INVESTIGATION OF A SINGLE PHASE UNIDIRECTIONAL SWITCH MODE ĈUK POWER FACTOR CORRECTED (PFC) RECTIFIER

A Thesis

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Master of Science in Electrical and Electronic Engineering

By

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Certification of Approval

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ABSTRACT

Single phase diode rectifiers are widely used in industrial, commercial, utility and domestic applications. Many input wave shaping methods have been proposed to solve the problem of poor power factor which can be classified as active and passive methods. Four different configurations based on single phase Ĉuk topologies have been proposed to solve poor input power factor and total harmonic distortion problems of AC-DC converters. The proposed topologies show superior performance over output voltage regulated conventional single phase AC-DC converters. The topologies proposed are Input Switched **Ĉ**uk Converter (output full bridge), Input Switched **Ĉ**uk Converter (output half bridge), Modified **Ĉ**uk Converter-1 (Switch within a Diode Bridge), Modified **Ĉ**uk Converter-2 (Switch within a Diode Bridge) configurations. The proposed configurations are designed for operating the converters both buck and boost voltage gain region. Results are compared with the results of conventional output switched single phase boost rectifier and conventional output switched Ĉuk rectifier. Proposed topologies show lower input current THD, higher power factor and high efficiency compared to the previously mentioned conventional rectifiers. Typical output voltage and input current waveforms are shown in the thesis work. It has been found that without feedback control input current THD is not in acceptable range. Therefore a feedback controller is designed in this thesis work which makes the power factor of the rectifier above 0.9 and keeps the input current THD less than 10%. The feedback controller with the power stage of the proposed topologies are also designed in such a way that gives regulated output voltage with load variation. The results show that, the proposed configurations based on **Ĉ**uk topologies give better performance over all the conventional output switched and input switched boost rectifiers and also output switched **Ĉ**uk rectifier.

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LIST OF ABBREVIATIONS OF TECHNICAL TERMS

PF	Power Factor
PFC	Power Factor Correction
BJT	Bipolar Junction Transistor
IEEE	Institute of Electrical and Electronic Engineers
IEC	International Electrotechnical Commission
IGBT	Insulated Gate Bipolar Transistor
MOSFET	Metal Oxide Semiconductor Field Effect Transistor
PWM	Pulse Width Modulation
THD	Total Harmonic Distortion
CCM	Continuous Current Conduction Mode
DCM	Discontinuous Current Conduction Mode

Chapter 1

Introduction

Single phase diode bridge rectifiers are building blocks of dc power supplies and are used in all electronic equipment/apparatus. All electronic devices require dc power supplies converted from AC of the grid or from batteries. Large capacitors used to smooth dc voltages make rectifiers input current non-sinusoidal and input power factor low. This causes high input current THD and low input power factor which is detrimental to utility power supply. The overall effect of a single power supply is not large, but when one considers the many such supplies in use, the combined effect on power quality of these power supplies can be substantial.

1.1 Background and Present Status of the Problem

There are strict regulations to limit the harmonic distortion permitted on the AC mains line. To comply with the harmonic requirements and maintain high overall power factor (PF) performance, it is necessary to incorporate power-factor correction (PFC) in the AC/DC front-end converter modules used in electronic systems. Implementing PFC achieves a high PF number and ensures low harmonics. There are a number of passive and active techniques available today for numerous power-supply topologies employed in the AC front-end supplies. The passive approach (L-C filters) improves waveforms only and the active approach improves waveforms and power factor both (by the use of combined high frequency switching and small low pass filters).

With the development of power electronics, input power factor and total harmonic distortion (THD) of diode bridge rectifiers can be improved by active filters. The most common active method of power factor correction (PFC) and input current improvement of a single phase diode bridge rectifier is the boost PFC circuits. Other circuit topologies like buck, buck-boost, Ĉuk and SEPIC topologies are also used for the same purpose [1-16]. In an active PFC technique either the output dc or the input ac is switched at high frequency to make the input current switched sine wave in phase with the input sinusoidal voltage [10, 13, 17, 18]. Proper feedback control of PFC circuit with feedbacks from output and input makes the rectifier power factor corrected and output voltage regulated with small input current THD and high conversion efficiency [1, 2].

