51	82.26	0.91
0.5	0.9	1.59	11.21	81.65	0.94
0.6	1.35	2.02	9.01	80.94	0.96
0.7	2.1	2.2	7.02	79.86	0.99
0.8	3.6	3.2	4.07	69.07	0.97
0.9	8.1	3.6	68.79	41.04	0.72

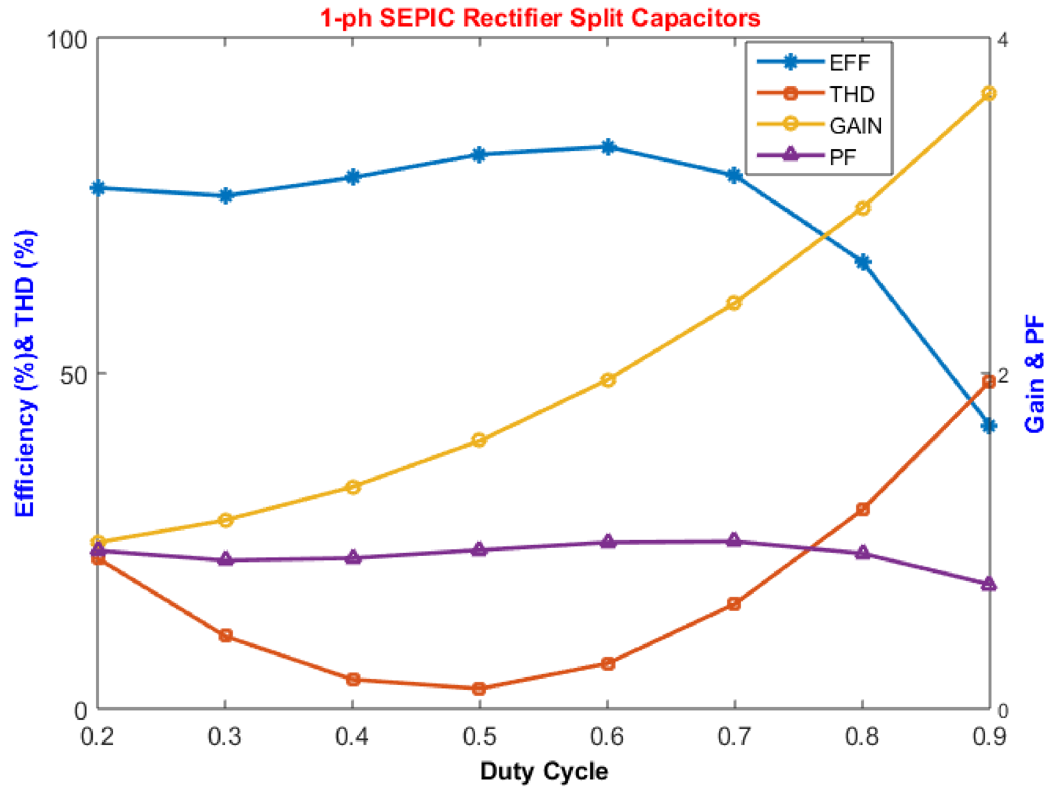


Fig. 2.4 Open loop performance of 1-phase SEPIC rectifier of Fig. 2.1 (a)

2.5 Proposed Single-Phase Version of the SEPIC Rectifier with Feedback Circuit

For improved performance of the circuit of Fig. 2.1 (a) the simulation circuit of Fig. 2.5 has been used with feedback for input power factor and the input current improvement. Representative results of the rectifier of Fig. 2.5 with fixed output load of 100 ohms are shown in Fig. 2.6. An improved performance of the circuit with high input power factor, low input current total harmonic distortion (THD) and high-power conversion efficiency has been observed. The same simulation circuit is also used for dynamic load change study with regulated output voltage. Parameters of components used in the circuit are given in Table 2.4.

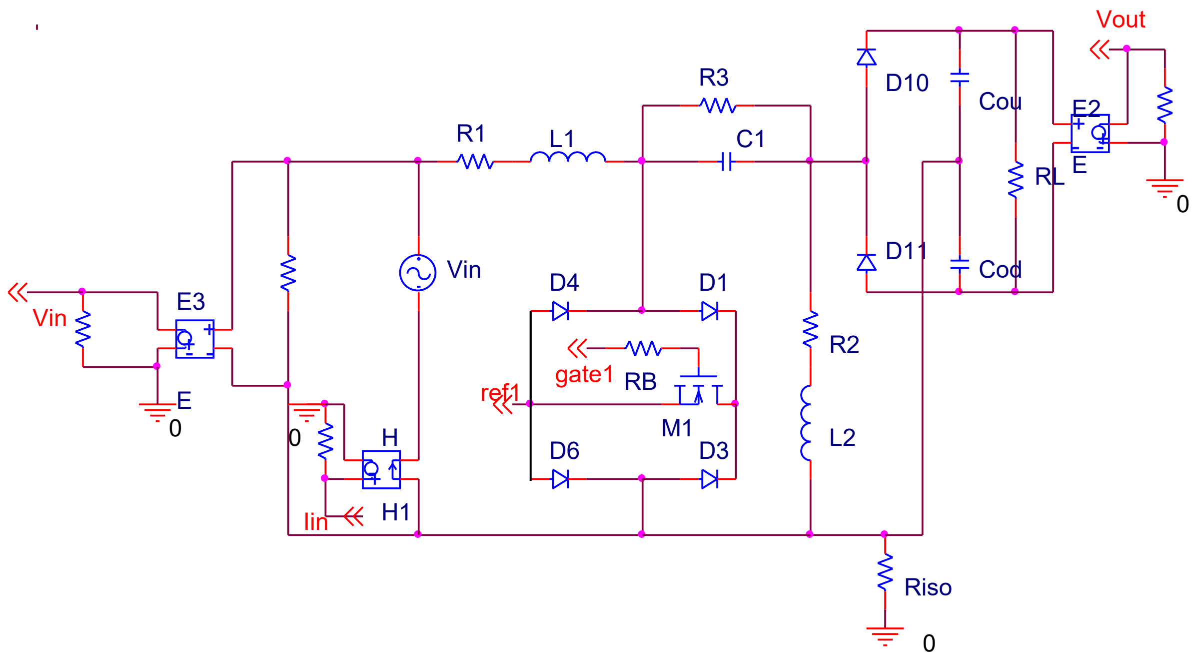


Fig. 2.5 Simulation Circuit of the Proposed Single Phase SEPIC PFC rectifier with feedback control.

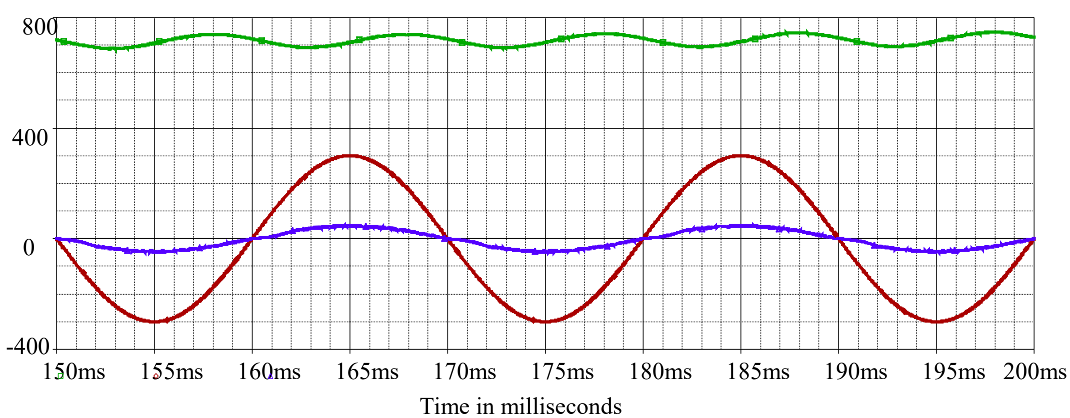


Fig. 2.6 Simulated waveforms of the proposed single phase SEPIC rectifier of Fig. 2.5 with feedback control (input/output voltages and input current for a load of 100 Ω) [input power factor = 0.95, input current THD = 5.9% and the conversion efficiency = 81% for output voltage regulated at 710V]

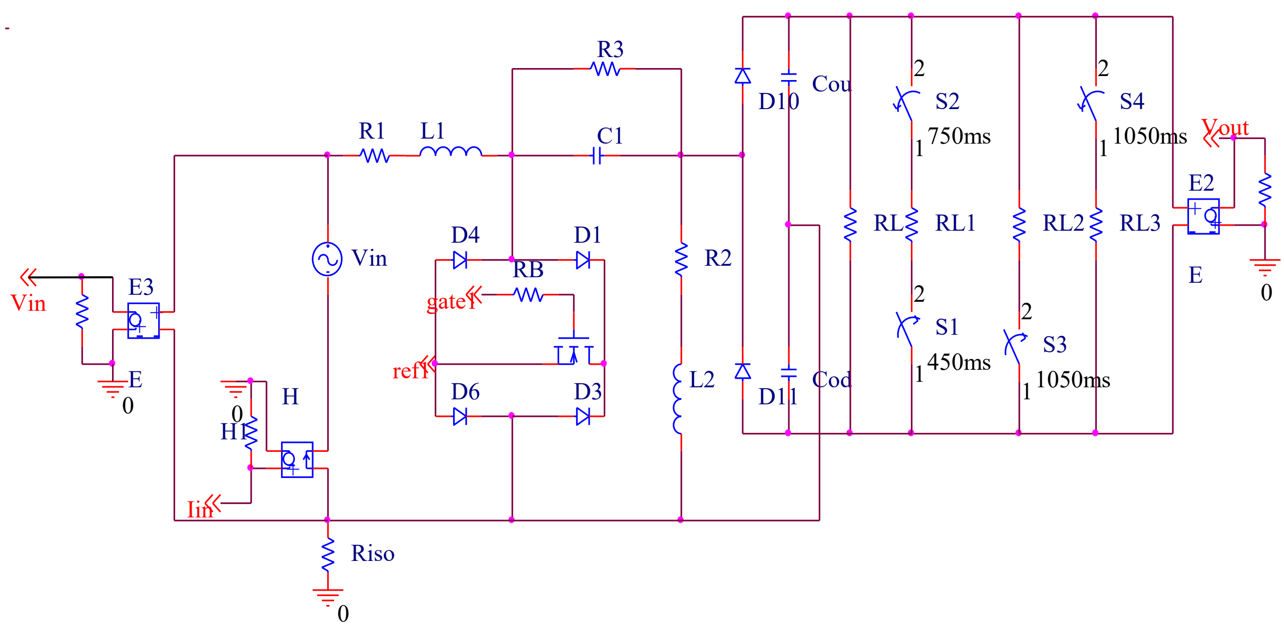


Fig. 2.7 Simulation Circuit of the Proposed Single Phase SEPIC PFC rectifier for dynamic response study with feedback control.

Table 2.4 Parameters of the proposed single-phase version of the rectifier of Fig. 2.1 (a) as used in simulation purposes of the circuit with feedback (Fig. 2.5) and feedback dynamic response (Fig. 2.7)

Component	**Value**
Inductor L_1, L_2	5 mH
Internal R of L_1 and L_2	0.001 Ω
Output capacitors C_{ou}, C_{od}	1000 µF
C_1	10 µF
Load resistors R_L, R_{L1}, R_{L2}, R_{L3}	200, 400, 300, 200 Ω
S1 (closes)	450 ms
S2 (opens)	750 ms
S3 (closes) and S4 (opens)	1050 ms
R_B	10 Ω
R_{iso}	10 KΩ

The ability of the feedback to maintain regulated output under load change and keep the good performance are also studied by simulation of the circuit of Fig. 2.7. The variation of the load changed at time instances for the study are provided in Table 2.5.

Table 2.5 Load variation with time as used in dynamic response study

Time in milliseconds	Load (ohm)
200-450	100
450-750	80
750-1050	100
1050-1400	120

Representative output voltage and input current waveforms are shown in Fig. 2.7. Those waveforms of Fig. 2.8 show that every time the load is changed, the voltage returns to the regulated value and the input current changes as required by the load. The regulation of the output voltage is maintained with fairly good performance of the circuit in terms of input current THD, input power factor and power conversion efficiency as indicated the Fig. 2.8.

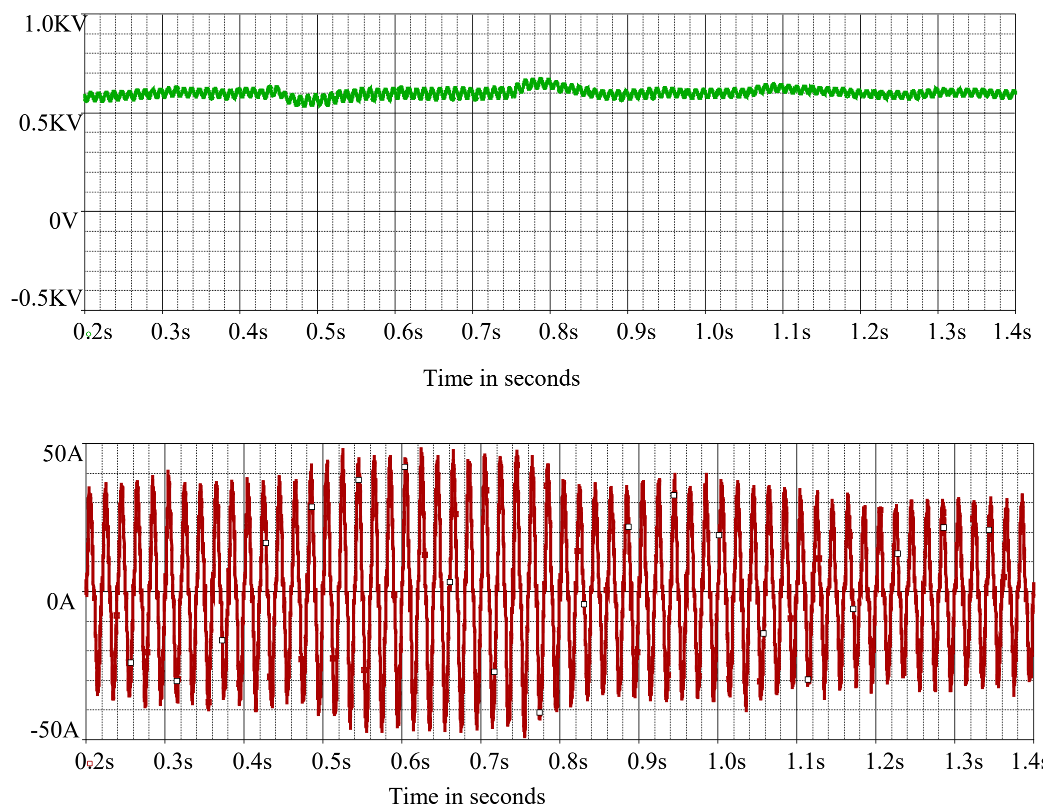


Fig. 2.8 Simulated dynamic response with change of load of the single-phase version of the proposed SEPIC rectifier (load change takes place at 450 msec., 750 msec., 1050 msec., output voltage is regulated to 600 V DC, input power factor is above 0.9, input current THD is lower than 16% and the power conversion efficiency is above 85%)

2.6 Discussions

It is clear from the waveforms of Figs. 2.2 that the proposed input switched SEPIC rectifier draws non-sinusoidal input current when operated without any feedback control. Non-sinusoidal input currents of the rectifier have large THD, causes low input power factor and extra losses in utilities with low conversion efficiency. These are verified from simulation results presented in Table 2.3. The THD and power factor of the circuit has been improved by properly designed PFC feedback controller which is apparent in simulated waveforms of Fig. 2.6. From the dynamic response of Fig. 2.8, the ability of the feedback to maintain regulated output under load change keeping the good performance is also verified.

Chapter 3

Proposed Three Switch Three Phase Modular SEPIC Rectifier

3.1 Introduction of Proposed 3-phase SEPIC Rectifier

For high power conversions, it is advantageous to use three phase rectifiers with active means for power factor correction and input current shaping. Applications requiring unidirectional power flow and controlled output voltage, single switch (between three-phase rectifier and the load) topology reported does not provide input current shaping without large input filters. The large filter at the input degrades the efficiency of the converter. In this regard three phase Vienna rectifiers are popular converter systems, where, input current waveforms are controlled by three switches and output is taken from a split DC rail. A brief survey of high performance three phase rectifiers is available in references [10, 16]. Improved performances of Vienna and modular three-switch three phase boost rectifiers when operated with appropriate feedback controls are found in reference [32]. But Vienna and boost rectifiers provide boost voltage gain characteristic only the application of which is limited.

Modular three phase rectifiers convert per phase ac to dc at the load and the feedback controllers track the input current as per corresponding phase voltage template of the supply. As a result, the input current shaping and input power factor improvement are expected. The voltage regulation is accomplished in the same control circuit by comparing a reference control voltage with the monitored output voltage. The concept of modular boost rectifier is extended to the proposed input switched and output regulated three-phase three switch Single Ended Primary Inductor Converter (SEPIC) rectifier. It is composed of three single phase PFC rectifiers with both step-up and step-down voltage gain characteristics. The rectifier shows promise of a high performance three-phase rectifier in terms of PFC, input current THD and efficiency when operated with proper feedback control.

3.2 Working Principle

A three-phase modular SEPIC rectifier with three controlled switches can be developed by cascading three proposed single phase SEPIC rectifier of Fig. 2.1(a). The proposed 3-switch 3-phase circuit is shown in Fig. 3.1. It works on per-phase basis, which is needed for enabling input current tracking with input voltage for power factor correction. The output of the three phases are superimposed at the load at the upper and lower output capacitors during the positive and negative supply cycle. The 6 output capacitors of the circuit of Fig. 3.1 may be considered as two common capacitors and can be replaced by two capacitors Cou and Cod as shown in Fig. 3.3. With the modifications made to the circuit of Fig. 3.1 circuit of Fig. 3.3 results with less elements. The operation per phase of the circuit of Fig. 3.1 is identical to that of single phase version of the circuit as illustrated in Fig. 2.1 (b-e).

The circuit of the Fig. 3.1 has three boost inductors distributed over three input lines. AC per phase positive and negative supply voltage is rectified independently. Input line currents of three phases therefore appear similar to 1-phase rectifier currents. This provides opportunity to adopt power factor correction and input current improvement method of 1-phase rectifier in the proposed three phase modular rectifier circuit.

Simulated output voltage and input currents of the circuit of Fig 3.1 for duty cycle of 0.3 and 0.6 with input voltage of 212 V RMS per phase are shown in Figs. 3.2 (a) and 3.2 (b) respectively. The waveforms of Figs. 3.2 are obtained without any feedback control of the circuit.

In Figs. 3.4 (a) and 3.4 (b) typical output voltage and input currents of the circuit of Fig 3.3 for duty cycle of 0.3 and 0.6 without any feedback are also shown. From the waveforms, it is evident that the circuit of Fig. 3.1 and Fig. 3.3 show almost same performance without any degradation.

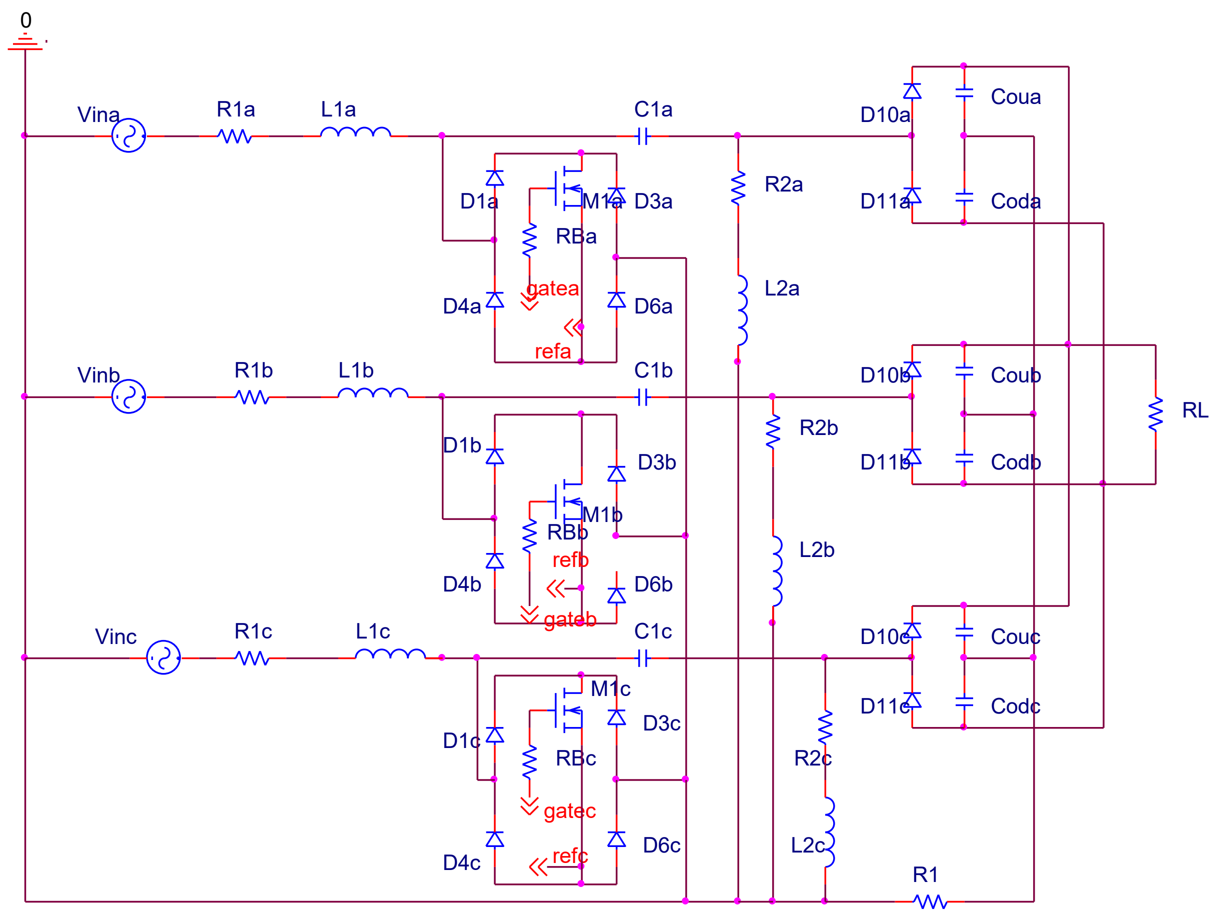


Fig. 3.1 The rectifier with three single phase half bridge rectifiers having three control switches and six output capacitors.

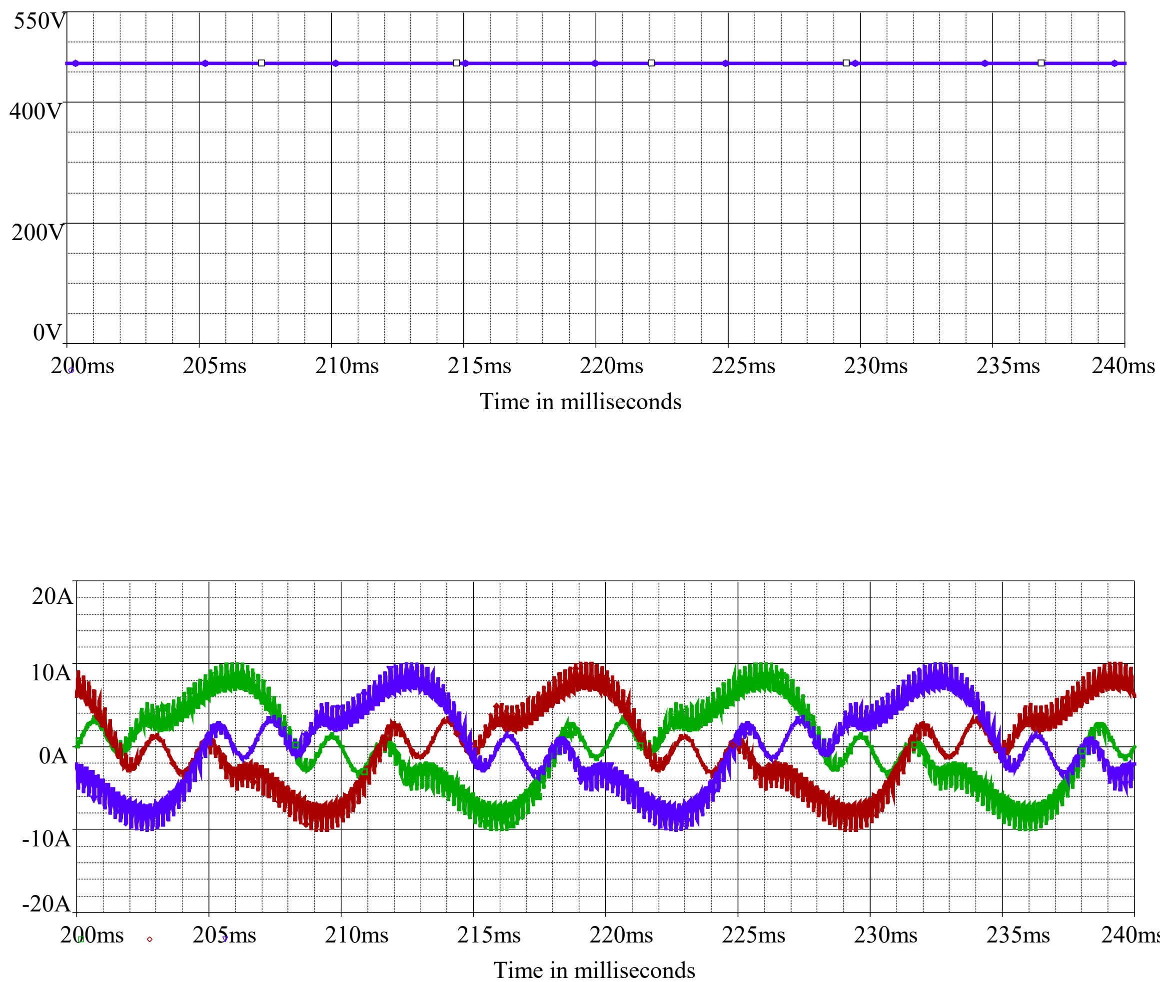

550V
400V
200V
0V
200ms
205ms
210ms
215ms
220ms
225ms
230ms
235ms
240ms
Time in milliseconds
20A
10A
0A
-10A
-20A
200ms
205ms
210ms
215ms
220ms
225ms
230ms
235ms
240ms
Time in milliseconds

Fig. 3.2 (a)

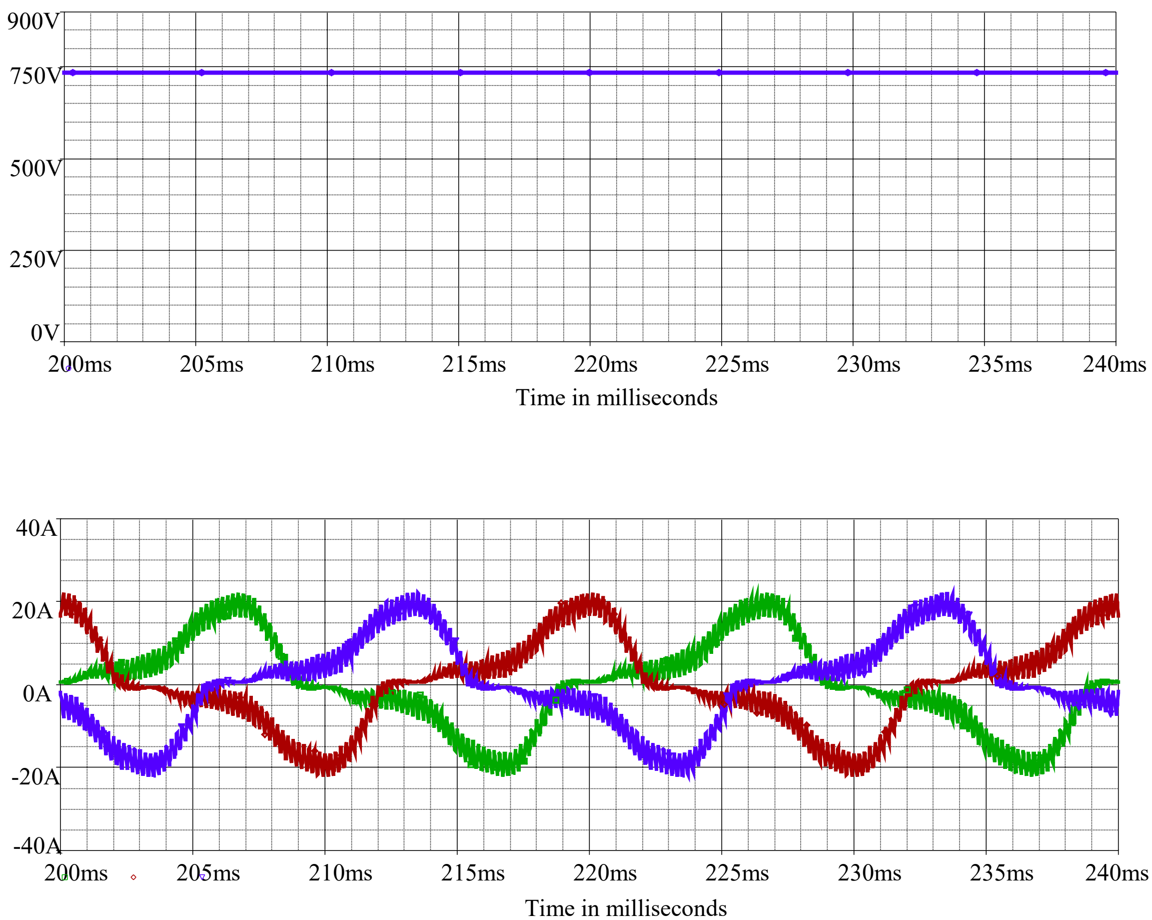


Fig. 3.2 (b)

Fig. 3.2 typical output voltage and input currents of the circuit of Fig. 3.1 at input voltage of 212 V AC (RMS) per phase.

(a) at duty cycle 0.3 (b) at duty cycle 0.6

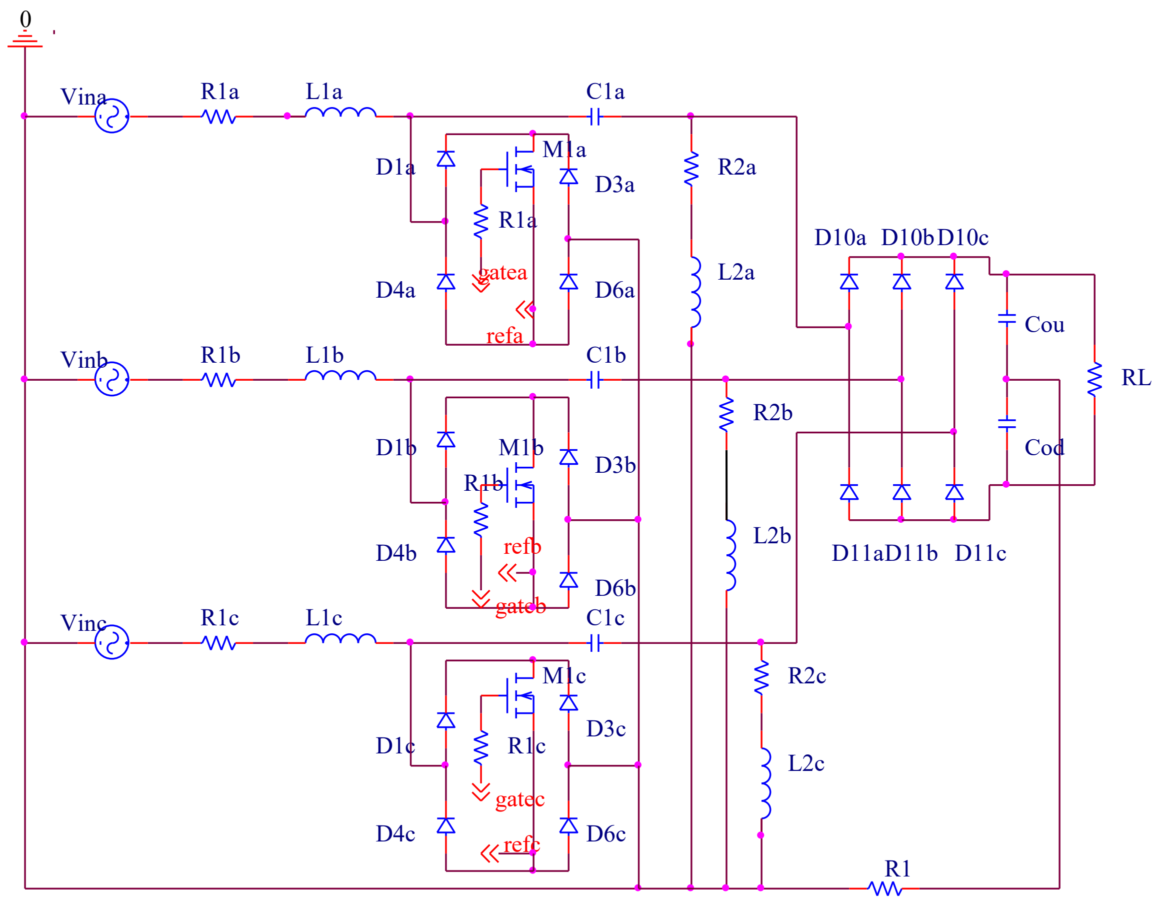


Fig. 3.3 The rectifier with three single phase half bridge rectifiers having three control switches and two common output capacitors.

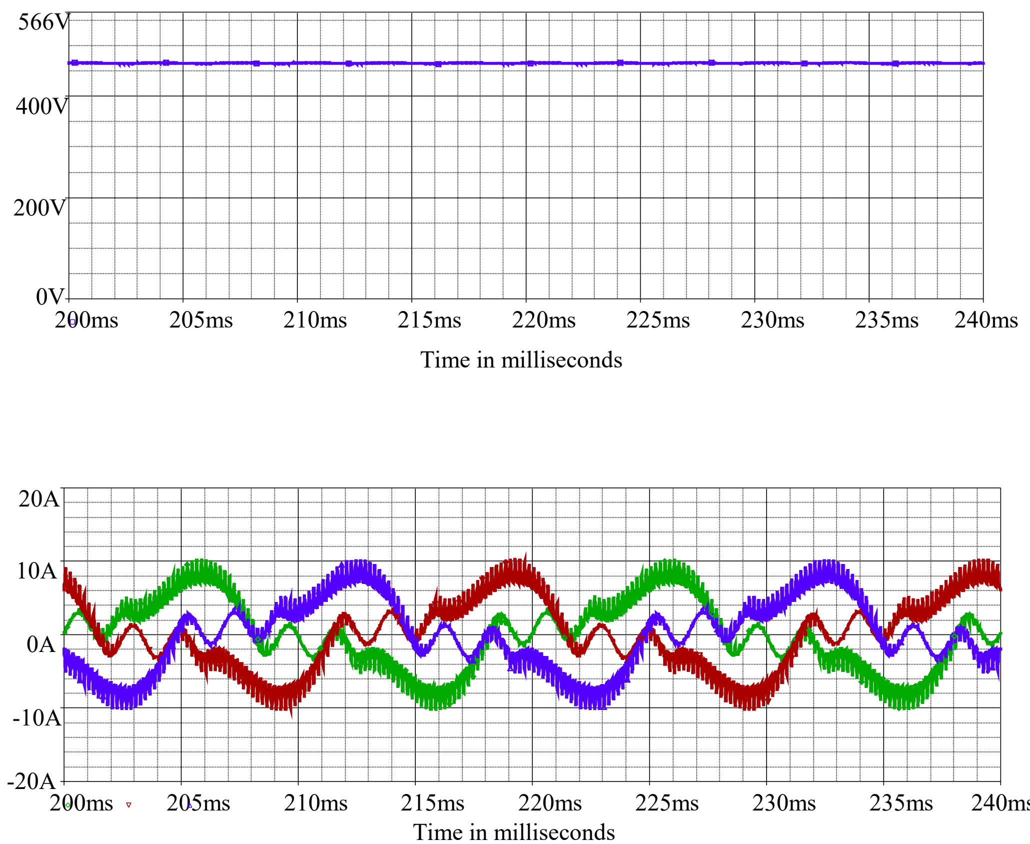
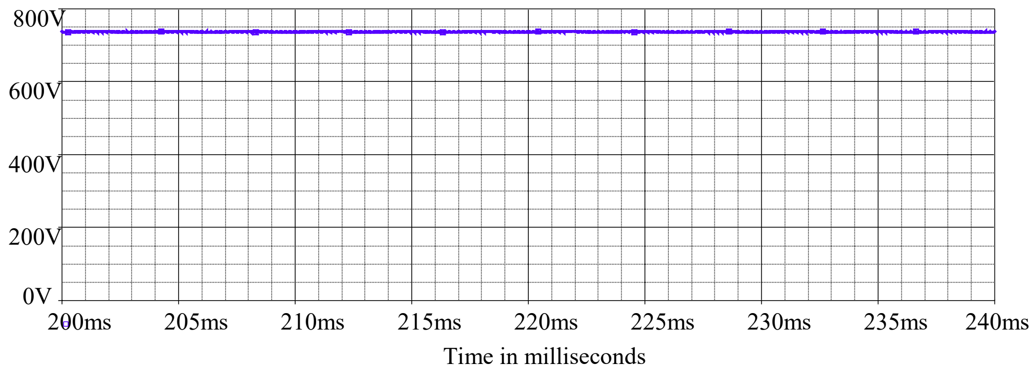

566V
400V
200V
0V
200ms
205ms
210ms
215ms
220ms
225ms
230ms
235ms
240ms
Time in milliseconds
20A
10A
0A
-10A
-20A
200ms
205ms
210ms
215ms
220ms
225ms
230ms
235ms
240ms
Time in milliseconds

Fig. 3.4 (a)



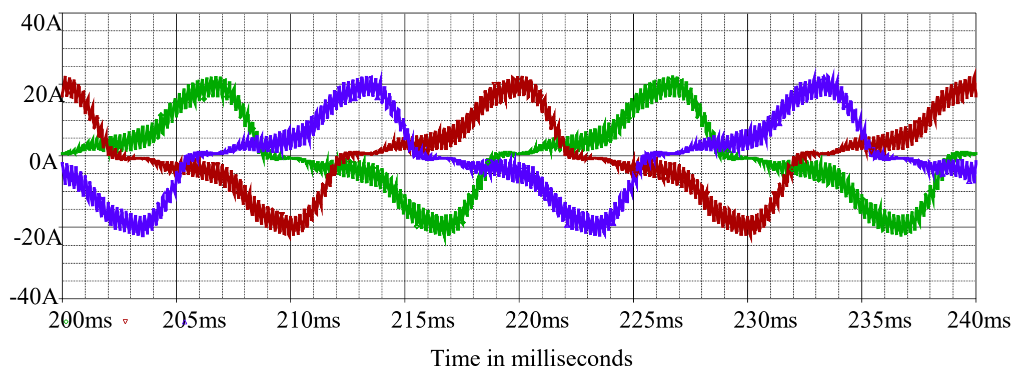


Fig. 3.4 (b)

Fig. 3.4 typical output voltage and input currents of the circuit of Fig. 3.3 at input voltage of 212 V AC (RMS) per phase.

(a) at duty cycle 0.3 (b) at duty cycle 0.6

3.3 Ideal Voltage Gain of 3-φ SEPIC Input Switched AC-DC Rectifier with Split Output Capacitors

The operation per-phase of the circuit of Fig. 3.1 and Fig. 3.3 to the output is same as the single-phase rectifier of Fig. 2.1 (a) and as derived in equation (2.3), the total average dc output voltage across upper and lower output capacitor (across load) due to each phase is,

$$V_{oAV} = \frac{2D}{(1-D)\pi} V_{inmax}$$

Since the output of the proposed three phase rectifier is the superposition of voltages of three phase at the output, the ideal voltage gain of the proposed three phase rectifier is,

$$V_{0AV} = \frac{1}{\frac{\pi}{3}} \int_{\frac{\pi}{3}}^{\frac{2\pi}{3}} V_{LLmax} \sin \omega t d(\omega t)$$

$$= \frac{3V_{LLmax}}{\pi} \int_{\frac{\pi}{3}}^{\frac{2\pi}{3}} \sin \omega t d(\omega t)$$

$$= \frac{3V_{LLmax}}{\pi} \left[-\cos\frac{2\pi}{3} + \cos\frac{\pi}{3} \right]$$

$$= \frac{3V_{LLmax}}{\pi} = \frac{3\sqrt{3}V_{LNmax}}{\pi}$$

$$V_{0AV} = \frac{3\sqrt{3D}}{\pi(1-D)} V_{inmax(LN)} \qquad (3.1)$$

The calculated values of output voltage of the proposed rectifier given by the formula of equation (3.1) and the simulated values for input voltage 212V AC (RMS) per phase are compared in Table 3.2. Except for very low and very high duty cycles the voltage gain are comparable. The deviation beyond certain range of duty cycle is due to the non-ideal device parameters and characteristics in the real world (L with internal R, switches and diodes with conduction drop resistances, switching losses etc.).

Table 3.1 Parameters of the proposed Three phase SEPIC rectifier of Fig. 3.1 and Fig. 3.3 as used for voltage gain calculations

Component	**Value**
L_{1a}, L_{1b}, L_{1c}	5 mH
C_{1a}, C_{1b}, C_{1c}	10 μF
L_{2a}, L_{2b}, L_{2c}	5 mH
C_{ou}, C_{od}	1000 μF
R_L	100 Ω
Internal Rs of inductances	.001 Ω
Switching frequency	5 KHz.
V_{ina}, V_{inb}, V_{inc}	212 V AC (RMS)

Table 3.2 Comparison of ideal and simulated voltage gains of the proposed three phase SEPIC rectifier of Fig. 3.1 with input 212 V AC (RMS) per phase

Duty Cycle D of the switching signal	Average Output Voltage calculated from Formula derived (V)	Output voltage obtained from simulation, Cou and Cod = 1000 µF each (volt)
0.2	123.97	447.5
0.3	212.52	464.59
0.4	330.6	482.4
0.5	495.9	523.8
0.6	743.8	734.29
0.7	1157.1	1011.1
0.8	1983.6	1329
0.9	4463.1	1091

Table 3.3 Comparison of ideal and simulated voltage gains of the proposed three phase SEPIC rectifier of Fig. 3.3 with input 212 V AC (RMS) per phase

Duty Cycle D of the switching signal	Average Output Voltage calculated from Formula derived (V)	Output voltage obtained from simulation, Cou and Cod = 1000 μF each (volt)
0.2	123.97	448.24
0.3	212.52	465.311
0.4	330.6	483.17
0.5	495.9	523.55
0.6	743.8	736.877
0.7	1157.1	1013.1
0.8	1983.6	1340.6
0.9	4463.1	1293.0

Performances of circuits of Fig. 3.1 and Fig. 3.3 for open loop system under different duty cycle are shown in tabular form in Table 3.4 and Table 3.5 and in graphical form in Fig. 3.5 and Fig. 3.6 respectively.

Table 3.4 Comparison of the ideal and the simulated voltage gains of the proposed 3-phase SEPIC rectifier of Fig. 3.1 [Input 212V LN AC RMS]

Duty Cycle (D) = T_{on}/T	Voltage gain = $V_{out(avg)}/V_{in(rms)(LL)}$	Simulation Gain	Input Current THD (%)	Efficiency, (η) = P_{out}/P_{in} (%)	Input Power factor = $P_{in}/(V_{in})_{rms}(I_{in})_{rms}$
0.2	0.34	1.218	60.35	84.9	0.83
0.3	0.58	1.26	55.49	88.6	0.89
0.4	0.90	1.31	50.85	95.18	0.87
0.5	1.35	1.42	54.63	97.5	0.82
0.6	2.02	1.99	45.73	92.1	0.91
0.7	3.15	2.75	36.7	90.84	0.816
0.8	5.4	3.61	21.72	76.45	0.77
0.9	12.15	2.96	3.86	33.4	0.57

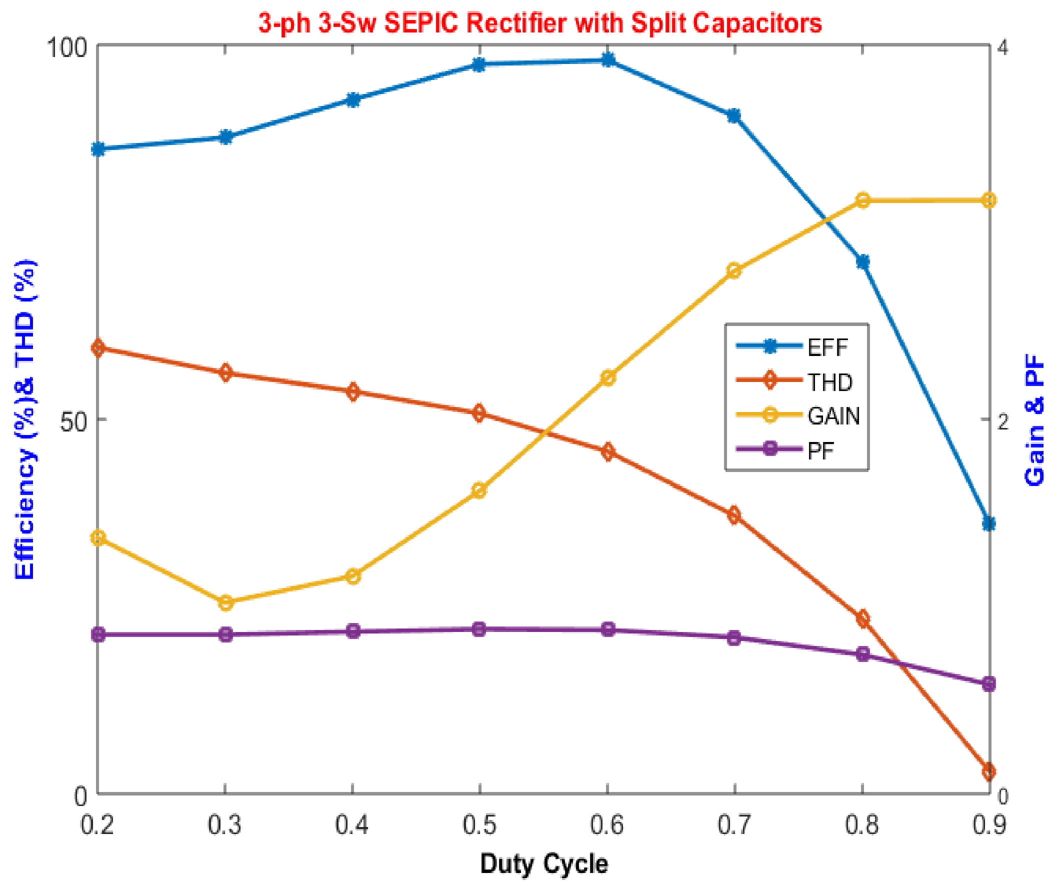


Fig. 3.5 Open loop performance of 3-phase SEPIC rectifier of Fig. 3.1.