Passive and Active PFC techniques used in applications of AC-DC converters are stated below:

Passive PFC

The simplest way to control the harmonic current is to use a passive filter that passes current only at line frequency (e.g., 50 or 60 Hz). This filter reduces the harmonic current, which means that the nonlinear device now looks like a linear load. Using filters built with capacitors and inductors, power factor can be brought to near unity [36].Despite being simple to design and use, passive PFC circuits offer a few disadvantages. First, the bulkiness of the inductor restricts its usability in many applications. Second, for worldwide operation, a line-voltage range switch is required. Incorporation of the switch makes the appliance/system prone to operator errors if the switch selection is not properly made. Finally, the voltage rail not being regulated leads to a cost and efficiency penalty on the AC/DC converter that follows the PFC stage.

Active PFC

Besides performance, the rising cost of copper and magnetic core material, coupled with the falling cost of semiconductors, has tilted the balance in favor of active PFC solutions, even in the most cost-sensitive consumer equipment. In the following scheme (Figure 1.1), the active PFC circuit is placed between the input rectifier and the storage capacitor, followed by the DC/DC converter. The PFC IC with associated circuitry shapes the input current to match the input voltage waveform and achieve PF that is 0.9 and higher. In properly designed PFC circuit with feedback input high frequency bypass capacitor is not necessary.

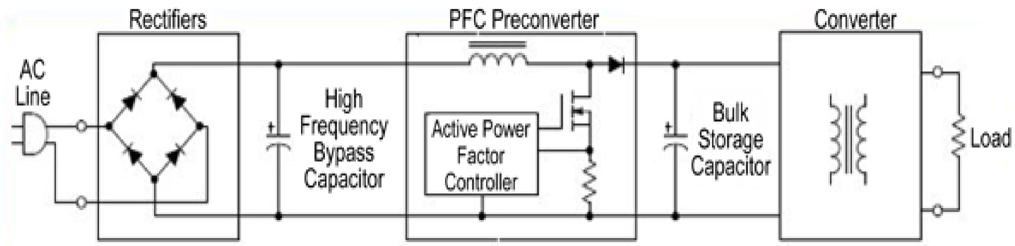


Figure 1.1: The active PFC controller circuit (Courtesy of ON Semiconductor.)

Fundamentally, there are three different schemes of active PFC controller. These include critical-conduction mode (CrM), continuous-conduction mode (CCM), and discontinuous-conduction mode (DCM). The CrM control scheme keeps the inductor current at the borderline limit between continuous and discontinuous conduction. It is used in medium power applications up to 300W.

CCM control is widely preferred in many applications, ranging from medium- to high-power applications due to low peak current stress, low ripples and easy filtering task. In the DCM space, which is also preferred for low- to medium-power applications, digital techniques are used to create a discontinuous-mode active PFC controller that eliminates the need for several passive components to offer a low-cost PFC solution for PCs, notebook adapters, and digital TV receivers.

Regarding the power factor correction stage, some other techniques used in applications of AC-DC converters are stated below:

Using As Input Current Shapers

The objective of input current shaper is to enlarge the conduction angle of a diode bridge reducing the harmonic content of the line current to comply with the regulations. This is achieved by means of addition of an auxiliary output connected in series with the input as shown in Figure 1.2. In these circuits there is a tradeoff between the conduction angle and the power delivered through the auxiliary output. The solution since adds few elements to a dc–dc converter (in some cases an inductor an auxiliary winding and a couple of diodes). The only problem is that the storage capacitor is placed in an intermediate position and its voltage is higher than the line voltage, penalizing its use in universal line voltage applications. Several circuits have been presented with a similar approach [20-22].

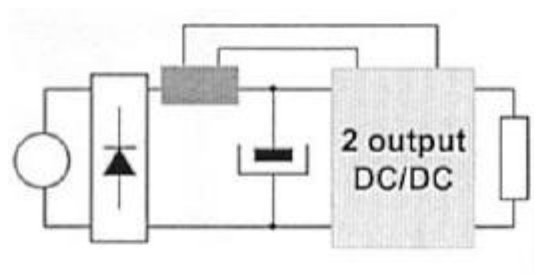


Figure 1.2: Power Factor Correction approach using input current shaper

Reducing the Number of Switches

Reduction of number of switches means reduction in control circuit and it's cost. This procedure has been the base to develop further solutions. An example using the boost and the flyback converters is shown in Figure 1.3. In this circuit, there is only one controlled switch. It is controlled to obtain a tightly regulated output voltage at the load. Thus, line current depends on the voltage follower capabilities of the first converter (boost). A high power factor is obtained, but the problem is that the efficiency is penalized because of the high voltage on the storage capacitor and because both converters should be designed in discontinuous conduction mode (DCM), limiting this solution to low power applications (100–200 W). Reference [23] shows a general procedure to reduce the number of switches of the two stage approach.