Table 3.5 Comparison of the ideal and the simulated voltage gains of the proposed 3-phase SEPIC rectifier of Fig. 3.3 [Input 212V LN AC RMS]

Duty Cycle (D) = T_{on}/T	Voltage gain = $V_{out(avg)}/V_{in(rms)(LL)}$	Simulation Gain	Input Current THD (%)	Efficiency, (η) = P_{out}/P_{in} (%)	Input Power factor = $P_{in}/(V_{in})_{rms}(I_{in})_{rms}$
0.2	0.34	1.22	60.6	86.9	0.78
0.3	0.58	1.26	56.06	88.76	0.83
0.4	0.90	1.31	51.27	92.8	0.84
0.5	1.35	1.42	54.78	98.7	0.83
0.6	2.02	2.00	46.29	96.27	0.816
0.7	3.15	2.75	37.19	93.75	0.84
0.8	5.4	3.64	22.3	80.84	0.77
0.9	12.15	3.52	4.72	47.1	0.59

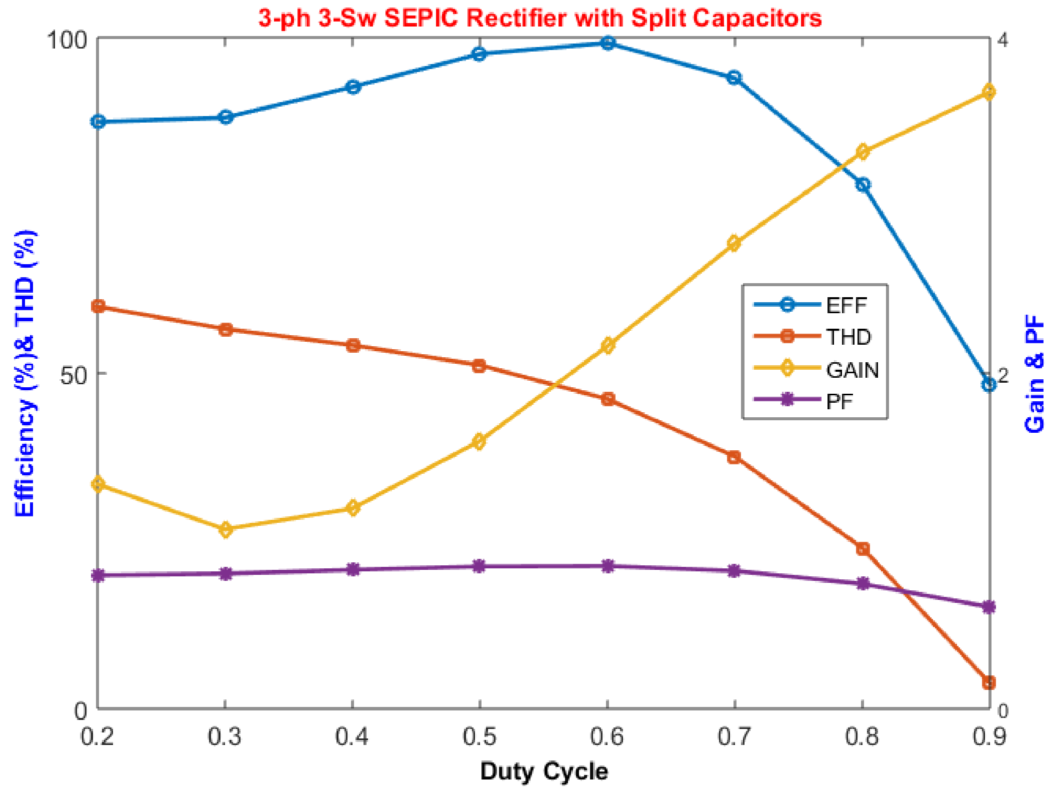


Fig. 3.6 Open loop performance of 3-phase SEPIC rectifier of Fig. 3.3.

3.4 Proposed Three-Phase SEPIC Rectifier with Feedback Circuit

For the results of Table 3.4 and Table 3.5, uniform gate pulses to switches of Fig. 3.1 and Fig. 3.3 are used. Fig. 3.1 and Fig. 3.3 are redrawn in Fig. 3.7 (a) and Fig. 3.7 (b) respectively which are used to obtain the results of the circuit by simulation with feedback for better performance in terms of Input current THD, Input power factor and efficiency. The parameters of the circuit are kept the same as shown in Table 3.1.

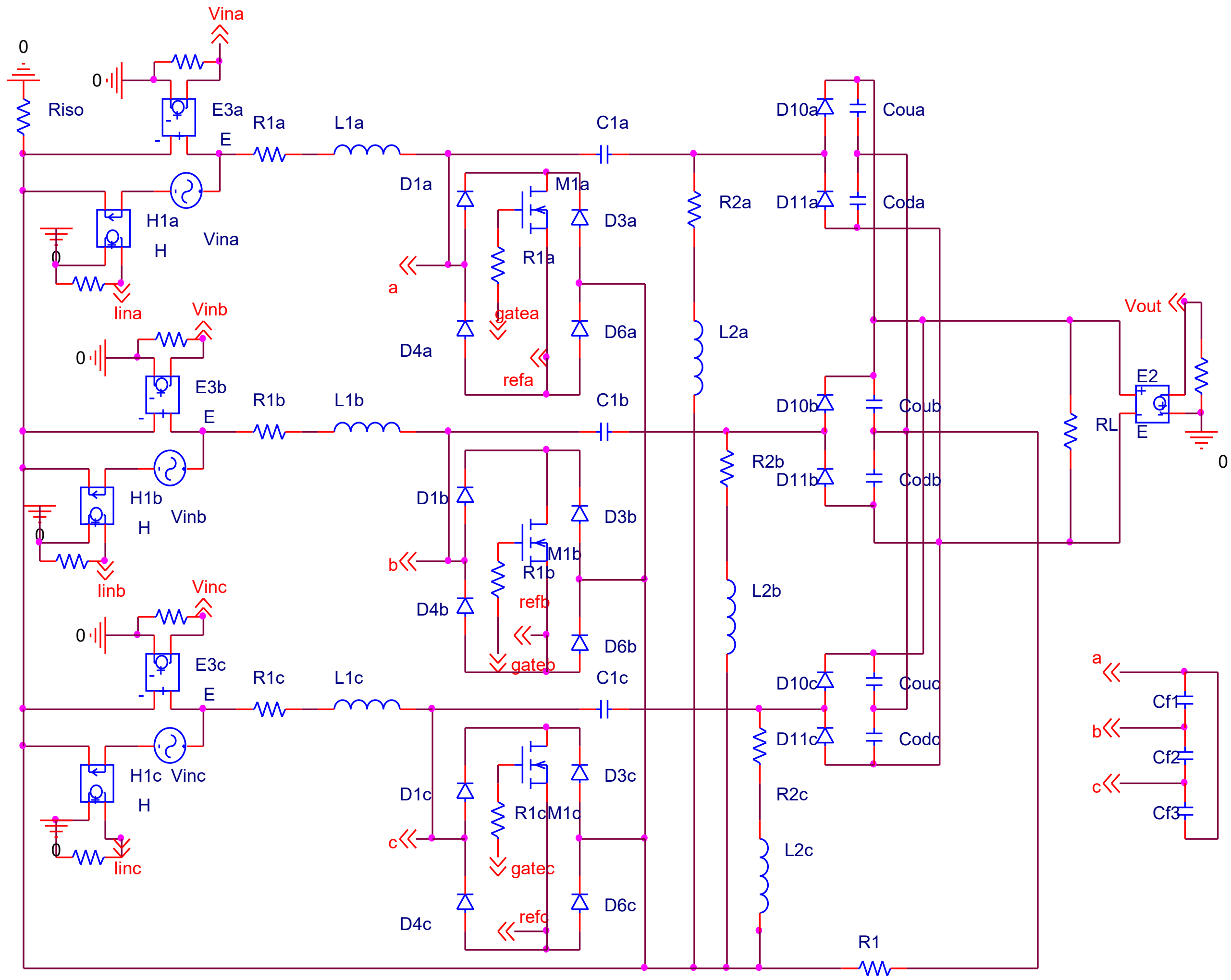

Vina
0
Riso
E3a
E
R1a
L1a
C1a
D10a
Coua
D11a
Coda
H1a
H
Vina
D1a
M1a
D3a
R2a
a
R1a
lina
Vinb
gatea
D4a
D6a
L2a
refa
E3b
E
R1b
L1b
C1b
D10b
Coub
R2b
D11b
Codb
H1b
H
Vinb
D1b
D3b
b
M1b
R1b
L2b
linb
refb
D4b
Vinc
D6b
gateb
E3c
E
R1c
L1c
C1c
D10c
Couc
D11c
Codc
H1c
Vinc
H
D1c
D3c
R2c
c
R1c
M1c
linc
gatec
L2c
D4c
refc
D6c
R1
Vout
E2
E
RL
a
Cf1
b
Cf2
c
Cf3

Fig. 3.7 (a)

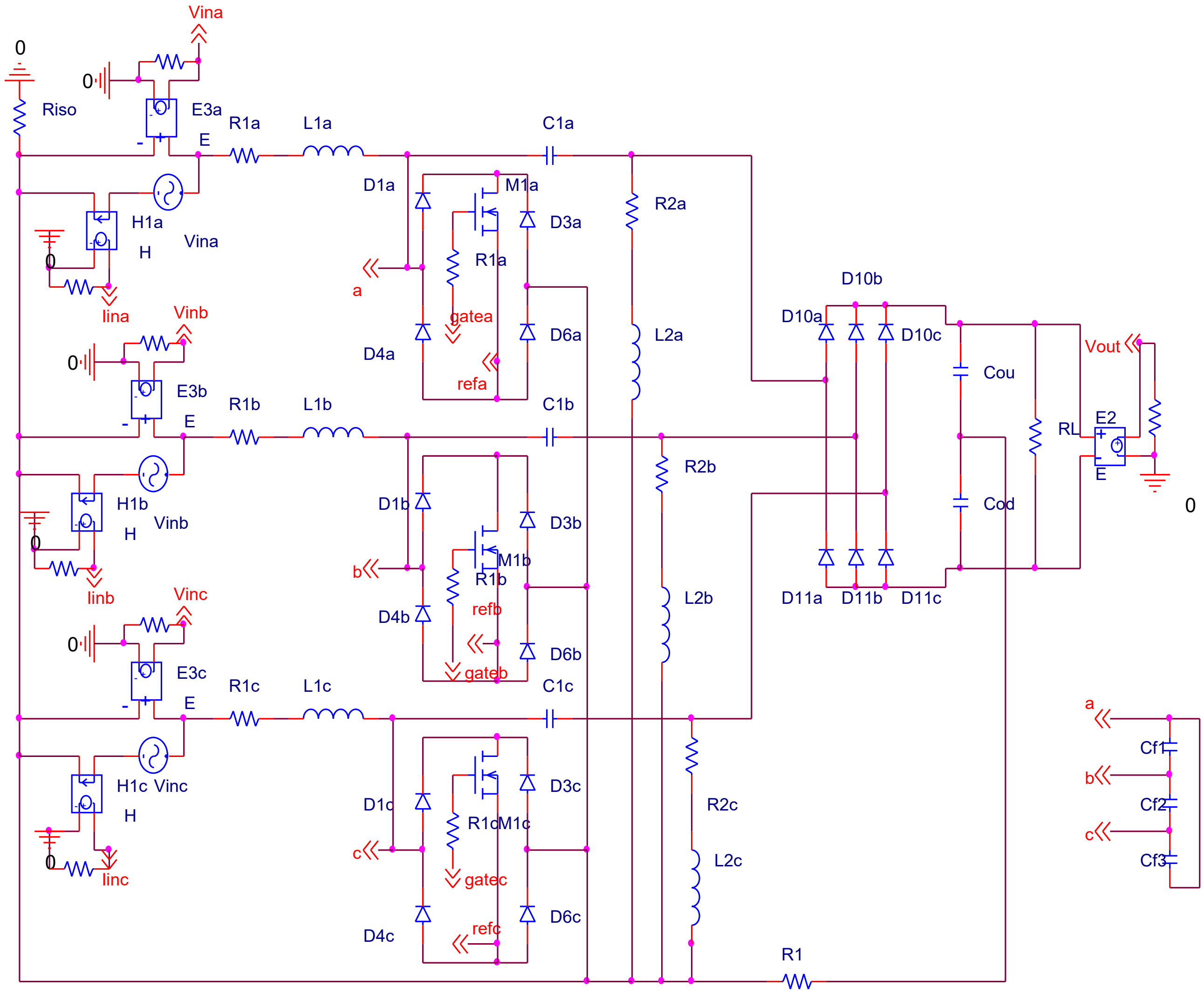


Fig. 3.7 (b)

Fig. 3.7 Proposed three phase three-switch SEPIC PFC rectifier circuit with feedback

(a) with six output capacitors (b) with two common output capacitors

Circuits of Figs. 3.7 (a) and (b) are studied for typical waveforms observation when operated with feedback control with a fixed load. Typical waveforms of output voltage, input voltage and input current are presented in Figs. 3.8 (a) and (b) for proposed three-phase three switch rectifier of 6 output capacitors and 2 common output capacitor version. Input current THD, input power factor and the conversion efficiency of the results of Figs. 3.8 (a) and (b) are presented in Table 3.6.

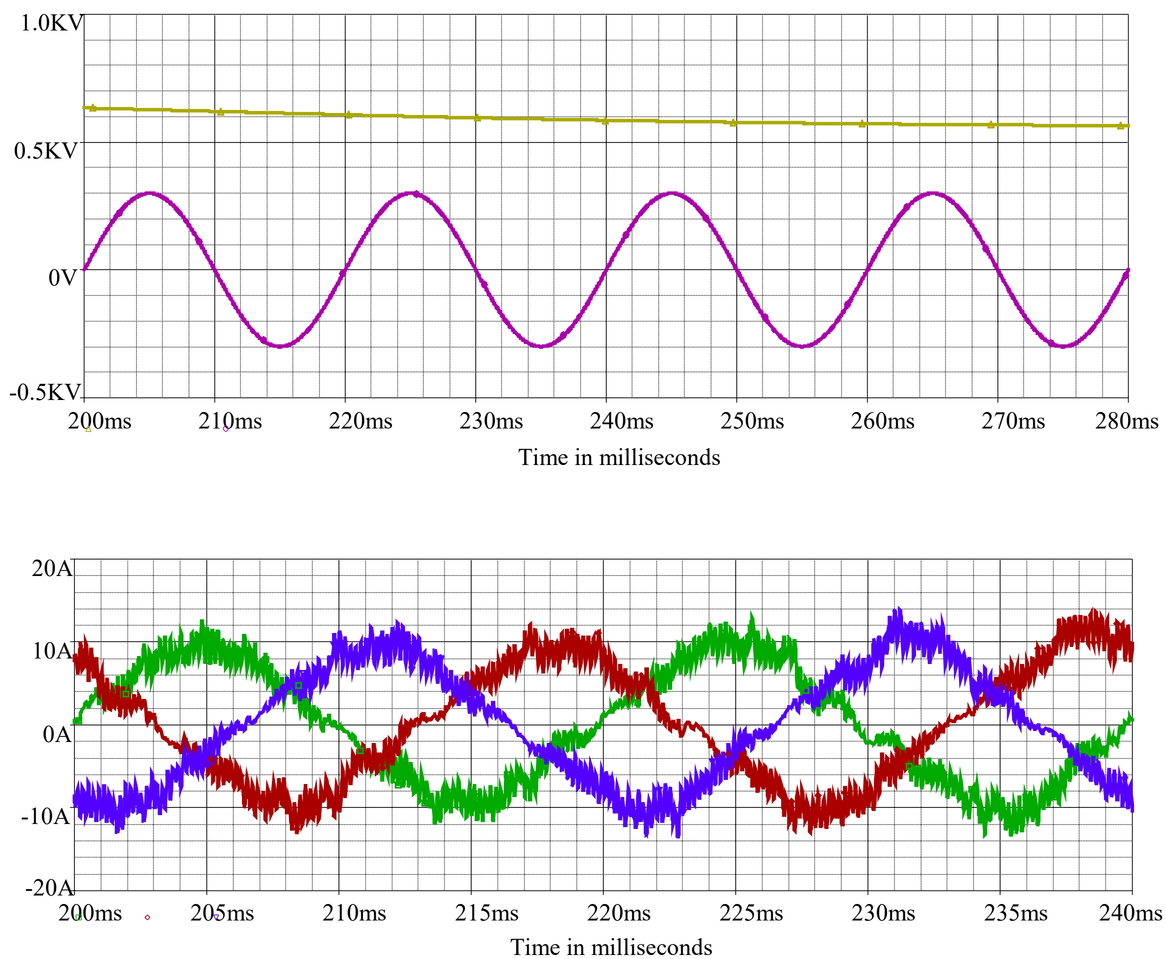


Fig. 3.8 (a)

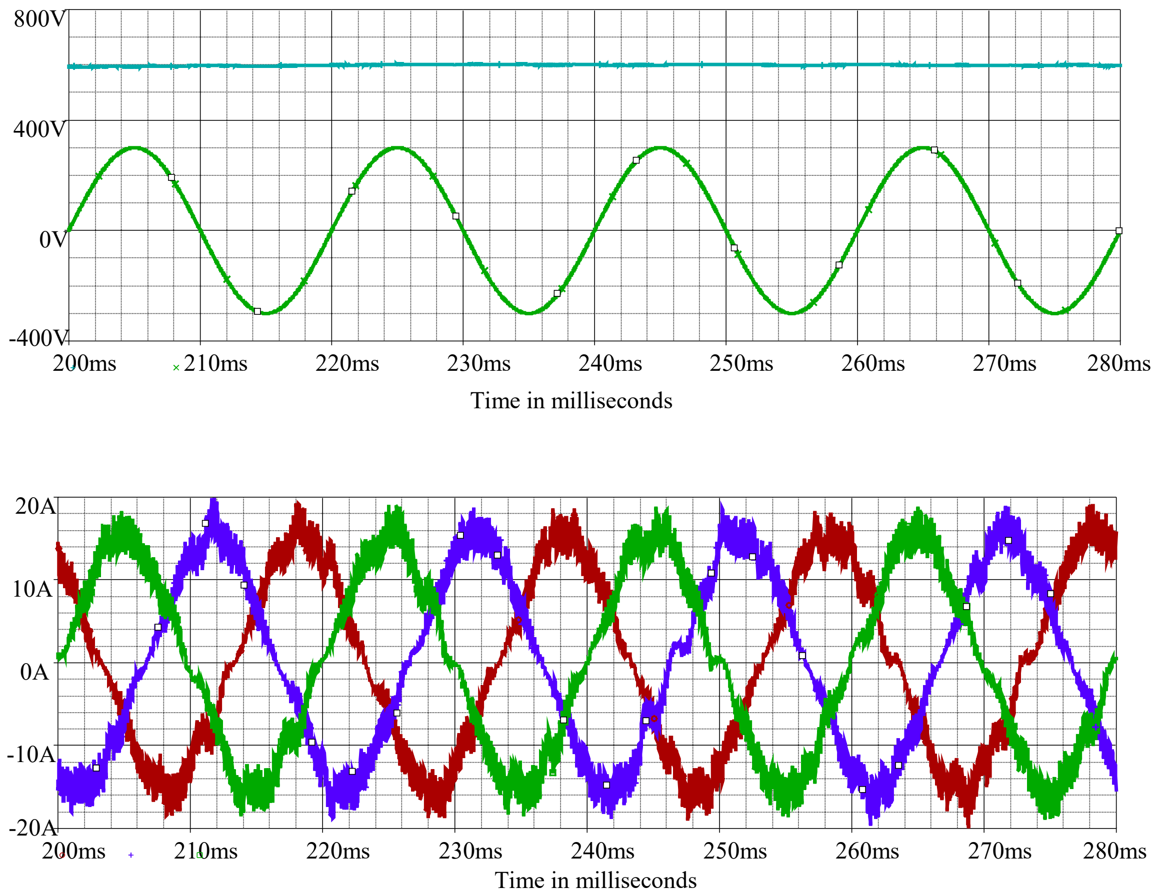


Fig. 3.8 (b)

Fig. 3.8 Typical simulated output voltage, input voltage and input currents of the circuit of Fig. 3.7 (a) and Fig. 3.7 (b) with a load of 100 ohms and the output voltage regulated to about 600 V DC (input 212 V AC RMS, per phase)

(a) Waveforms of Fig. 3.7 (a) (b) Waveforms of Fig. 3.7 (b)

Table 3.6 Input current THD, input power factor and conversion efficiency of results of Fig 3.7 (a)

Proposed three-switch three phase SEPIC PFC rectifier of Fig. 3.7 (a)		
Input current THD (%)	Input power factor	Conversion efficiency (%)
13.2	0.98	90.5

Table 3.7 Input current THD, input power factor and conversion efficiency of results of Fig 3.7 (b)

Proposed three-switch three phase SEPIC PFC rectifier of Fig. 3.7 (b)			
Filter Capacitor value	Input current THD (%)	Input power factor	Conversion efficiency (%)
0.5 μF	10.8	0.98	82.8
0.2 μF	17.2	0.97	87

For dynamic load change study with regulated output voltage the circuits of Fig. 3.7 (a) and Fig. 3.7 (b) are redrawn as shown in Fig. 3.9 (a) and Fig. 3.9 (b) respectively. Parameters of components used in these circuits are same as given in Table 3.1.

The dynamic behaviours of circuits of Figs. 3.9 (a) and (b) as the load is changed as per time shown in Table 3.8 are shown in Figs. 3.10 and 3.11 respectively. Both three switch proposed rectifiers show regulated voltage with proper feedback control maintaining the rectifier performance satisfactory with small degradation of the input current THD and the conversion efficiency.