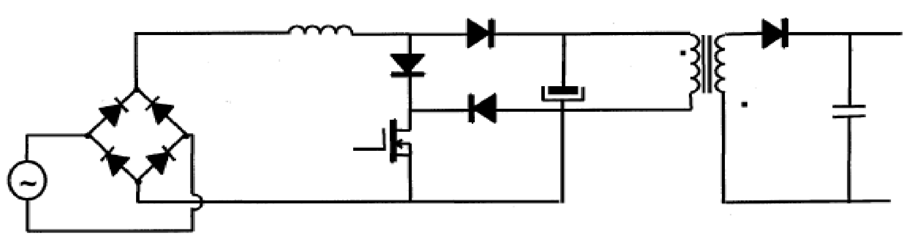


Figure 1.3: Combination of boost PFC and Flyback dc-dc converter with a single switch

Removing of Control Loops

This is similar to the previous one but without combining the switches. The two stages share the duty cycle. With a proper selection of the converters, the line current can be made almost sinusoidal. For instance, a continuous conduction mode (CCM) dc–dc converter gives a constant duty cycle which is less sensitive to load variations. This converter with a DCM PFP converter such as flyback, produces near sinusoidal line current. Reference [24] shows an example where part of the output power is processed once.

Resonant Input Filter

Figure 1.4 shows the series filter arrangement for power factor correction [25-28], which results in good power factors as high as 0.94. Thus, harmonic performance is also good. This circuit arrangement is popularly used in applications where the supply frequency is high. The disadvantage with this type of arrangement is the use of large size of elements and large r.m.s currents in filter capacitors if the supply frequency is low.

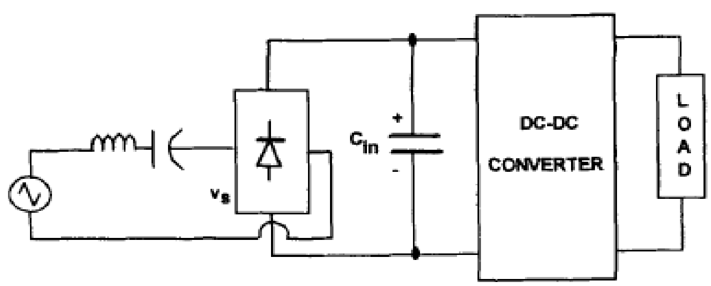


Figure 1.4: Rectifier circuit with series resonant input filter [29]

Some researchers [30], [31], suggest the use of parallel resonant filter (Figure 1.5) for PF improvement. With this arrangement power factor close to 0.95 is achievable. The filter is tuned to offer high impedance to the third harmonic component (the most predominant). The high value parallel resistor is added to damp out circuit oscillations.

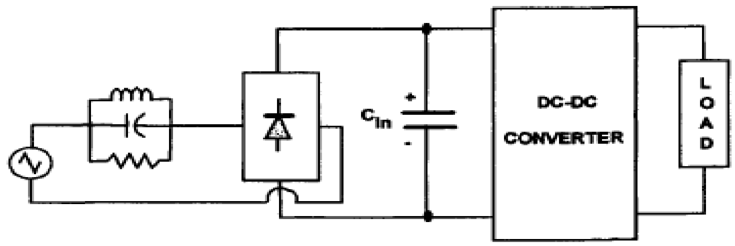


Figure 1.5: Rectifier with parallel resonant filter [29]

Using Active Filters

The use of active filters is common in high power installations. Figure 1.6 shows the parallel configuration. The power stage has two switches and the control circuit is implemented using a common PFC controller. This solution can be used in existing systems to convert a distorted line current into sinusoidal without any change in the system. Therefore, it can be considered as optional equipment used only in those cases where regulations need to be complied.

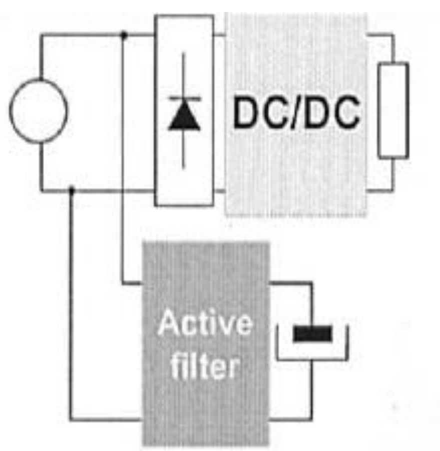


Figure 1.6: Power Factor Correction approach using Active Filter in parallel configuration

One of the recent active power factor correction methods is briefly discussed in the present work. A switch is used on the input side in one of the proposed topology and in between bridge rectifier in another proposed topology to provide alternative path for the input current to flow and hence makes it continuous. The rectifier is connected to the topologies through a combination of inductor and capacitor, which keeps the input current smooth and in-phase with the supply voltage.

Though the Ĉuk topology of switching ac-dc converters is not common in PFC rectifiers, it has several advantages over input boost topology stage, boost-buck gain characteristics and single ended capacitively isolated output [1-3].

1.2 Objective of the Thesis

The objectives of the proposed research are,

- To investigation high frequency switched and feedback controlled Ĉuk topology based single phase diode bridge rectifier to improve its input current shape and the input power factor. The switch for output voltage regulation, input current shape and input power factor correction will be positioned within the rectifier (neither at the output nor at the input as conventionally done). The change in position of the switch will be done with the objective that the topology may be advantageously used in three phase PFC rectifier in the long run.
- To design and study the appropriate feedback control circuit for new Ĉuk topology based single phase PFC rectifier to improve the input current THD and input power factor of the rectifier and,
- To study the performances of the new Ĉuk topology based single phase diode bridge PFC rectifier and compare the performance improvement over the conventional Ĉuk topology based single phase PFC rectifier.

1.3 Possible Outcome of the Research

Possible outcome of the research will be,

- A high performance boost-buck regulated single phase AC-DC converter (rectifier) with near unity input power factor and low input current THD. The conversion efficiency of the proposed rectifier will be high.
- The proposed rectifier will be capable of boost-buck voltage and current gain.
- The topology may be used effectively in boost-buck three phase ac to dc conversion for input current and input power factor improvement.

1.4 Thesis Outline

New topologies of a single phase Ĉuk AC-DC converters operated along with a properly designed PFC feedback controller are proposed in this thesis. These topologies are investigated by designing them to operate for buck-boost voltage and current gain in bridge and bridgeless configurations.

Chapter-2 contains the introduction of conventional single phase boost rectifier and describes the necessity of the power factor correction schemes.

In chapter-3 new topologies of a single phase Ĉuk AC-DC rectifiers are proposed with description of their basic operation. Performance advantages over conventional single phase Ĉuk rectifier are highlighted in this chapter.

Chapter-4 deals with the work of this thesis. It presents the study and description of new Ĉuk topology based AC-DC converters designed to operate in buck and boost mode of operation at constant switching frequency with a PFC feedback controller. The design of the feedback controller and the simulated results, wave shapes and graphical representations are included in this chapter.

Chapter-5 shows comparison analysis of the performance improvement of proposed configurations over the conventional Ĉuk topology based single phase PFC rectifier.

Chapter-6 describes the practical implementation of the proposed Ĉuk topologies without feedback and contains the justification of the practically measured results with the theoretically shown results of the proposed topologies.

Chapter-7 this chapter concludes the thesis with conclusion, summary and suggestion on future works.