Table 3.8 Load variation with time as used in dynamic response study

Time in milliseconds	Load (ohms)
200-450	100
450-750	80
750-1050	100
1050-1400	120

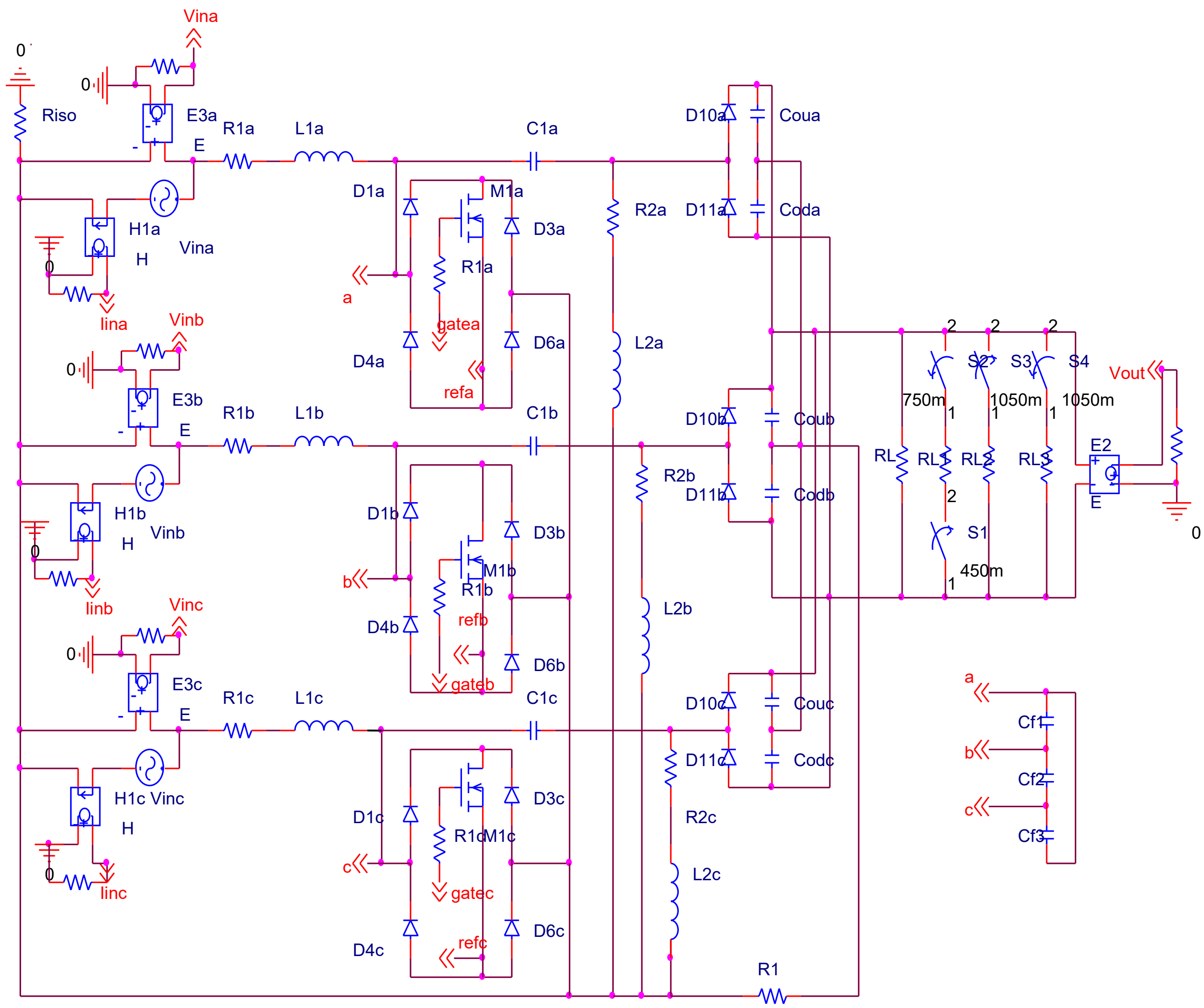

Vina
Riso
E3a
R1a
L1a
C1a
D10a
Coua
D11a
Coda
H1a
Vina
Iina
D1a
M1a
D3a
R1a
R2a
gatea
D4a
D6a
refa
L2a
Vinb
E3b
R1b
L1b
C1b
D10b
Coub
D11b
Codb
R2b
H1b
Vinb
Iinb
D1b
D3b
M1b
R1b
refb
D4b
D6b
gateb
L2b
Vinc
E3c
R1c
L1c
C1c
D10c
Couc
D11c
Codc
H1c Vinc
D1c
D3c
R1cM1c
gatec
R2c
L2c
D4c
D6c
refc
R1
S2
S3
S4
750m
1050m
1050m
RL
RL1
RL2
RL3
S1
450m
Vout
E2
Cf1
Cf2
Cf3

Fig. 3.9 (a)

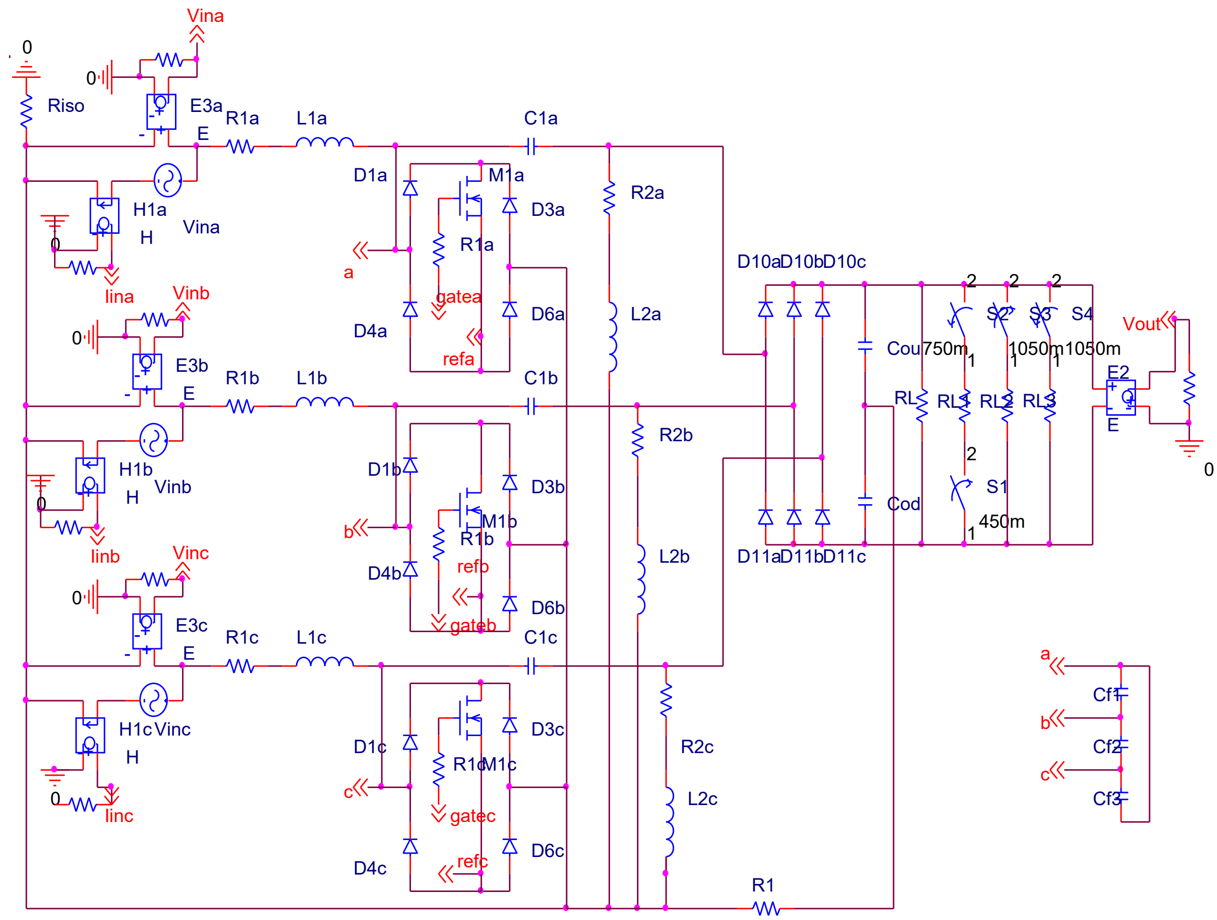


Fig. 3.9 (b)

Fig. 3.9 Simulation Circuit of the Proposed Three Phase three switch SEPIC PFC rectifier for dynamic response study with feedback control

(a) with six output capacitors (b) with two common output capacitors

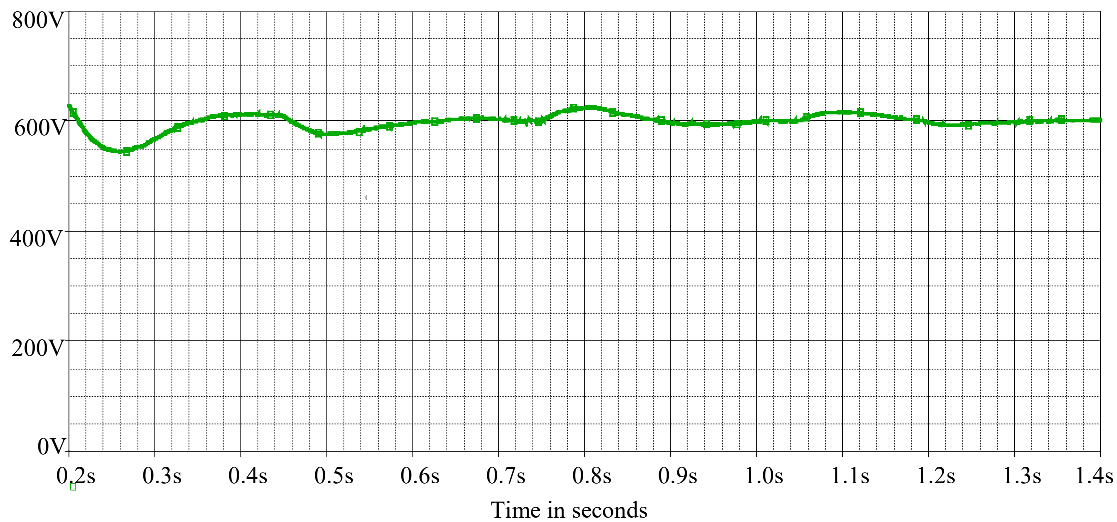


Fig. 3.10 (a) Trace of Output voltage

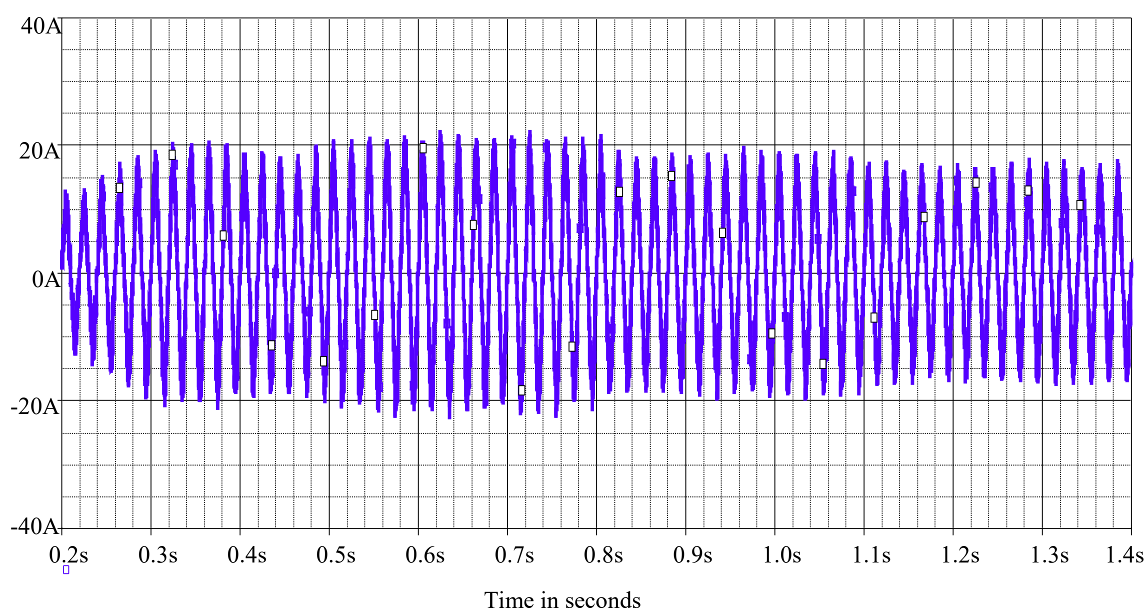


Fig. 3.10 (b) Trace of Input Current of Phase A

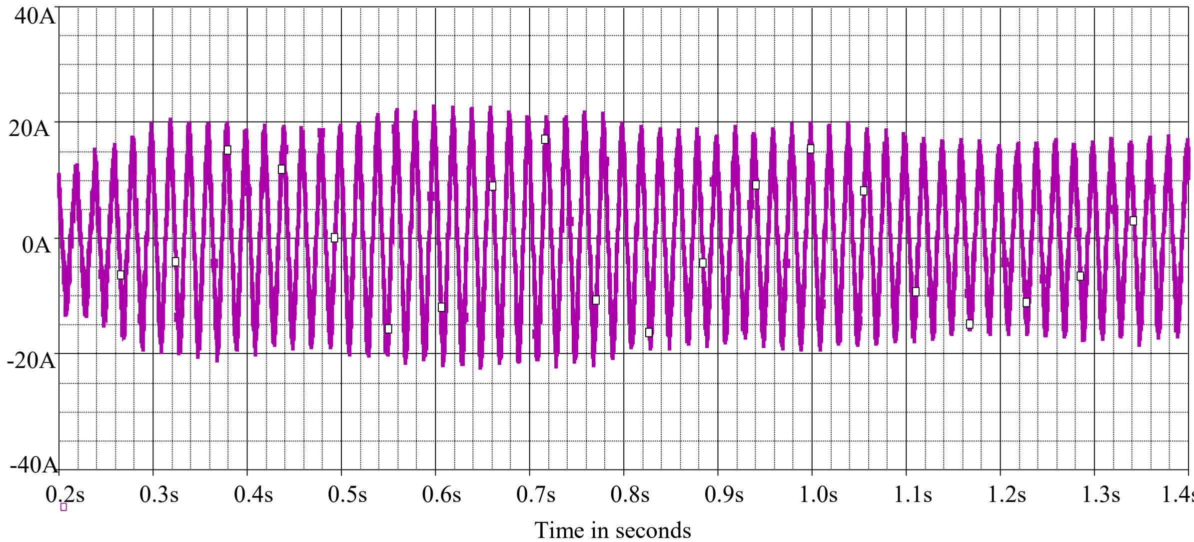


Fig. 3.10 (c) Trace of Input Current of Phase B

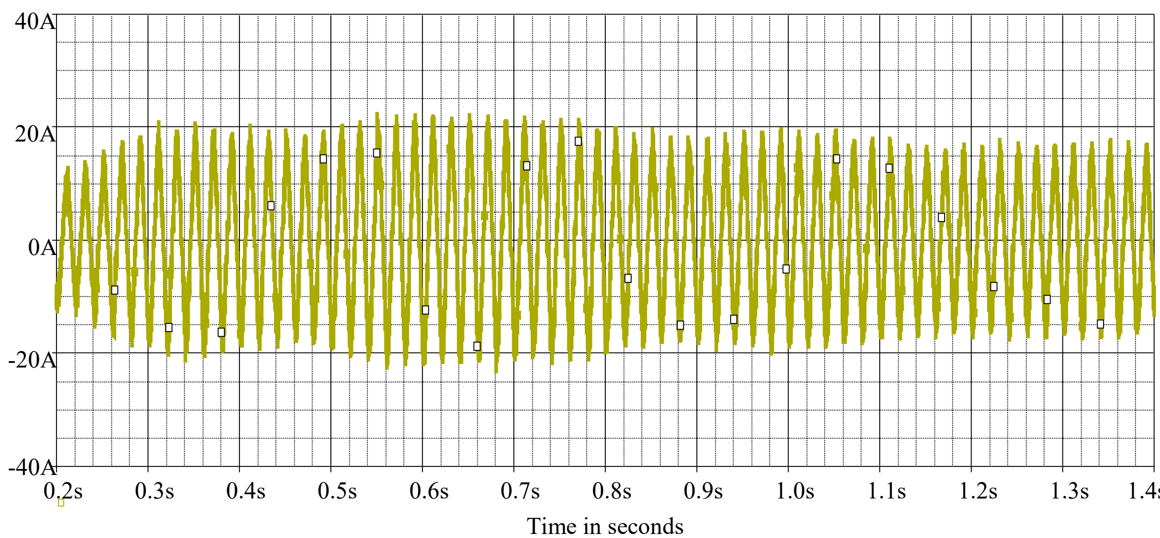


Fig. 3.10 (d) Trace of Input Current of Phase C

Fig. 3.10 Typical simulated output voltage and input current of the proposed 3 switch three phase PFC SEPIC rectifier of the circuit of Fig. 3.9 (a) for variation of loads regulated at around 600V DC.

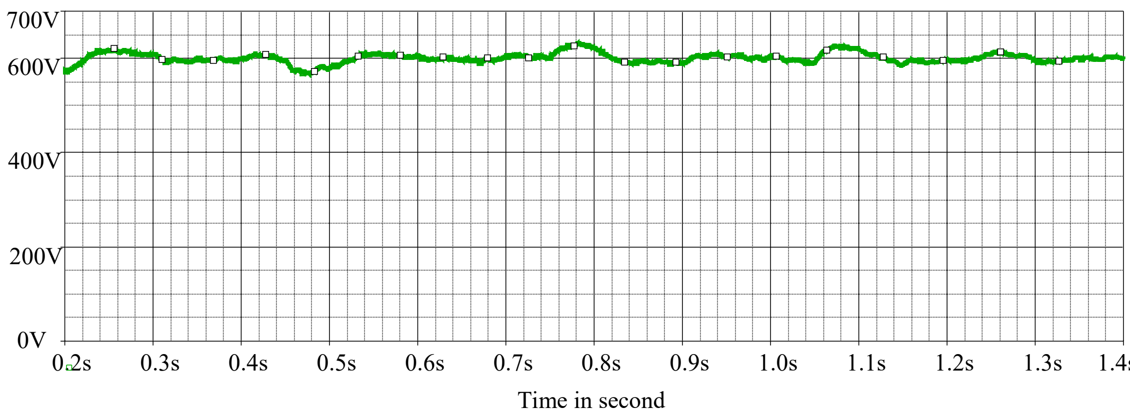


Fig. 3.11 (a) Output voltage trace

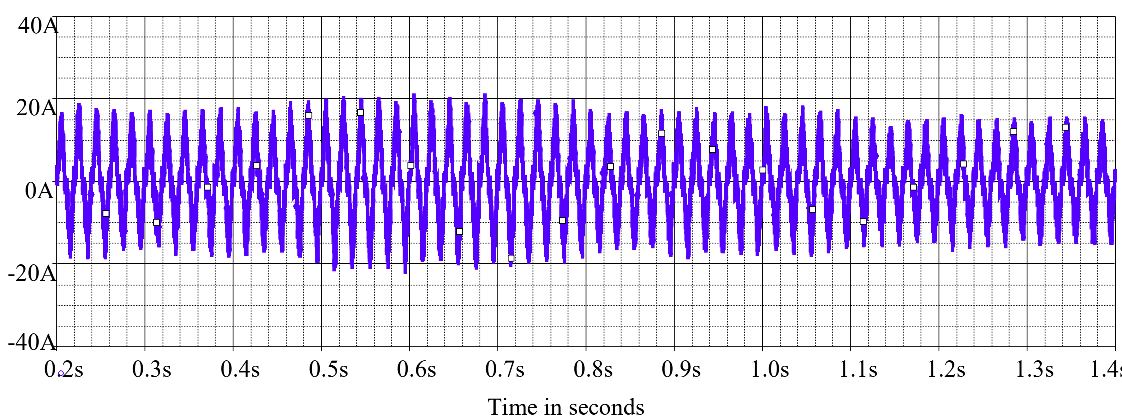


Fig. 3.11 (b) Input Current Trace of Phase A

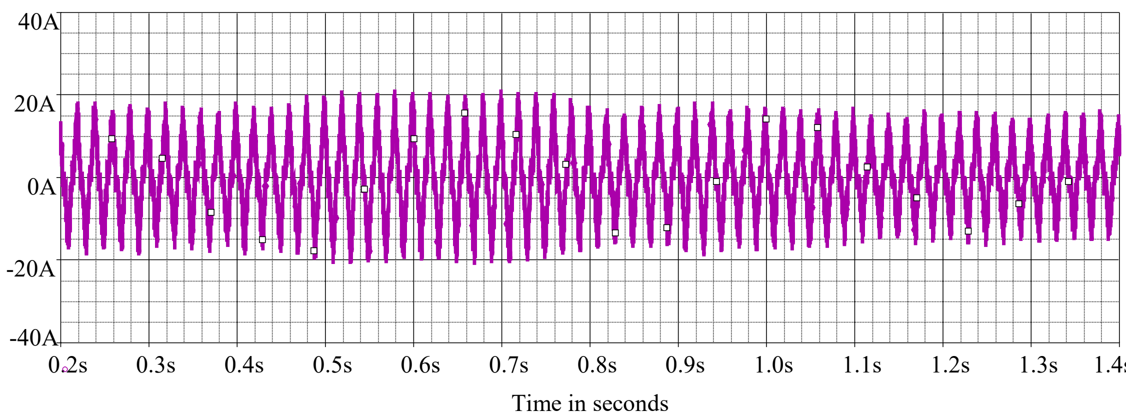


Fig. 3.11(c) Input Current Trace of Phase B

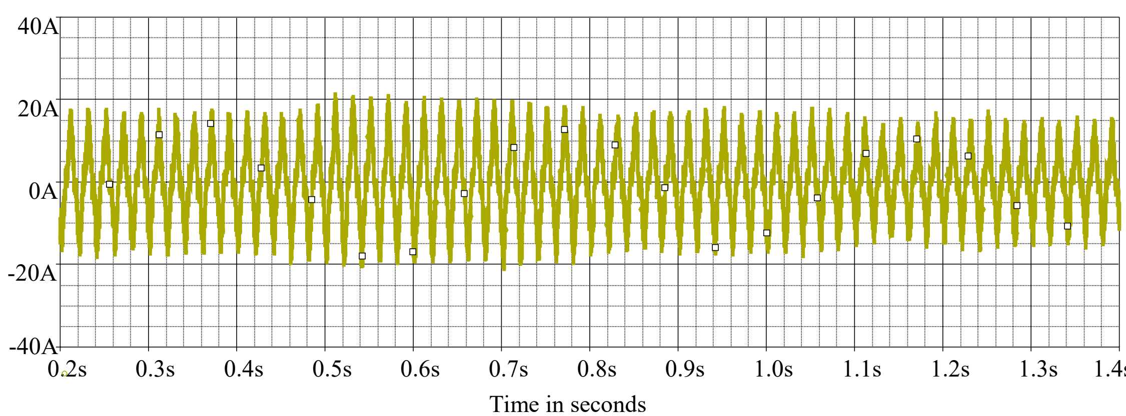


Fig. 3.11(d) Input Current Trace of Phase C

Fig. 3.11 Typical simulated output voltage and input current of the proposed 3 switch three phase PFC SEPIC rectifier of the circuit of Fig. 3.9 (b) for variation of loads regulated at around 600V DC.

In Figs. 3.10 and 3.11 voltage dips as load is increased at 450 ms and returns to 600 V DC, voltage swells at 750 ms and 1050 ms as load is reduced with return to set regulated voltage of 600 V DC. During this time input current adjusts to load changes. After return to regulated voltage in each case it is observed that the output voltage, input current shapes and the power factor remains almost the same. Same behaviour of the circuits are also observed for change of input voltage keeping the load same.

3.5 Discussions

The proposed SEPIC rectifier of Fig. 3.1 has been redrawn as shown in Fig. 3.3. In the Fig. of 3.3, the 6 output capacitors have been reduced to 2. That is, 4 passive elements have been reduced. From the tabular representations of the performances of proposed rectifiers shown in Table 3.4 and Table 3.5, it is evident that both of the rectifiers show almost same performance without any degradation. The proposed rectifiers give non-sinusoidal input currents, cause large THD, low input power factor and extra losses in utilities when operated without any feedback control as shown in Figs. 3.2 and 3.4. But these drawbacks have been overcome by designing proper feedback control circuit. It is clear from the simulated waveform of Figs. 3.8 that the input current waveforms have significantly improved when the rectifier has been operated with appropriate feedback controller. From the simulation results of the proposed SEPIC PFC rectifier shown in Table 3.6 it is proved that, the proposed circuit has low input current THD and almost unity power factor. The dynamic response of the proposed rectifier is also satisfactory. From Figs. 3.10 and 3.11 it is seen that the output voltage adjusts to its original setting with load change. The proposed 3-phase 3-switch AC-DC converter is a robust one compared to the traditional ones.