Chapter 2

Single Phase Conventional Boost Rectifier

2.1 Single Phase Output Switched Boost AC-DC Converter

One of the common active power factor corrected (PFC) rectifier circuit is the boost PFC converter, the circuit is a relatively simple and low-cost. The extra components that are required beyond the ones used in a linear AC-DC converter are a switch, a diode and an inductor. Figure 2.1 shows a boost PFC converter which consists of a linear power supply with a boost converter inserted between the rectifier and the filter capacitor. In this topology, the output capacitor ripple current is very high and is the difference between diode current and the dc output current. To control the input current within a narrow window around sinusoidal reference current, either inductor L should have a high value or the switching frequency of the device is kept high. The later is chosen to down size the rectifier unit. With higher switching frequency the switching power loss increases. At higher frequency the increased power loss in switch S owes to turn ON and OFF rate of a high current. This increased power loss brings down the efficiency of the rectifier.

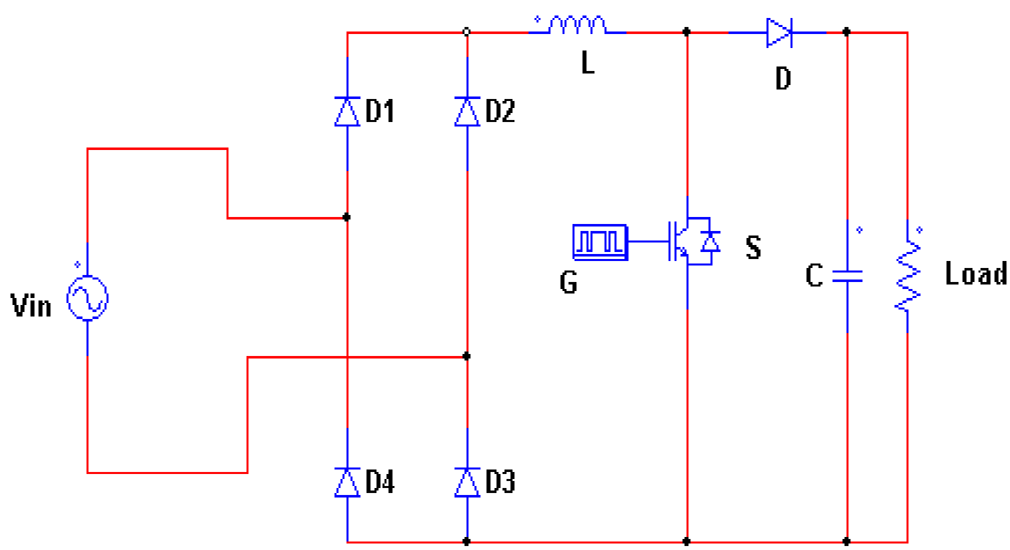


Figure 2.1: Single Phase Output Switched Boost AC-DC Converter

The typical input, output voltage and the input current of the circuit of Figure 2.1 are shown in Figure 2. 2 and the spectrum of the input current is shown in Figure 2.3.

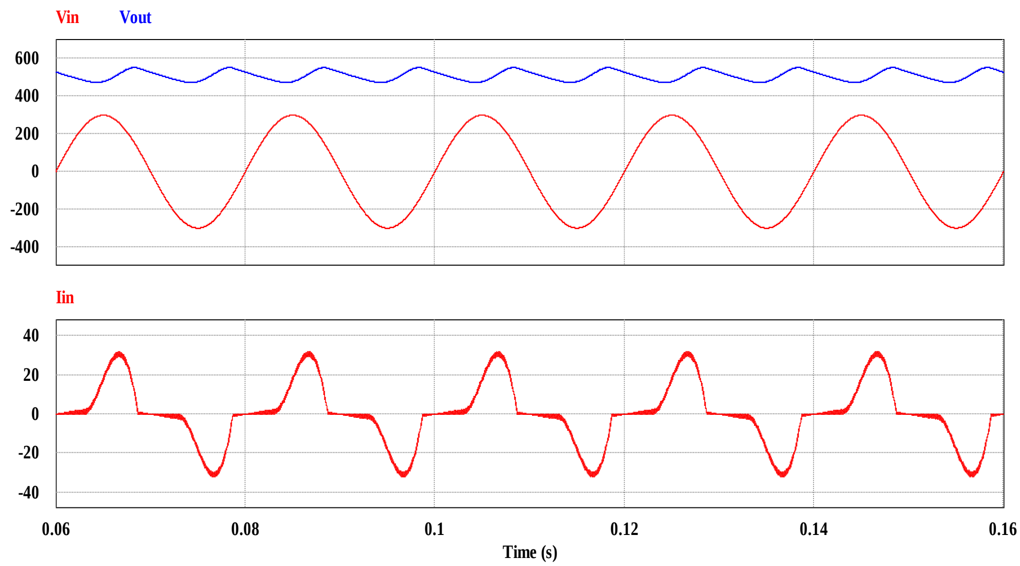


Figure 2.2: Input and output voltage (upper Figure) and input current (lower Figure) of the conventional output switched single phase boost rectifier of Figure 2.1

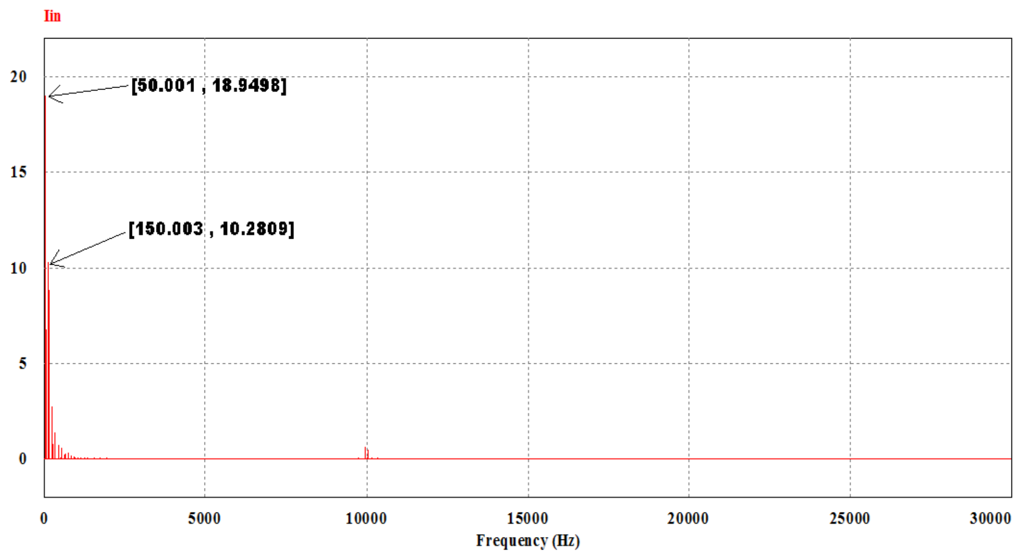


Figure 2.3: Spectrum of the input current of Figure 2.2 of the conventional output switched single phase boost rectifier

2.2 Single Phase Input Switched Boost AC-DC Converter

Figure 2.4 shows a single phase input switched boost AC-DC converter. This type of configuration uses a bidirectional switch. Bi-directional switches have higher current carrying capacity which is the predominant approach of modern power electronics for high power application. Because of input current switching it ensures input AC current to be in phase with input voltage where there is no output filter. This would result shaping of input current to near sinusoid by use of small filter and will ensure good input power factor without having much impact of output filter, input voltage and change of load. This type of boost AC- DC converter provides step-up output dc voltage with the duty cycle control of the switch.