Chapter 4

Input Current and Power Factor Improvement of Proposed AC-DC Converter

There are several control mechanisms to attain the stable regulated operation of SMPS based converter circuits. Among them, the sliding mode control, PID control, Fuzzy logic control, PLL control, Hysteresis control, SVM control etc. are popular [1-6]. A tuned proportional Integral (PI) controller circuit has been developed to get several benefits from proposed converter. The benefits that are obtained are discussed later. Design and tuning of controller is described first. A Proportional-Integral is a control loop feedback mechanism which calculates the error value as the difference between the desired set point and a measured process variable. The controller attempts to minimize the error over time by the adjustment of control variable. A simple PI controller has a control variable *U (t)* as a weighted sum which can be defined as [8-12]

$$U\,(t) = K_p\, e\,(t) + K_i \int_0^t e\,(t) dt$$

Where K_p and K_i are the proportional and integral gain of the controller circuit respectively. These gains depend upon the parameters (resistance, capacitance) of the control circuit. During the control circuit tuning, these gains play a significant role.

4.1. Control Circuit of proposed AC-DC Converter

To control the output voltage of proposed converter for any fluctuations of load or input source voltage, to shape the input current nearly sinusoidal irrespective of input boost inductor value and to improve the input power factor a tuned PI control circuit is designed. The circuit configuration of the controller is shown in Fig 4.1.

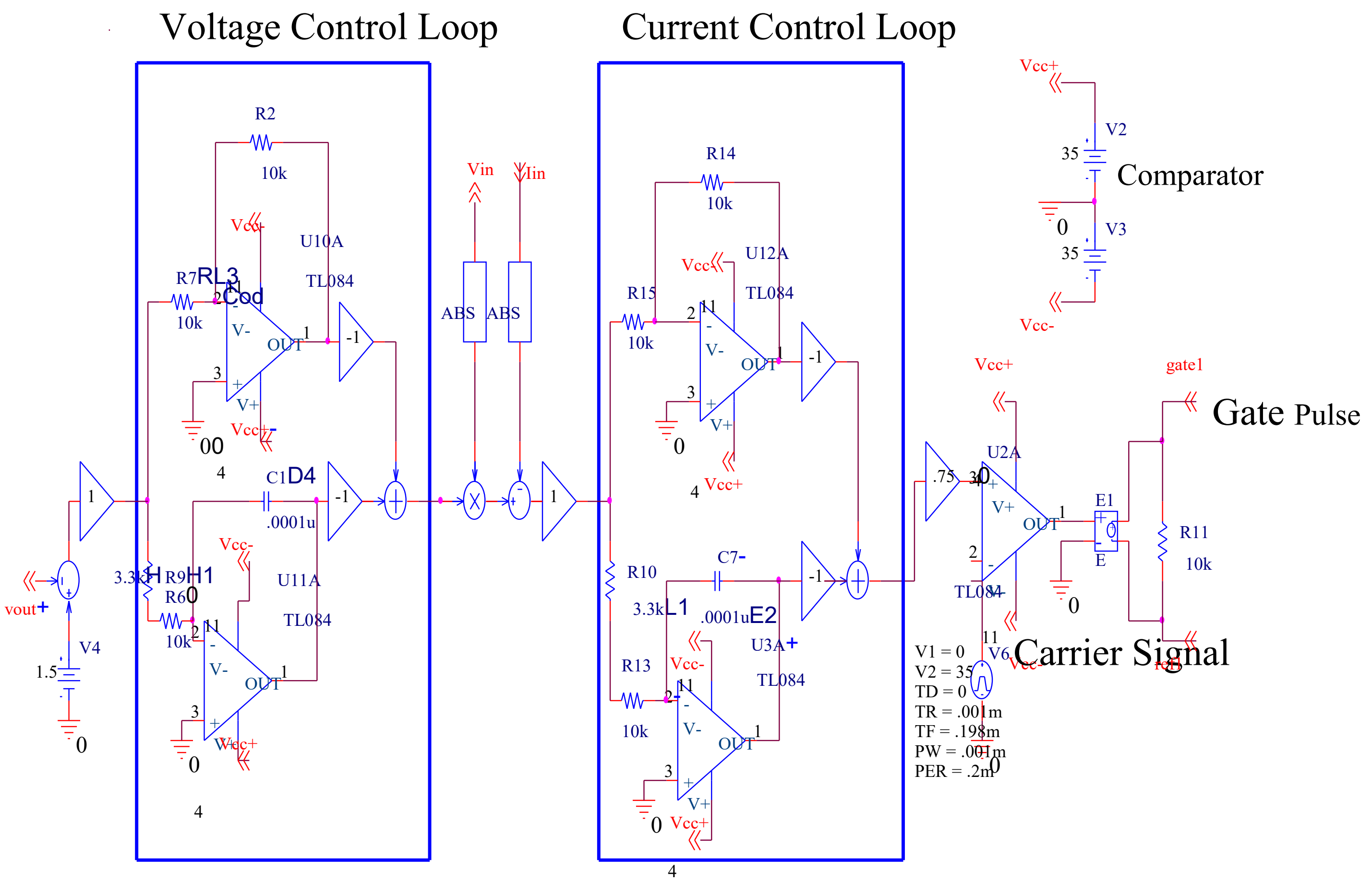


Fig. 4.1 Tuned per phase PI controller circuit of proposed AC-DC converter

4.2. Working Procedure

The output voltage is fed back to the input of the controller circuit. The controller circuit consists of a voltage control loop and a current control loop. Each loop contains a PI controller, output voltage is compared with the reference voltage and generates an error voltage. Generated error voltage goes through the PI controller and produces the reference current signal which has to be compared with the input current. It generates the error current signal and sent to the input of the PI current controller circuit. After being processed in current controller circuit, the modulating signal is generated and is compared with the high frequency carrier signal V_6. After comparison in a comparator, modulated pulse output is obtained. Block diagram of the control circuit is shown in Fig. 4.2 and typical waveforms of the controller obtained during simulation are shown in Figs. 4.3 to 4.6.

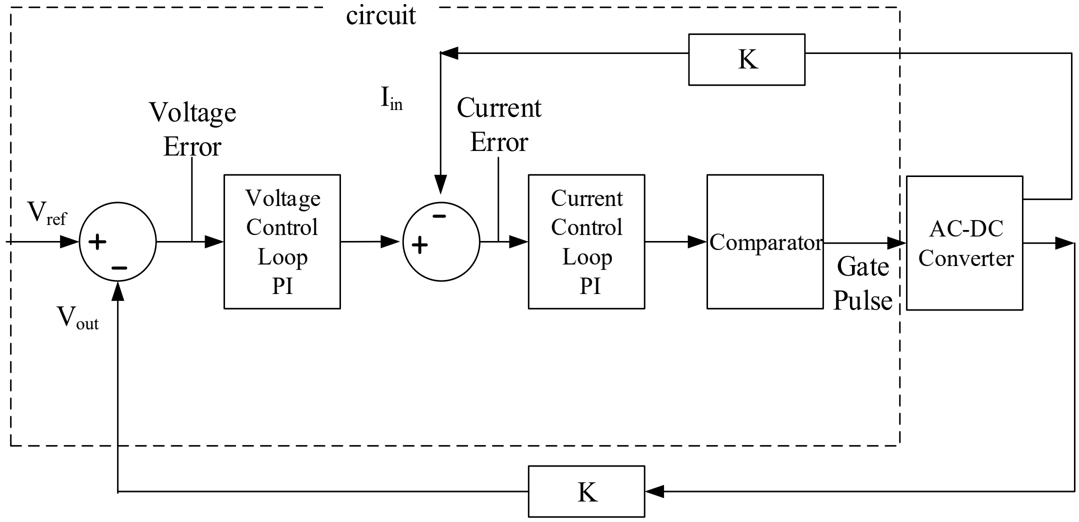


Fig. 4.2 Block diagram of the control circuit

The voltage error signal of the converter is given below:

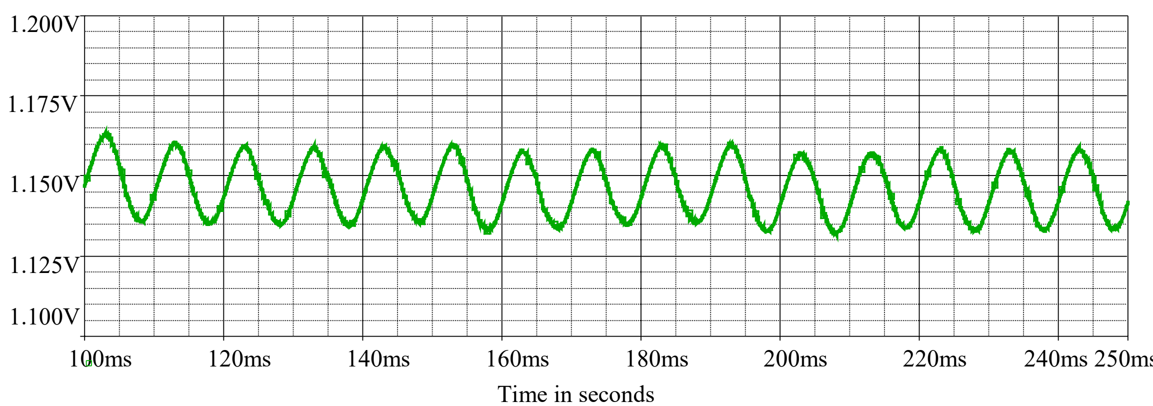


Fig. 4.3 Voltage Error Signal

Output of voltage control is shown from simulation:

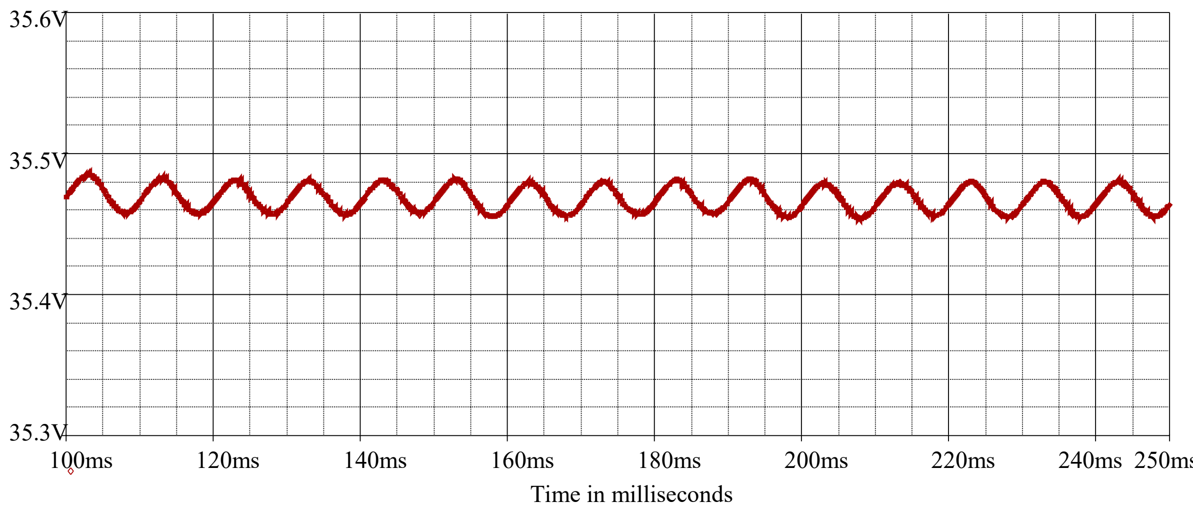


Fig. 4.4 Output of Voltage Controller

Gate pulse signal has been generated by comparing the current controller output to the high frequency carrier signal. The controller output and high frequency carrier signal have been shown which are responsible to generate gate pulse.

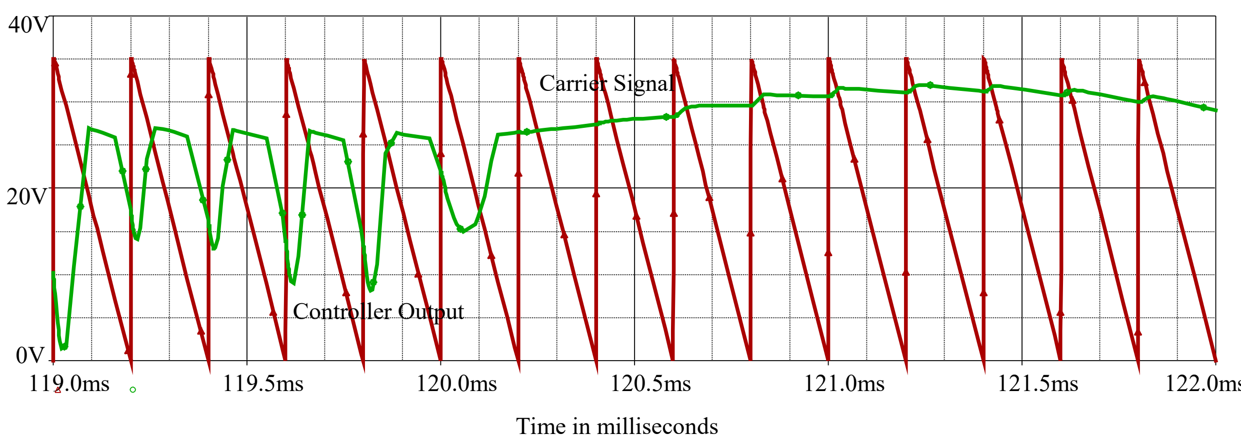


Fig. 4.5 Current Controller output and 5 KHz Carrier Signal

The generated Pulse width modulated gate pulse:

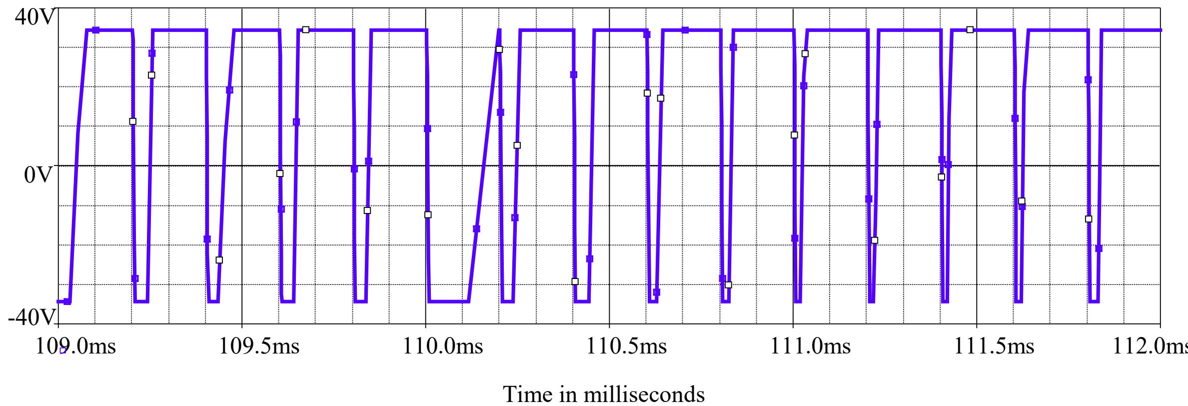


Fig. 4.6 Generation of gate pulse at different scale

4.3 Tuning of PI Control Circuit

To get the proper operation of the PI control circuit, the controller has been tuned. There are several techniques to tune the PI controller. These are manual tuning, Ziegler-Nichols tuning, Cohen-Coon tuning, Astro-Hagglund methods etc. We have used the manual tuning method to tune the controller, the steps that have been followed are,

1. At first the gain of the integrator is kept very small.
2. Then raise the proportional gain gradually and check the response of the circuit. For a proportional block, the gain depends upon the feedback resistance and input resistance. The relation is given by-

   $K_p = -\frac{R_f}{R}$, where R_f is feedback Resistance and R is input side resistance of Proportional block.
3. Now slowly increase the integral gain K_i and observer its response. The integral gain is related by the following equation-

   $K_i = -\frac{1}{RC}$, where C is the feedback capacitance and R is the input side resistance.
4. For different combinations of K_p and K_i, the best response of controller has been found.

Aforementioned steps have been followed to find out the value of K_p and K_i. The values thus obtained are,

For Voltage Control Loop,

$K_p = -1$ and K_i= -751.87K

For Current Control Loop,

$K_p = -1$ and $K_i = -751.87$K

Benefits of tuned PI controller can be perceived in case of input current shaping of the converter. In the following Figs of 4.7 and 4.8, input current curves with tuned and without tuned controller are presented.

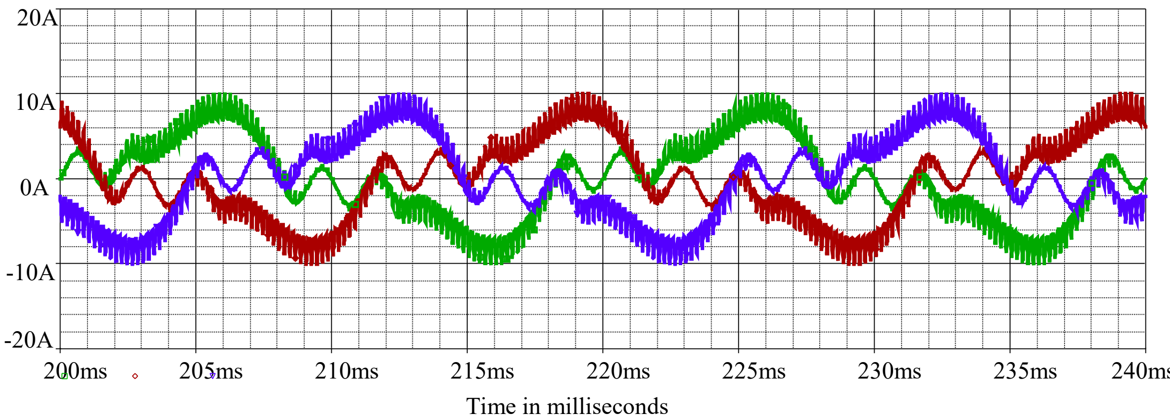


Fig. 4.7 Input current of the proposed 3-phase converter without PI controller; THD= 55.49%, Duty cycle= 0.3

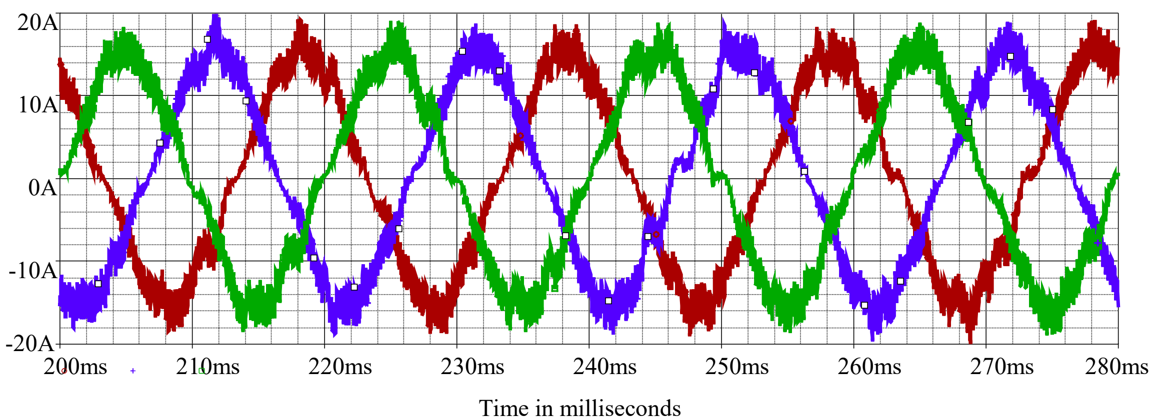


Fig. 4.8 Input current of proposed 3-phase converter with PI controller; THD= 6.6%

The output voltage of the proposed converter is controlled by a proportional Integral (PI) controller which need to be designed and tuned. The designed PI controller provides several benefits when it is integrated with proposed converter. It is robust control system which can provide:

a. Stable output voltage of the converter during its output load change. It means dynamic response is good.
b. Make the converter output voltage stable during voltage sag or voltage swell or any disturbances occurs at the input source.
c. It helps to shape the input source current and reduces total harmonic distortion (THD) irrespective of all values of input inductors.
d. The control system provides high Input Power factor (above 0.94 all time) for both buck and boost modes.

4.4 Stable Dynamic Response of Proposed Converter using PI controller

A suitably designed and tuned PI control system has been integrated during the frequent load change at the output of the converter. The dynamic response of the converter has been observed. The output voltage remains stable during the variation of the load. To evaluate the performance of the converter, a dynamic load change unit is connected which has been shown in Fig.4.9. The load change unit is designed to operate at a certain pattern. At first stage, R_L (200 Ohms) and R_{L3} (200 Ohms) loads are connected at the output of the converter, so the resultant load is 100 Ohms. After 450 ms, the R_{L1} (400 Ohms) load has been connected and made the current carrying capacity higher at the output as the resultant load is now (80 Ohms). This time, due to the increment of current across the load, the output voltage decreases. But after a small time, a quick recovery is seen at the output voltage and it remains stable. This quick recovery is possible due to the integration of the PI controller unit. The total phenomenon has been depicted in Fig.4.9 and Fig.4.10. Later at 750 ms the R_{L1} load has been cut off from the unit and once again the converter falls down and voltage goes up. This time the controller circuit operates to retain the converter voltage at a stable state. At last stage of 1050 ms, R_{L3} (200 Ohm) is disconnected and R_{L2} (300 Ohm) is connected. This phenomenon increases the load voltage slightly and decreases the current at the output.