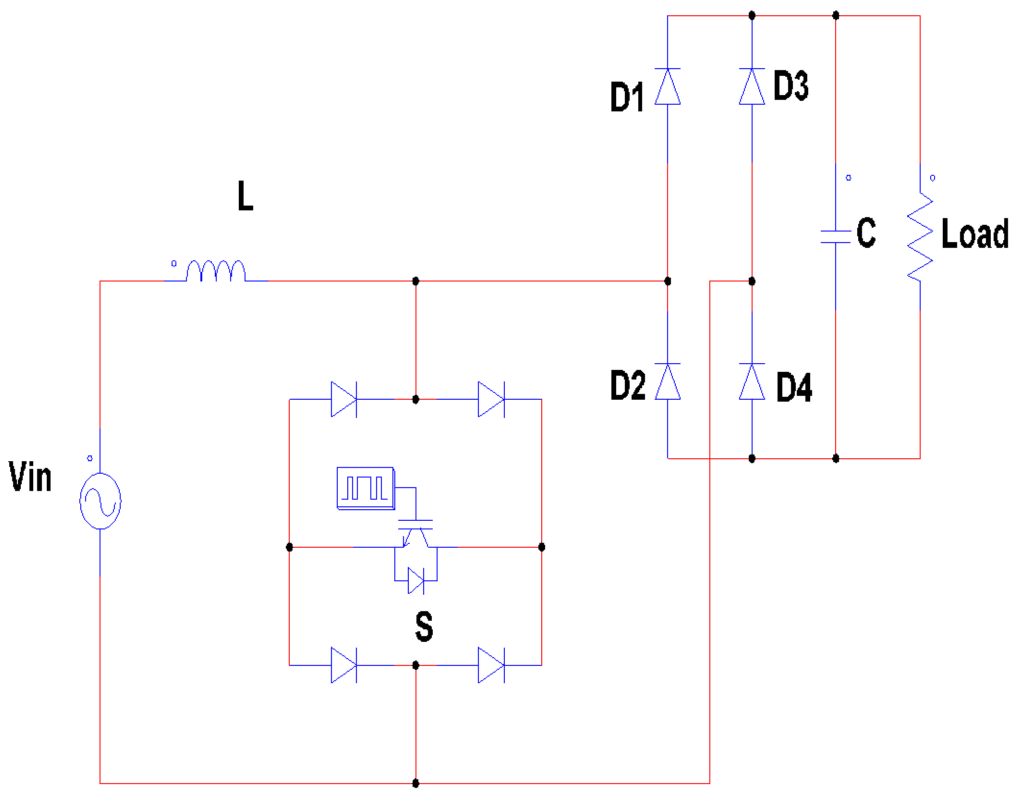


Figure 2.4: Single Phase Input Switched Boost AC-DC Converter

The typical input, output voltage and the input current of the circuit of Figure 2.4 are shown in Figure 2.5 and the spectrum of the input current is shown in Figure 2.6.

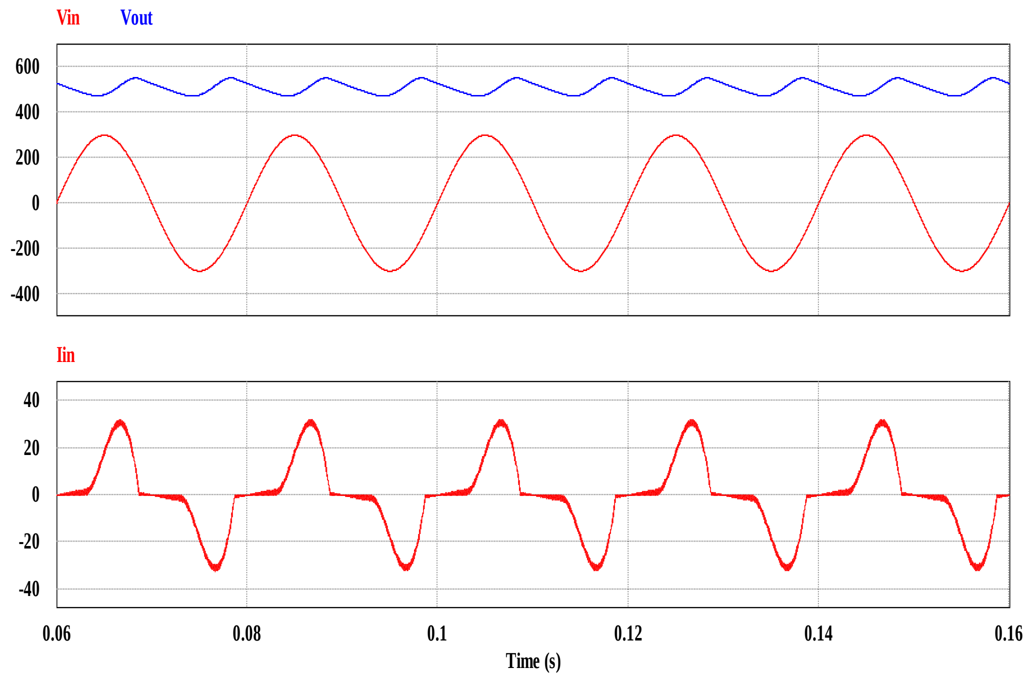


Figure 2.5: Input and output voltage (upper Figure) and input current (lower Figure) of the conventional input switched single phase boost rectifier of Figure 2.4