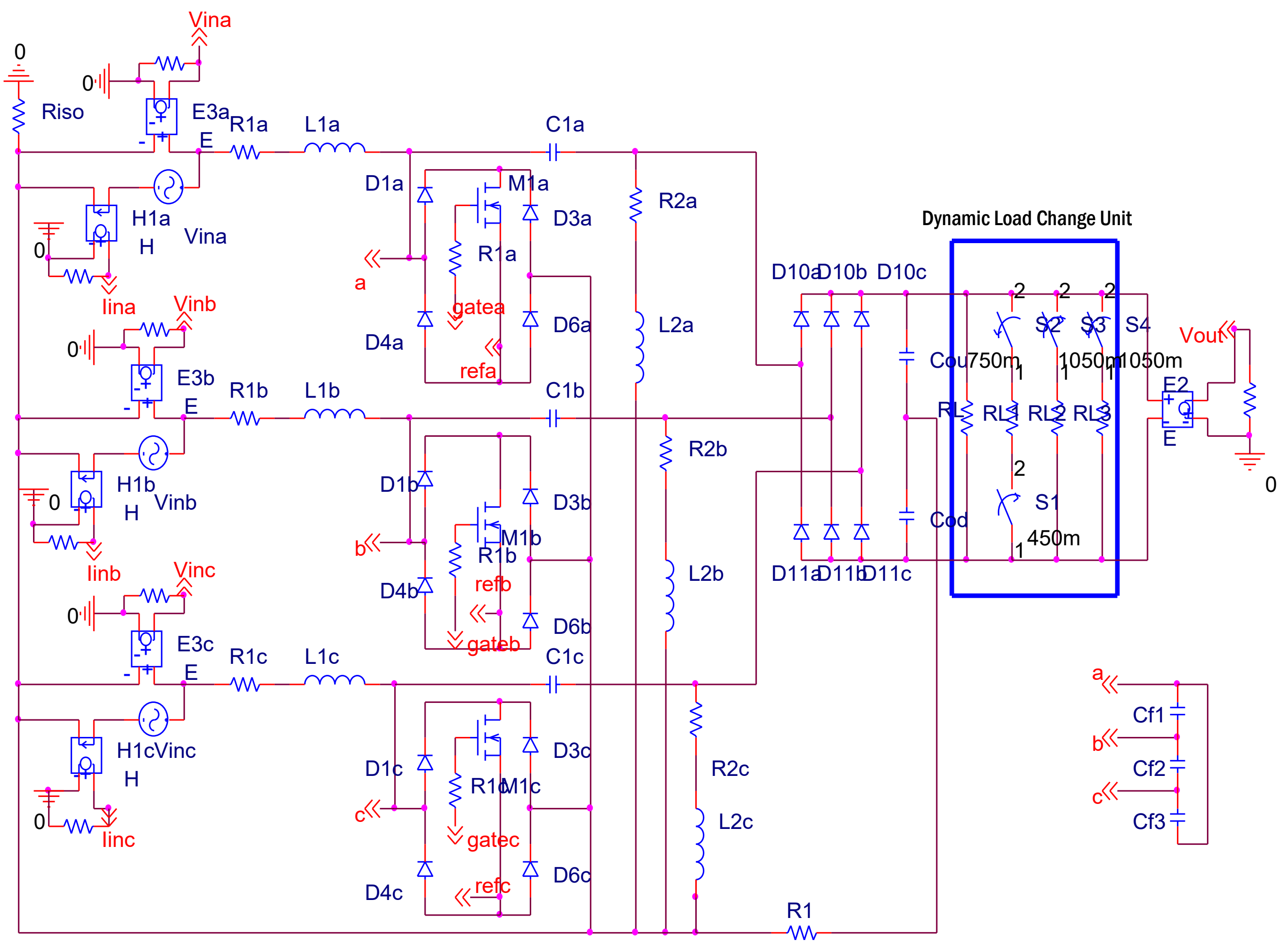


Fig. 4.9 Proposed converter circuit with PI controller having Dynamic load change unit.

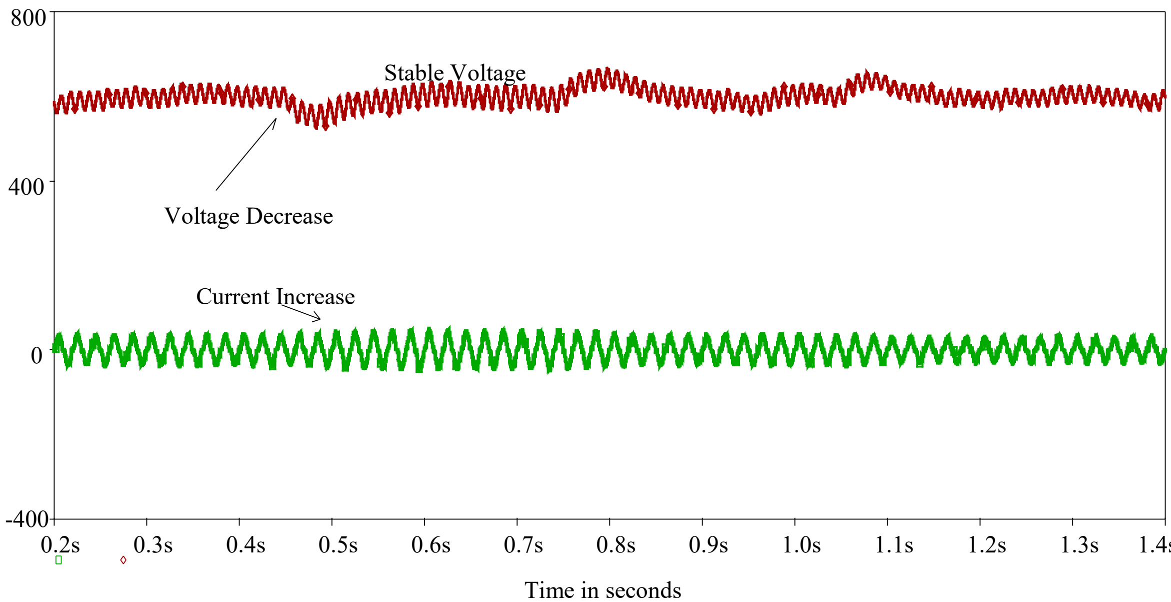


Fig. 4.10 Voltage stabilization of phase A due to PI Controller during load change.

4.5 Input current shaping by PI controller

One of the feature of the proposed converter is by using boost inductor (L_1), one can make the output voltage buck-boost having low harmonics in input current. But the value of this input boost inductor plays a significant role in case of input current of the converter. Without control circuit (Converter open loop state), the inductor L_1 determines the shape of the input current as well as the total harmonic distortion. A series of input current curves show that, the lower value of boost inductor (L_1) distorts the input current and increases its total harmonic distortion. It is also obvious that the larger value of boost inductor shapes the input current near about sinusoidal and reduces total harmonic distortion.

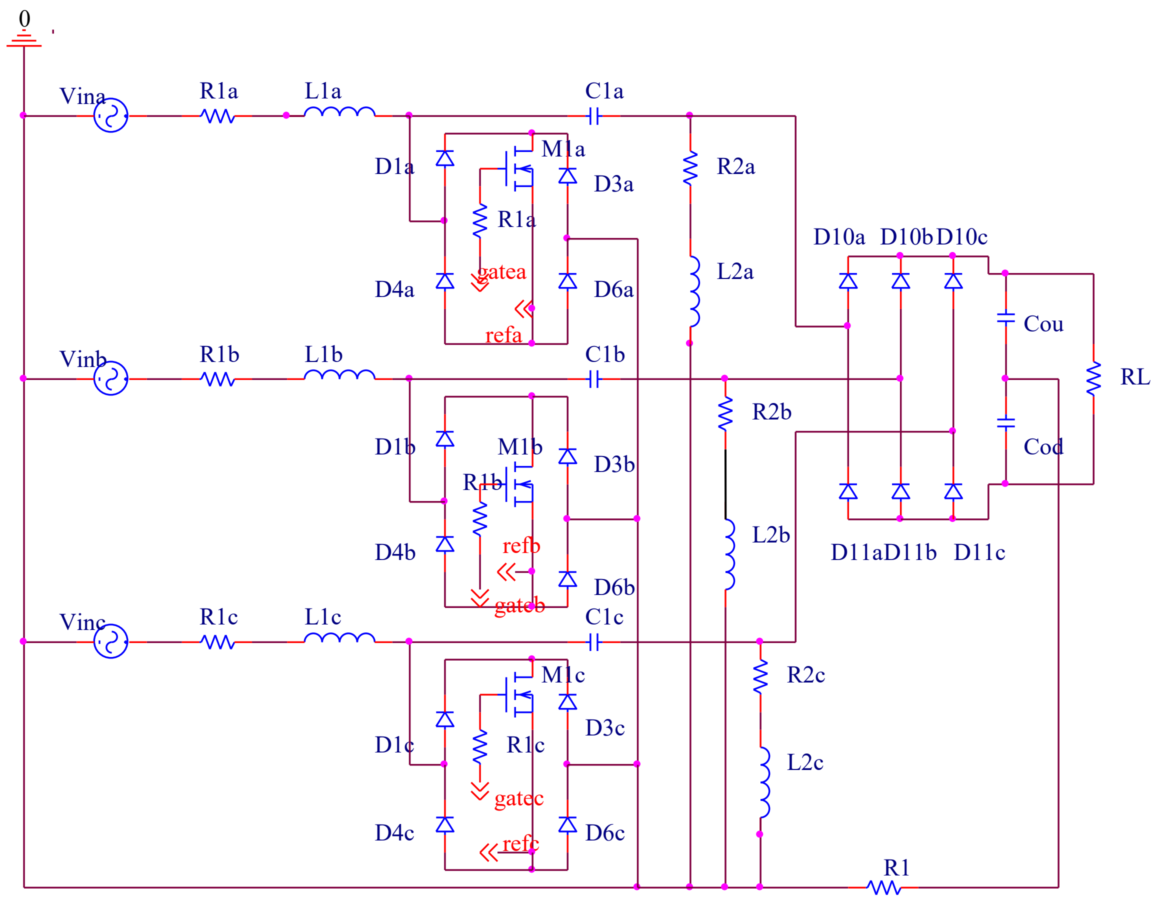


Fig. 4.11 (a) Three-phase proposed converter without control

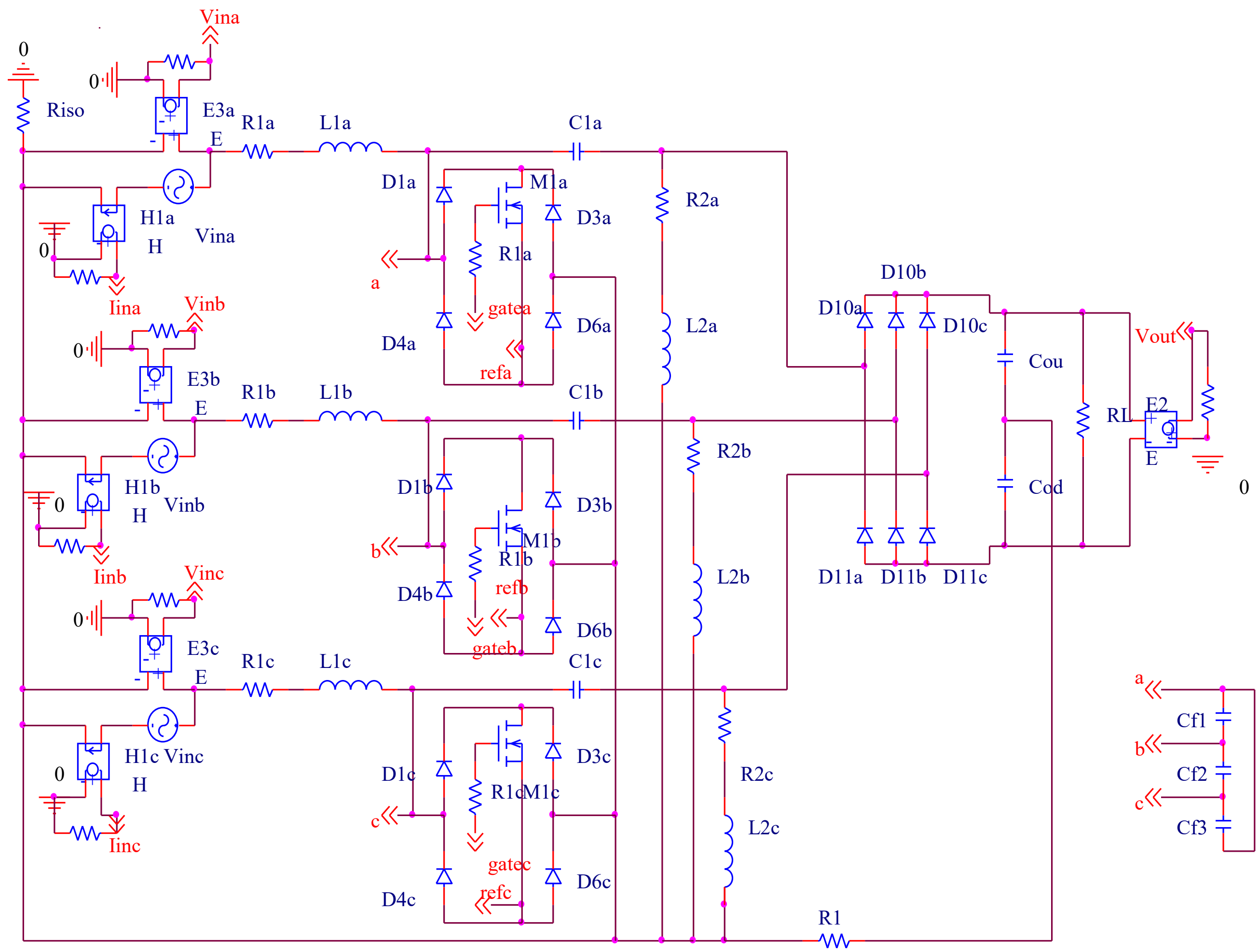


Fig. 4.11 (b) Three-phase proposed converter with PI Control.

But larger inductance causes larger voltage drop across it which reduces output voltage and the efficiency of the converter. To encounter the problem, PI controller has been designed and integrated with the proposed converter. The controller determines the input current error and then generates necessary gate pulse to shape the input current near about sinusoidal at any value of input boost inductor. The simulation and evaluation has been made by the simulation circuits shown in Fig. 4.11 (a) and Fig. 4.11 (b).

In Fig. 4.11 (a) the switching frequency and duty cycle is 5 KHz and 0.7 respectively. In Fig. 4.11 (b) the carrier switching frequency and V_{ref} is 5 KHz and 1.5 V respectively. The simulated current wave shapes of the proposed three-phase converter are shown for voltage references set for 250 V DC and 600 V DC in figs. 4.12 and 4.13 for input inductor 5 mH and the output inductor 2 mH. The waveforms of the current have hysteresis sine wave shape of 50 Hz with total harmonic distortion of 8 and 10 percent respectively. Due to hysteresis, current shaping of the converter and current tracking the input voltage shape the power factor of the circuit are 0.98 and 0.95 respectively. The conversion efficiency of the converter stands at 67 % and 70 % respectively.

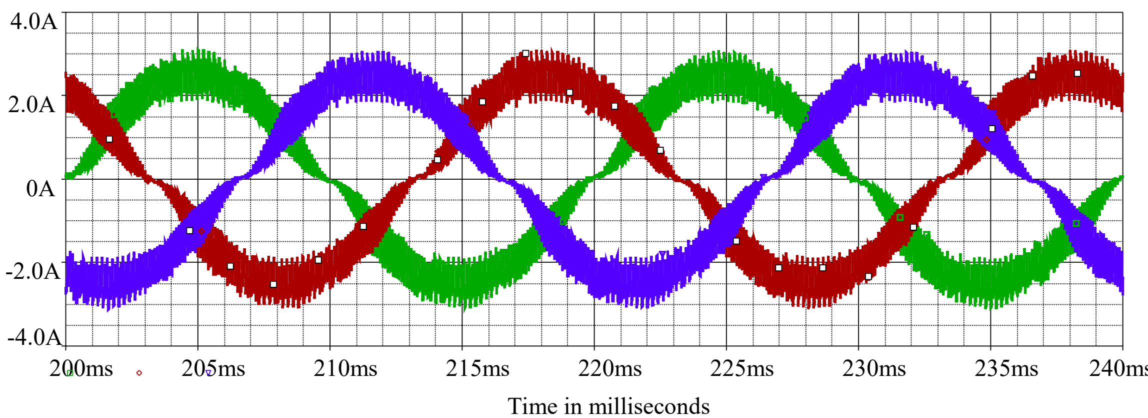


Fig. 4.12 Input current with PI controller when reference voltage is set to 250 V, THD = 8.29 %

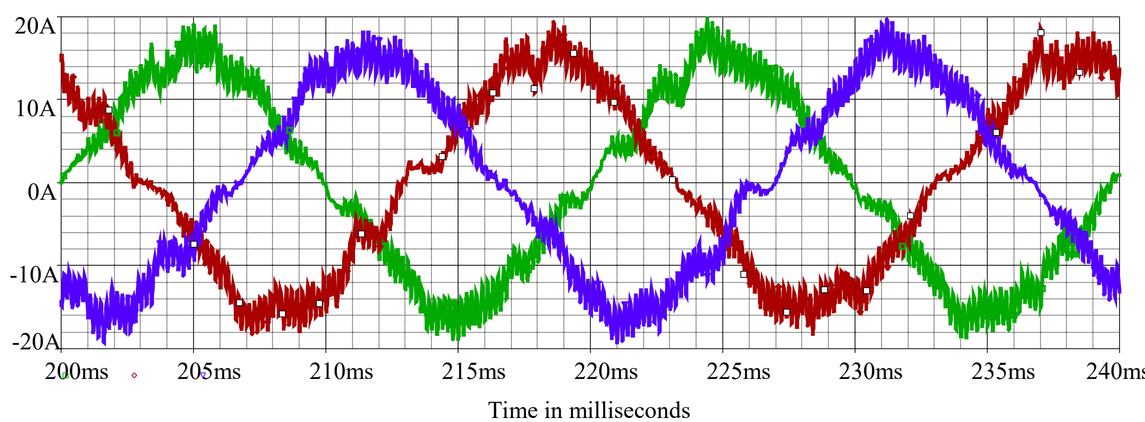


Fig. 4.13 Input current with PI controller when reference voltage is set to 600 V THD = 10.2%

4.6 Stability of output voltage in case of source disturbances

Various types of input source disturbances may cause the fluctuations in input voltage. This fluctuation impacts on the output voltage of the converter when it works without feedback. But the PI controller can solve the problem. Simulations have been carried out by changing the input voltage of the converter at both with and without control circuit. Here the reference input voltage has been considered 300 V. the observations have been given below,

At first, when input voltage, V_{in} = 300 V for all three phases, we get output voltage near about 600V for both control and without control circuit.

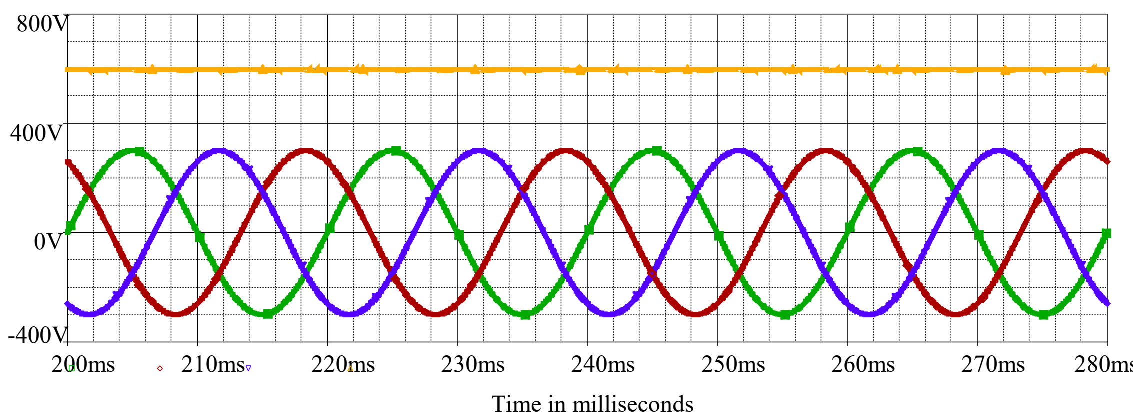


Fig. 4.14 Input-Output Voltage of the converter without PI controller; V_{in} = 300 V (per phase) and V_{out} = 600 V

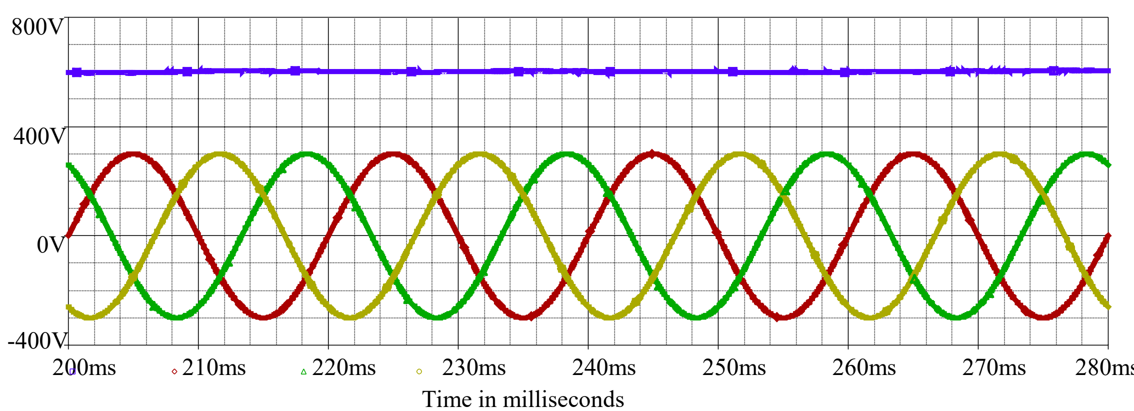


Fig. 4.15 Input-Output Voltage of the converter with PI controller; V_{in} = 300 V (per phase) and V_{out} = 600 V

When voltage rise occurs at the input (Per phase voltage, $V_{in} = 350$ V), without feedback converter (Open loop) could not retain the previous stable voltage at its output but the converter with PI controller can do so. Input-output voltage waveforms are shown in Figs. 4.16 and 4.17 respectively.

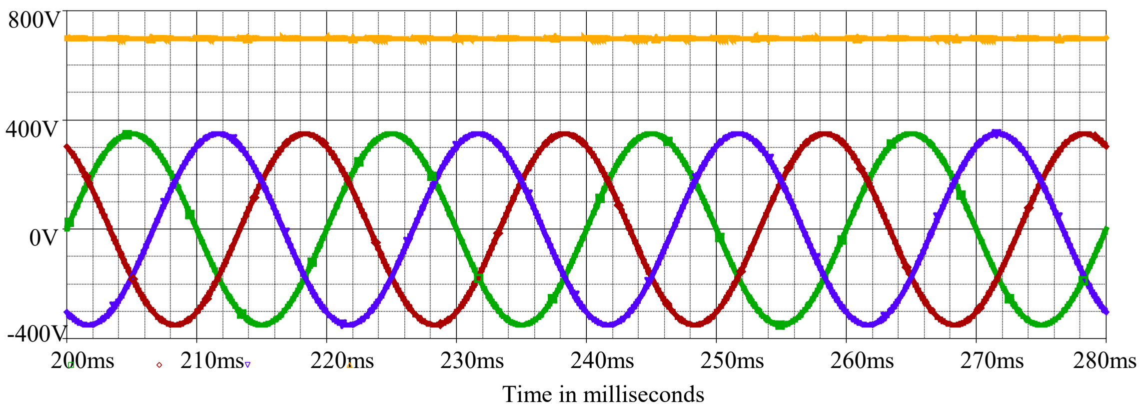


Fig. 4.16 Input-Output Voltage of the converter without PI controller; $V_{in} = 350$ V (per phase) and $V_{out} = 700$ V

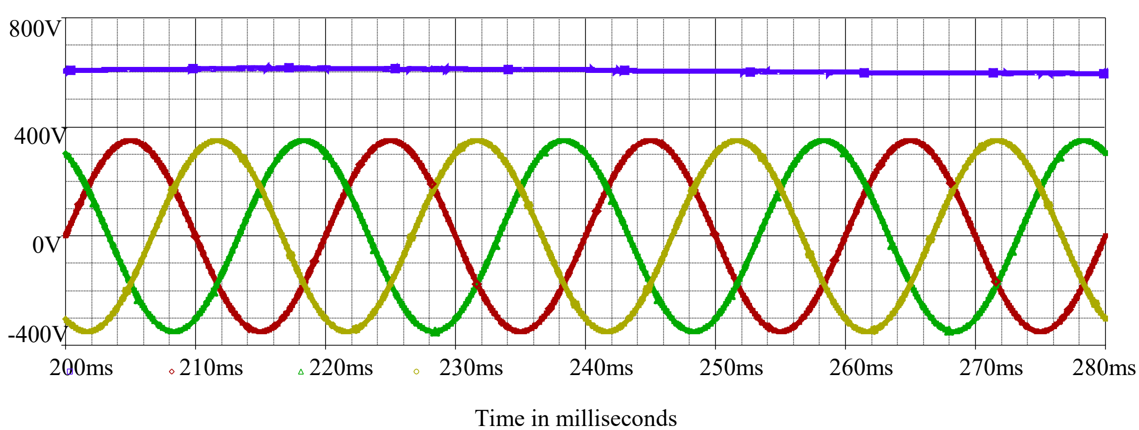


Fig. 4.17 Input-Output Voltage of the converter with PI controller; $V_{in} = 350$ V (per phase) and $V_{out} = 600$ V

The same phenomenon happens for per phase input voltage of 400 V. Corresponding output voltage waveforms are shown in Figs. 4.18 and 4.19 respectively,

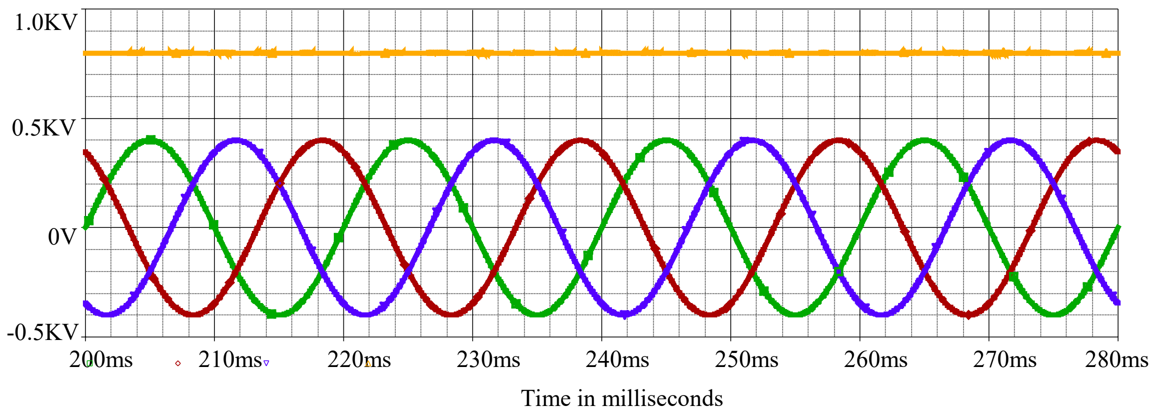


Fig. 4.18 Input-Output Voltage of the converter without PI controller; $V_{in} = 400$ V (per phase) and $V_{out} = 800$ V

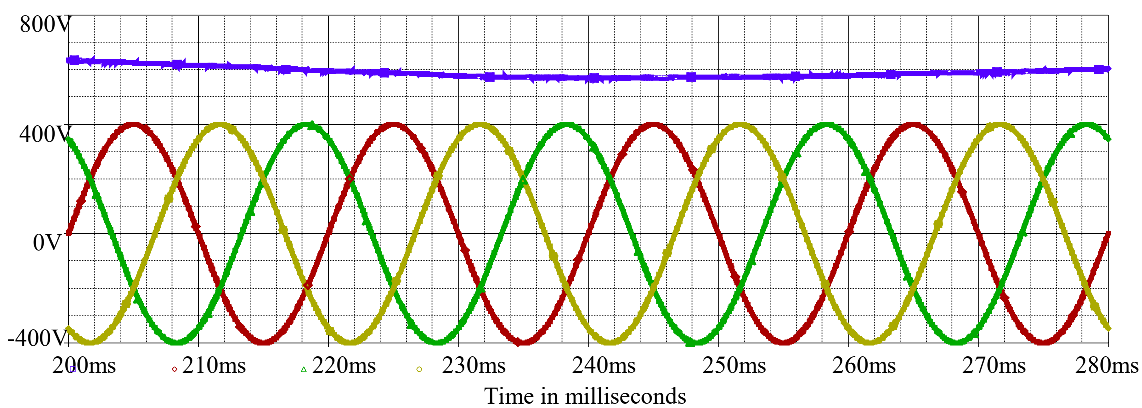


Fig. 4.19 Input-Output Voltage of the converter with PI controller; $V_{in} = 400$ V (per phase) and $V_{out} = 600$ V

The observations have also been made for input voltage lower than 300 V. In each case input-output voltage shape has been taken and it exhibits the previous relationship. Simulations have been carried out for 250 V input voltage as shown in Figs 4.20 and 4.21.

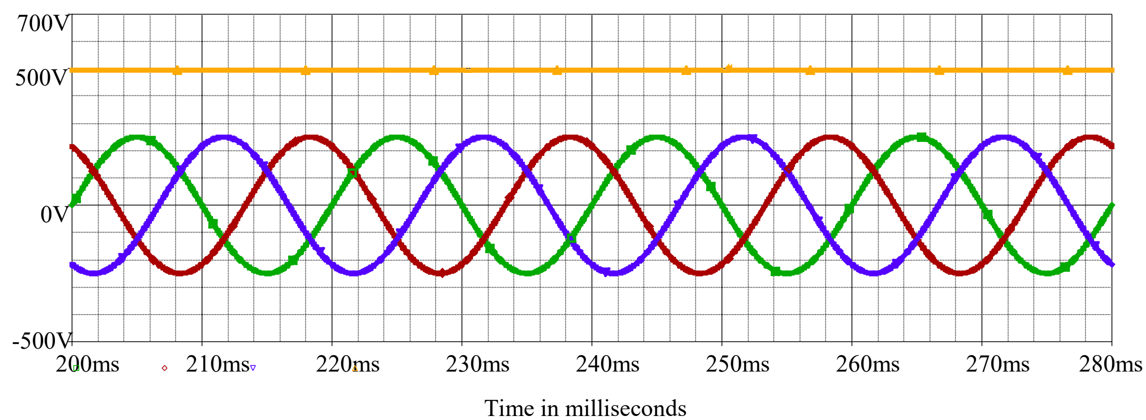


Fig. 4.20 Input-Output Voltage of the converter without PI controller, V_{in} = 250 V (per phase) and V_{out} = 500 V

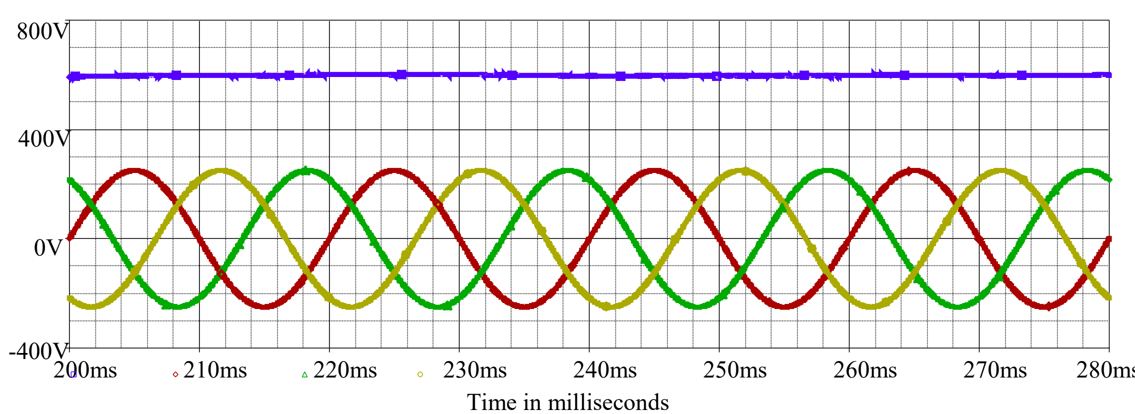


Fig. 4.21 Input-Output Voltage of the converter with PI controller; V_{in} = 250 V (per phase) and V_{out} = 600 V

The simulation results for operation of the converter with 200 V input are shown in Figs. 4.22 and 4.23.

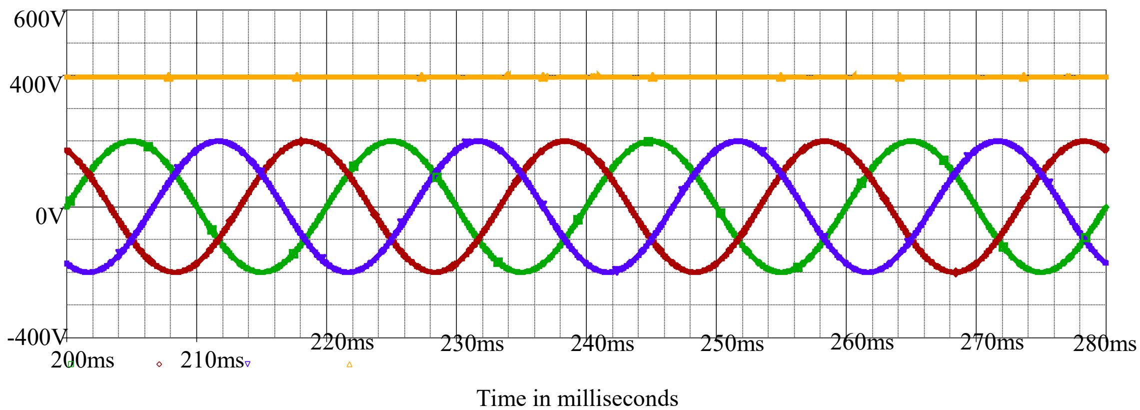


Fig. 4.22 Input-Output Voltage of the converter without PI controller, $V_{in} = 200$ V (per phase) and $V_{out} = 400$ V

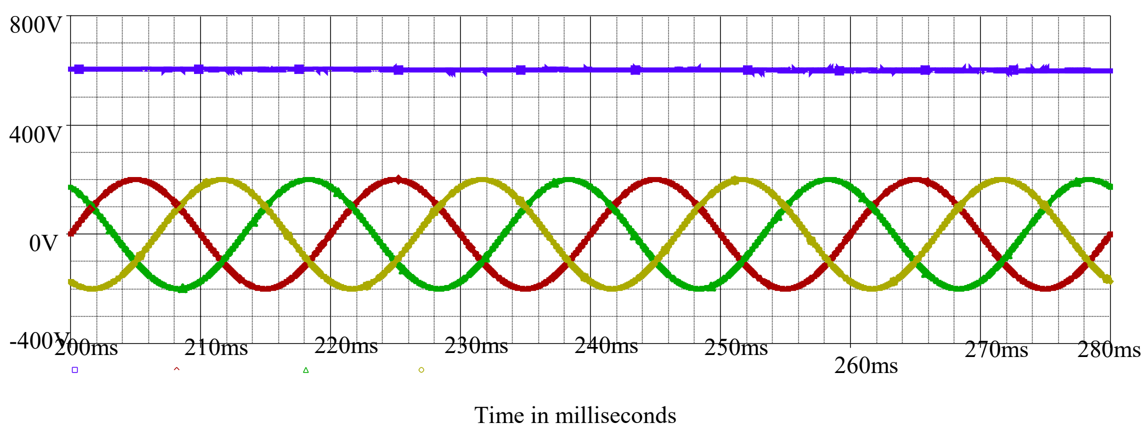


Fig. 4.23 Input-Output Voltage of the converter with PI controller; $V_{in} = 200$ V (per phase) and $V_{out} = 600$ V

4.7 Input power factor improvement by PI controller

Close loop control of proposed converter provides improved input power factor compared to the open loop converter. Through performing simulations, power factor for both with and without controller has been studied. It is observed that for buck as well as boost mode, the converter with control provides higher power factor compared to the converter without control. The investigation shows that for closed loop converter the minimum power factor at buck mode is 0.92 and for boost mode it is 0.93 the simulated values are shown for both buck and boost mode below-

Table 4.1 Input Power factor of the converter (Buck mode)

Input Voltage (V_{L-LRMS})	Output voltage	Power Factor without control	Power Factor With control
367.42	200	0.801	0.919
367.42	217	0.772	0.921
367.42	264	0.784	0.934
367.42	316	0.832	0.956

A comparison curve has been plotted in MATLAB to illustrate the relationship more vividly. It is shown in the following Fig. 4.24.

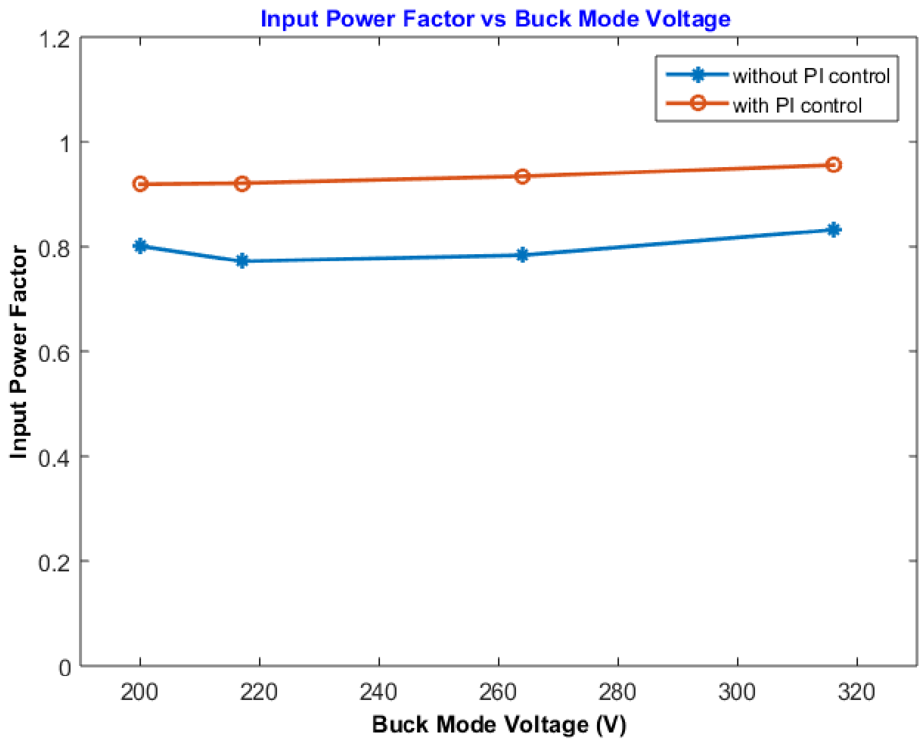


Fig. 4.24 Power factor improvement by using PI controller at buck mode.

Table 4.2 Input Power factor of the converter (Boost mode)

Input Voltage ($V_{L\text{-}LRMS}$) (V)	Output voltage (V)	Power Factor without control	Power Factor With control
367.42	387	0.89	0.934
367.42	530	0.93	0.978
367.42	760	0.94	0.979
367.42	1000	0.86	0.998

The comparison curve of power factor of the converter at Boost mode with and without PI controller is shown in the Fig. 4.25

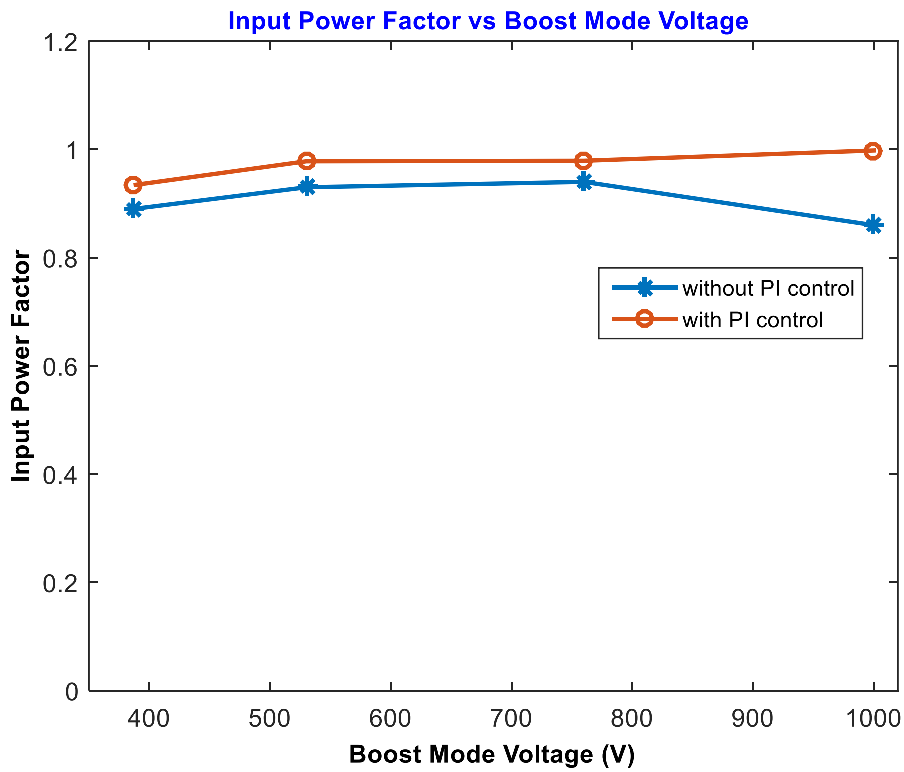


Fig. 4.25 Power factor improvement by using PI controller at boost mode.

4.8 Discussions

In this chapter, working procedure of the controller circuit of the proposed converter has been illustrated. The process of variable width gate pulse generation through voltage and current control loops is shown from Figs 4.3 to 4.6. The controller circuit helps the converter to maintain a fixed output voltage in spite of load change or source disturbance. Proper tuning of the PI controller also ensures input power factor improvement, input current shaping and input current THD reduction.

Chapter 5

Experimental Results of the Proposed Converter

A generalized power circuit board with measuring/monitoring devices (Agilent four channel Oscilloscope and Fluke power quality analyzer) have been set up in the laboratory for observing the performance of the proposed 3-switch 3-phase SEPIC converter without any feedback. Typical experimental results shown in this chapter are input/output voltages, input current, input current THD and power factor of the proposed circuit of Fig. 3.3. The input voltage to the setup has been stepped down in two stages; once by a three-phase autotransformer (variac) and in the second stage by a delta wye (neutral not earthed) three phase transformer. The waveforms of input, output voltages and input currents are taken by Agilent four channel Oscilloscope and power factor and THD are observed using Fluke power quality analyzer.

5.1 Experimental Results of Proposed 3-Switch 3-Phase SEPIC Rectifier with Split Capacitor Configuration

Laboratory experiment has been carried out on a low voltage low power prototype three switch three phase SEPIC rectifier with split capacitor configuration. The reading of power quality analyzer presented in table 5.1 shows the input voltage and input current, power factor and the input current THD. The circuit has 4.2 mH inductor for input filter and intermediate SEPIC inductor, 1.5 μF input filter capacitor and 220 μF output filter capacitor.

The circuit of Fig. 3.3 have been practically implemented with following circuit parameters,

L_{1a} = 4.2 mH, L_{1b} = 4.2 mH, L_{1c} = 4.2 mH

C_{1a} = C_{1b} = C_{1c} = 1.5μF (Coupling capacitor)

L_{2a} = 4.2 mH, L_{2b} = 4.2 mH, L_{2c} = 4.2 mH

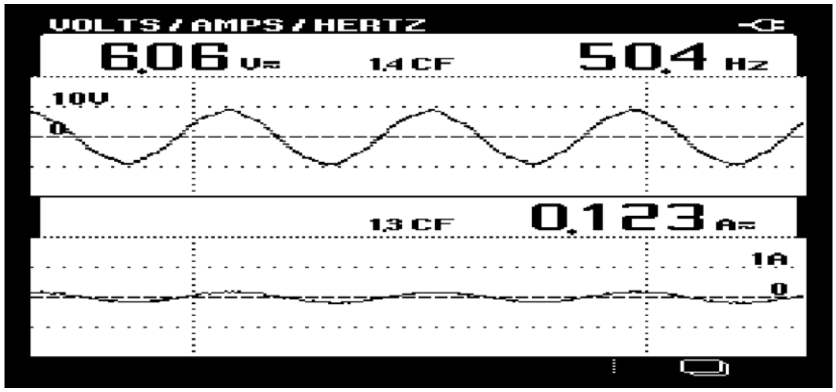
C_{ou} = C_{od} = 220 μF (Output capacitor) ESR = 100 Ω (Equivalent SEPIC Resistor/output resistor)

f_{switch} = 5 KHz

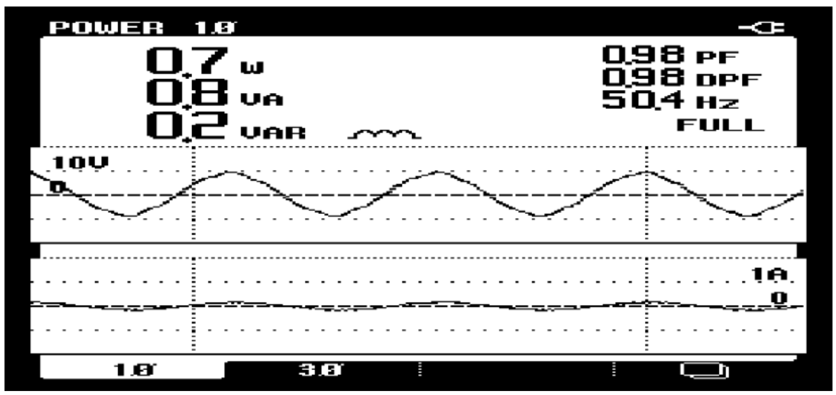
Corresponding records of the power quality analyzer are shown in Figs. 5.1 and 5.3 for duty cycle (D) of 0.3 and 0.7 respectively (resulting output voltages as provided in Table 5.1). The output dc voltage and input currents corresponding to condition of Fig. 5.1 as obtained by Four Channel Agilent/Keystone are shown in Fig. 5.2 (a) and (b). The output dc voltage and input currents of the rectifier corresponding to condition of Fig. 5.3 as obtained by oscilloscope are shown in Fig. 5.4 (a) and (b). In Figs. 5.2 (b) and 5.4 (b), input current of one phase together with its harmonic spectrum are displayed.

Table 5.1 Power quality analyzer readings of set up of 3-switch 3-phase SEPIC rectifier with split capacitor configuration of Fig. 3.3 of chapter 3.

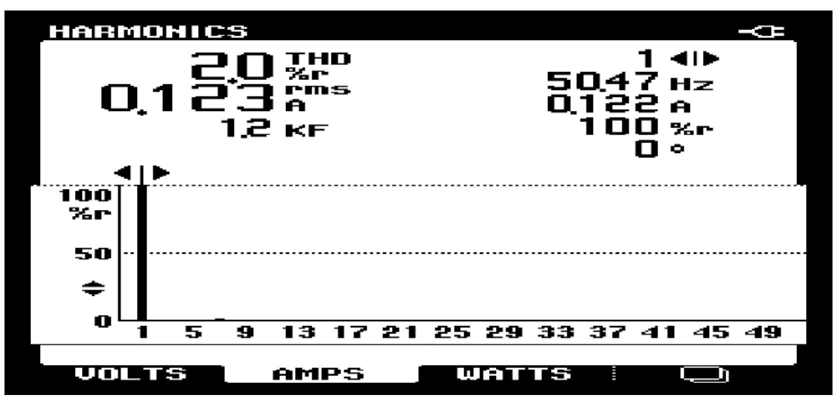
Duty Cycle (D)	RMS input Voltage (L-N) (V)	RMS Input Current (A)	Power Factor	THD of input current (%)	Output voltage (DC V)
0.3	6.06	0.123	0.98	2	5.6V
0.7	5.96	0.27	0.96	1.3	8.9V



(a)



(b)



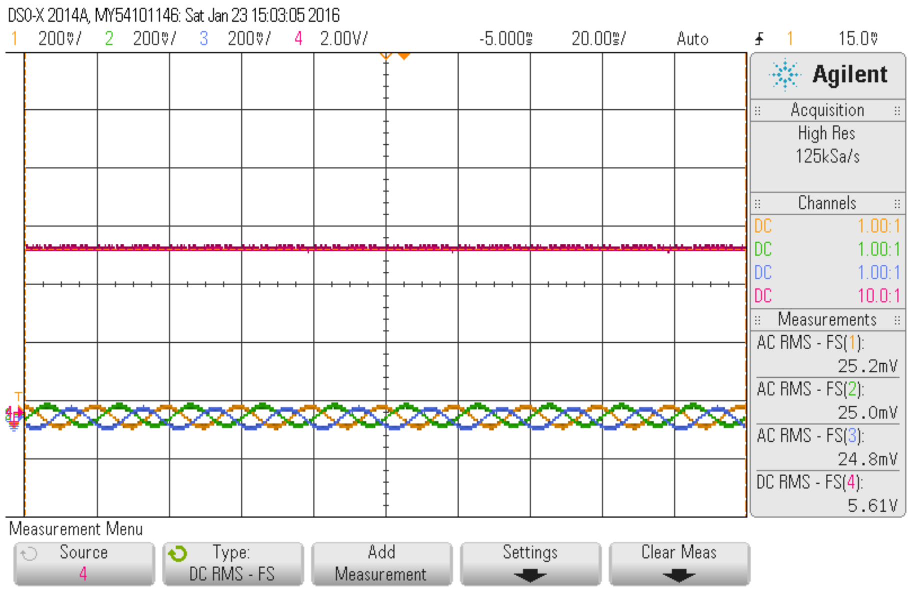
(c)

Fig. 5.1 Wave Shapes of Power Quality Analyzer 3-Switch 3-Phase SEPIC Rectifier with Split Capacitor Configuration for Duty Cycle (D) of 0.3

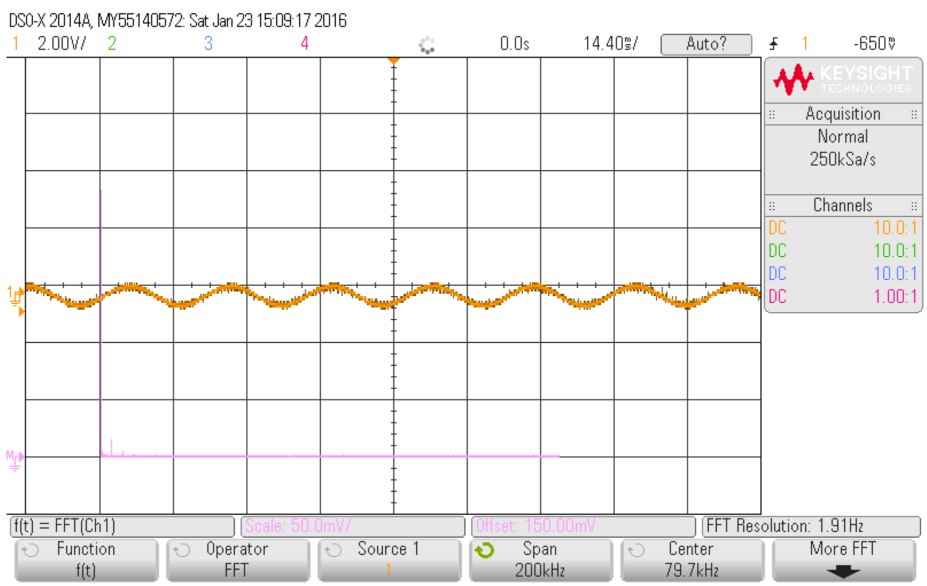
(a) Input Voltage and Input Current

(b) Input Power and Power Factor of a Phase

(c) THD of the Input Current



(a)

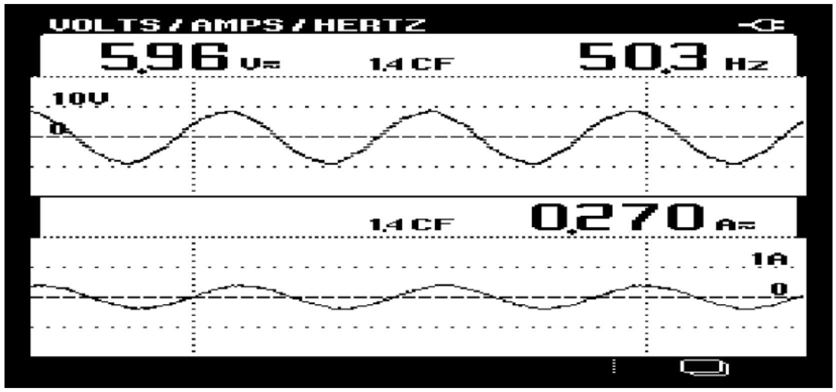


(b)

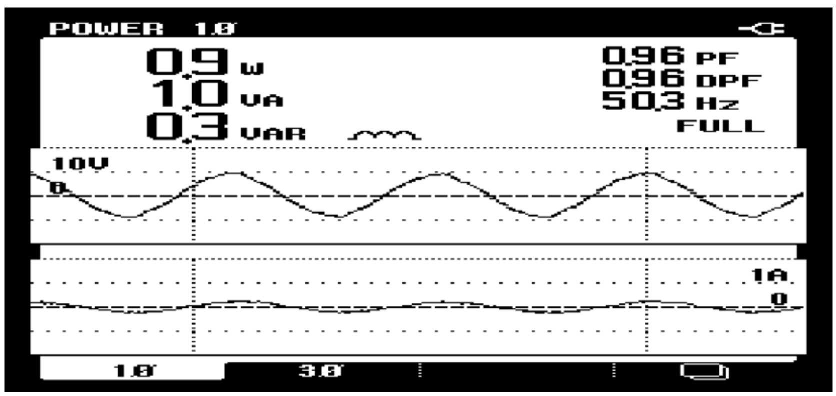
Fig. 5.2 Wave Shapes of Oscilloscope 3-Switch 3-Phase SEPIC Rectifier with Split Capacitor Configuration for Duty Cycle (D) of 0.3

(a) Input Currents and Output Voltage

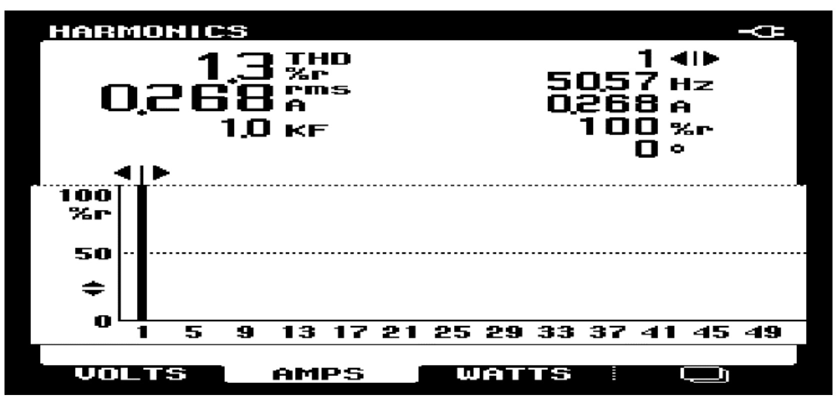
(b) Input Current of a Phase and FFT of the Current



(a)



(b)



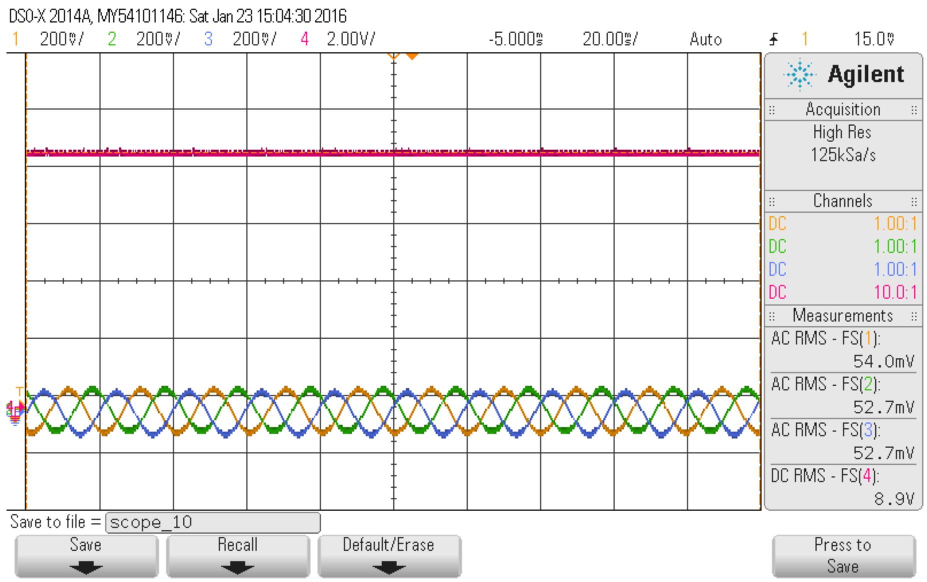
(c)

Fig. 5.3 Wave Shapes of Power Quality Analyzer for 3-Switch 3-Phase SEPIC Rectifier with Split Capacitor Configuration for duty cycle (D) of 0.7

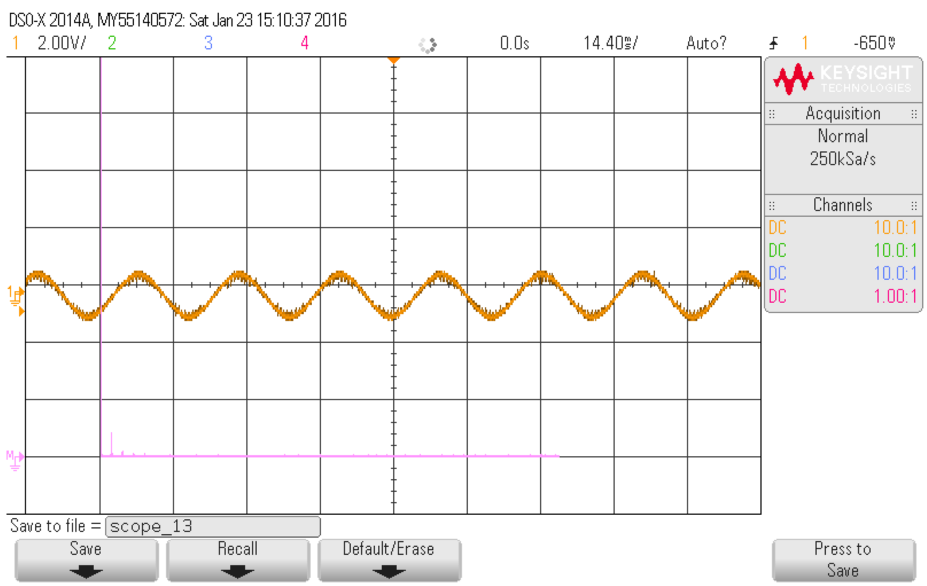
(a) Input Voltage and Input Current

(b) Input Power and Power Factor of a Phase

(c) THD of the Input Current



(a)



(b)

Fig. 5.4 Wave Shapes of Oscilloscope 3-Switch 3-Phase SEPIC Rectifier with Split Capacitor Configuration for duty cycle (D) of 0.7

(a) Input Currents and Output Voltage

(b) Input Current of a Phase and FFT of the Current

5.2 Discussions

The experimental results of the input switched SEPIC topology based power factor corrected (PFC) rectifier without feedback have been recorded in Table 5.1 and graphically represented in Figs. 5.1 to 5.4 for duty cycle (D) of 0.3 and 0.7. The power quality analyzer and oscilloscope records indicate that the converter has buck-boost voltage gain, power factor above 0.95 and THD of input current is lower than 2 percent. Also, the harmonics of certain bands are much lower than IEEE and other standard guidelines.

Chapter 6
Conclusion

Use of single and three phase unidirectional and bidirectional rectifiers are common in power supplies of electronic circuits, computers, telecommunications, biomedical instrumentations, mechatronics, various drives, magnet power supplies, chemical process industries, dc drives, inverters, stepper/brushless motors and DC transmission lines etc. In high power applications where three-phase systems are required to avoid the system unbalance, the search for three-phase PFC rectifier topologies with good efficiency, reliability, simple control and high-quality input currents have increased in the last decade. DC sources see loads as resistances. The output of AC-DC converters being dc, any load at their output will act resistively from their input sides. As a result, it is expected that the input power factor of AC-DC converters will be unity. Due to non-sinusoidal input current and ripples at the output voltage the rectifiers do not exhibit unity power factors. Reduction of input current distortion and improvement of input power factor of rectifiers at high conversion efficiency is a concern in the use of these converters. Passive, active and combined passive and active methods are used to enhance the performance of rectifiers. No individual method alone can solve the problems of AC-DC converters (rectifiers). Single phase rectifiers use either output or input switching as active filter method for power factor correction. As in three-phase diode bridge rectifiers input and output currents are not converted on phase to output basis and hence the PFC techniques are performed in per phase basis. Vienna and Swiss rectifiers are popular modular three phase rectifiers used for three phase Power Factor Correction. But they provide boost voltage gain characteristic only. Modular rectifiers are composed of three single phase PFC rectifiers that can rectify individual voltage of three phases separately and superpose them at the load. Per phase rectification allows sinusoidal input current shaping in the circuit by standard feedback control.

6.1 Summary of the thesis

The concept of modular three-phase rectifier is applied to the proposed three-phase, 3-switch SEPIC rectifier. In this thesis simulations have been carried out initially for observing the performance of the proposed SEPIC rectifier without feedback controller. It is found that input current THD are not in acceptable range and power factor deteriorates at higher and lower duty cycles. For improved power factor, lower input current THD and regulated output voltage proper feedback controller is designed in this thesis theoretically and studied by simulation. With change of ± 20 Ω of l00 Ω load the output voltage has been kept regulated at a fixed level by feedback controller. The feedback controller is able to keep the output rectified voltage at a constant level even when the input voltage is increased or decreased up to a certain limit. PFC controller of the rectifier was able to keep input current THD below 10 % and power factor of the circuits above 0.95. Laboratory experiments have been carried out on a low voltage low power prototype three switch three phase SEPIC rectifier with split capacitor configuration. Experiments were performed for without feedback configuration of the proposed circuit.

The new three switch SEPIC rectifier controlled by three single phase PFC controllers show good performance with step-up/down voltage gain. Dynamic response due to load change shows simple controller circuit can regulate output voltage to a desired value. The circuit is rugged in terms of reliability, operation and maintenance.

6.2 Future Work

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

- The proposed topology is implemented in a low voltage and low current prototype module. As future work, a high voltage high power properly designed circuit is recommended.
- The circuit is not implemented with feedback controllers due to non-availability of appropriate ICs and sensors. In future work, proposed circuit may be designed,

fabricated and tested at practical operating voltages and currents with proper feedback control circuits.

- The 3-phase 3-switch SEPIC topology based input switching circuit can be modified to have fewer active and passive components in the power circuit. The 3- switches can be reduced to 1-switch and performance of that 3-phase 1-switch topology can be investigated to find out its performance in comparison with three-switch rectifier.
- Circuit and device analysis may be carried out in details to obtain ideal and practical voltage/current expressions of the proposed circuit. To estimate the practical voltage/current gains of the proposed circuit it is necessary to obtain some form of expressions to calculate switching, conduction losses of the devices and stray losses of non-ideal inductors and components used in the circuits. These loss estimation methods may ease the design procedures of the feedback controller circuits of the proposed 3-phase AC-DC converters.

References

[1] M. H. Rashid, “Power Electronics Handbook”, 2001, Academic Press.

[2] N. Mohan, “First course on Power Electronics and Drives”, MNPERE, Minneapolis, 2003.

[3] Hart D. W., (2011) Power Electronics McGraw-Hill Companies, Inc, New York.

[4] X. Jiang, J. Yang, J. Han, T. Tang, "A Survey of Cascaded Multi-level PWM Rectifier with VIENNA Modules for HVDC System", Electronics and Application Conference and Exposition (PEAC), pp. 72-77, 2014.

[5] A. Z. Azazi, E. E. EL Kholy, S. A. Mahmoud and S. S. Shokralla, “Review of Passive and Active Circuits for Power Factor Correction in Single Phase, Low Power AC-DC Converters”, International Middle East Power Systems Conference, Cairo University, Egypt, pp. 217-224, December 2010.

[6] M. S. Jamil Asghar, “Power Electronics”, 2004, Prentice Hall India.

[7] B. N. Singh; P. Jain, G. Joos, "Three-Phase PWM Voltage Source Rectifier with a Reduced Number of Switches," Electrical and Computer Engineering, 2000 Canadian Conference on., vol.2, pp.951,955, 200.

[8] O. Garcia, J. A. Cobos, R. Prieto, P. Alou and J. Uceda, "Single Phase Power Factor Correction: A Survey.", IEEE Transactions on Power Electronics, vol. 18, no. 3, pp. 749-755, May 2003.

[9] B. Singh, B. N. Singh, A. Chandra, K. Al-Haddad, A. Pandey and D. P. Kothari, "A Review of Single-Phase Improved Power Quality AC-DC Converters." IEEE Transactions on Industrial Electronics, vol. 50, no. 5, pp. 962-981 October 2003.

[10] Johann W. Kolar, and Thomas Friedli " The Essence of Three-Phase PFC Rectifier Systems—Part I", IEEE Transactions on Power Electronics, VOL. 28, NO. 1, pp. 176-198 January 2013.

[11] J. Salmon, "Techniques for Minimizing the Input Current Distortion of Current-Controlled Single-Phase Boost Rectifiers", IEEE Transaction on Power Electronics, pp. 509-520, 1993.

[12] J. P. M. Figueiredo, F. L. Tofoli and B. L. A. Silva "A Review of Single Phase PFC Topologies based on Boost Converter", IEEE/IAS International Conference on Industry Application, INDUSCON, pp.1-6, 2010.

[13] M. S. Patil, and S. P. Patil, "Single-Phase Buck-Type Power Factor Corrector with Lower Harmonic Contents in Compliance with IEC 61000-3-2", International Journal of Engineering Science and Technology, vol. 2, no.11, pp. 6122-6130, 2010.

[14] W. Y. Choi, J. M. Kwon, E. H. Kim, J. J. Lee, and B. H. Kwon, "Bridgeless Boost Rectifier with Low Conduction Losses and Reduced Diode Reverse-Recovery Problems," IEEE Transaction on Industrial Electronics, vol. 54, no. 2, pp. 769–780, April 2007.

[15] Mesaad Waleed Albader, "Advance Three Phase Power Factor Correction Schemes for Utility Interface of Power Electronic Systems", MSc thesis, Electrical and Electronic Engineering, Texas A&M University.

[16] Thomas Friedli, Michael Hartmann, and Johann W. Kolar, " The Essence of Three-Phase PFC Rectifier Systems—Part II", IEEE Transactions on Power Electronics, VOL. 29, NO. 2, pp. 543-560, February 2014.

[17] Raggl, K.; Nussbaumer, T.; Doerig, G.; Biela, J.; Kolar, J.W., "Comprehensive Design and Optimization of a High-Power-Density Single-phase Boost PFC," Industrial Electronics, IEEE Transactions on, vol.56, no.7, pp.2574,2587, July 2009.

[18] Z. Janda and P. Pejovic, "A High-Power Factor Three Phase Rectifier based on Adaptive Current Injection applying Buck Converter", International Conference on Power Electronics and Motion Control, pp.140-144, 2000.

[19] Fang Lin Luo and Hong Ye, "Power Electronics: Advanced Conversion Technologies", CRC Press, 2010.

[20] Y. Jang and M. M. Jovanovic, “Robust, Harmonic Injection System for Single Switch, Three Phase, Discontinuous Conduction Mode Boost Rectifiers “, Patent No. 5847944, August 1997.

[21] S. M. Bashi, N. Mariun, S.B. Noor and H. S. Athab, “Three Phase Single Switch Power Factor Correction Circuit with Harmonic Reduction”, Journal of Applied Science vol. 5, no. 1, pp. 80-84, Asian network for Scientific Information 2005.

[22] A. Toumi, M.Ghariani, I.Ben Salah and R.Neji, “Three Phase PFC Rectifier Using a Switching Current Injection Device for Vehicle Power Train Application”, International Renewable Energy Congress, Sousse, Tunisia, pp. 417-420, November 2010.

[23] A. R Prasad. and P. D Ziogas., “An Active Power Factor Correction Technique for Three Phase Diode Rectifiers”, IEEE Transaction Power Electronics, vol.6, no.1, 1991, pp. 8392.

[24] D. Mukherjee and D. Kastha, "Voltage Sensor-less Control of the Three-Level Three-Switch Vienna Rectifier with Programmable Input Power Factor.", IET Power Electronics, vol. 8, no. 8, pp. 1349–1357, 2015.

[25] A. D. Pathak, R. E. Locher, H. S. Mazumdar, “3-Phase Power Factor Correction, Using Vienna Rectifier Approach and Modular Construction for Improved Overall Performance, Efficiency and Reliability”, Power Electronics Conference in Long Beach, CA, 2003, pp. 1-13.

[26] C. Qiao and K. M. Smedley, “Three-phase Unity-Power-Factor VIENNA Rectifier with Unified Constant Frequency Integration Control”, IEEE International Power Electronics Congress, CIEP 2000, pp. 125-130.

[27] A. B. Reddy and G. T. Ram Das, "High Quality Rectifiers with Reduced THD for Enhanced Mains Power Quality - Vienna with Synchronous Logic", Journal of Engineering and Applied Sciences, vol. 6, no. 7, July 2011, pp. 97.

[28] M. M. S. Khan, M. S. Arefin, M. R. T. Hossain, M. A. Kabir, A. H. Abedin and M. A. Choudhury, "Input Switched Single Phase Buck and Buck-Boost AC-DC Converters with Improved Power Quality", International Conference on Electrical and Computer Engineering, pp. 189-192, December 2012.

[29] M. A. Kabir, A. H. Abedin, H. A. Moonmoon, M.A. Choudhury and M.N. Uddin, "Cuk Topology based Single Switch Single Phase High Poor Quality AC Voltage Controller", IEEE Industrial Application Society Annual Meeting, pp. 1-6, October 2012.

[30] A. H. Abedin, M. R. T. Hossain, M. H. Rahman, M. M. S. Khan, M. A. Choudhury and M. N. Uddin, "Input Switched Single Phase High Performance Bridgeless Ćuk AC-DC Converter", IEEE International Conference on Power Electronics, Drives and Energy System, Bangaluru, pp. 1-5, December 2012.

[31] M. R. T. Hossain, A. H. Abedin, M. H. Rahman, M. S. Arefin, M. A. Choudhury and M. N. Uddin, "Input Switched Single Phase High Performance Bridgeless AC-DC Zeta Converter", IEEE International Conferencec on Power Electronics, Drives and Energy System, Bangaluru, pp.1-5, December 2012.

[32] K. L. Bashar, A. H. Abedin, M. N. Uddin and M. A. Choudhury, "Three Phase Three Switch Modular Vienna, Boost and SEPIC Rectifiers", CIEC, Kolkata, India, 2016.