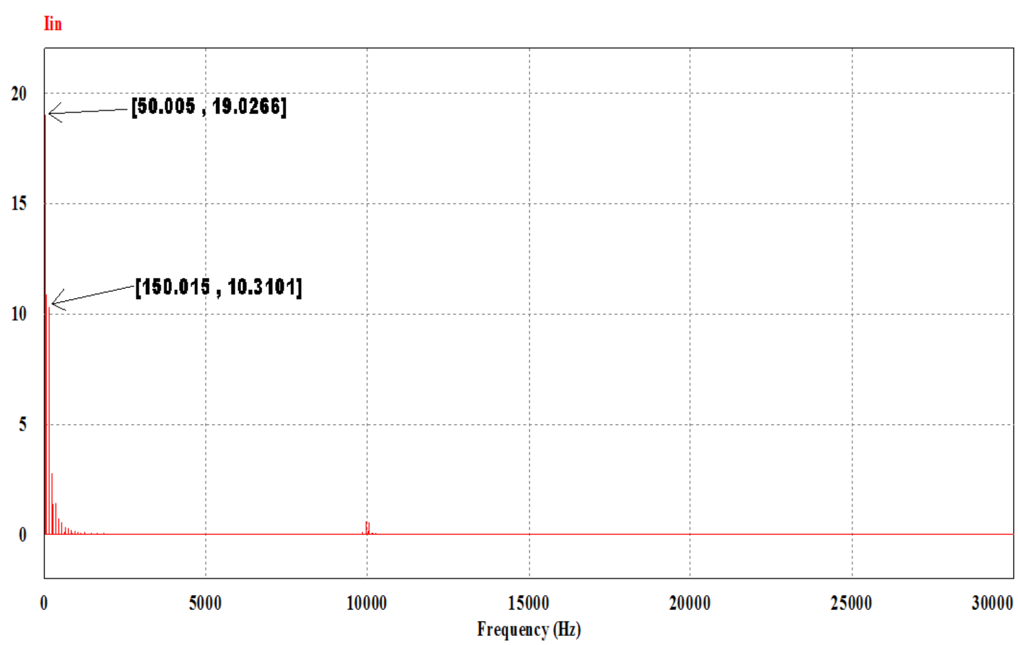


Figure 2.6: Spectrum of the input current of Figure 2.5 of the conventional input switched single phase boost rectifier

It is clear from the Figures 2.2 and 2.5 that conventional output and input switched boost rectifiers draw non-sinusoidal input currents. Non-sinusoidal input currents of rectifiers cause low input power factor. In case of low power factor, input current will increase, and high input current will cause to large line losses (Copper losses), large kVA rating and size of electrical equipment, greater conductor size and cost, poor voltage regulation and large voltage drop, low efficiency and penalty from electric power Supply Company. Because of the non-zero source impedance in the utility supply, the harmonic currents flowing through the conventional AC-DC utility interface will cause a distortion in the voltage waveform at the point of common coupling. This may cause malfunction of power system protection, loads and metering devices. Besides voltage waveform distortion and harmonic components may also cause the problems of overheating of neutral line, distribution transformers and distribution lines, interference with communication and control signals, over voltages due to resonance conditions. Poor power factor of operation implies ineffective use of the volt-ampere ratings of the utility equipment such as transformers, distribution lines and generators. Also, it places a restriction on the total equipment load that can be connected to a typical home or office wall-plug with specified maximum rms current rating.

The total harmonic distortion (THD) of the input current and the input power factor of the circuit can be improved by properly designed PFC feedback controller.

2.3 Single Phase Conventional Boost Rectifier with Feedback Circuit

Feedbacks from output voltage, input voltage and boost inductor current for a properly designed controller circuit is needed to ensure regulated output voltage and the AC input current being sinusoidal and in phase with the AC voltage. Figure 2.7 gives a general idea of the overall system. It shows a boost PFC circuit with a controller block that accepts four inputs and generates a pulse-width-modulated (PWM) output applied to the gate of the switch S_1. The control system would typically be a PI or PID control system that ensures that the differences between the reference signals and the required signals are as small as possible. This technique enables to keep power factor above 0.9 and the THD is about 10%. These numbers indicate good power quality and meet sufficient harmonic current restriction as well as the power factor requirement.

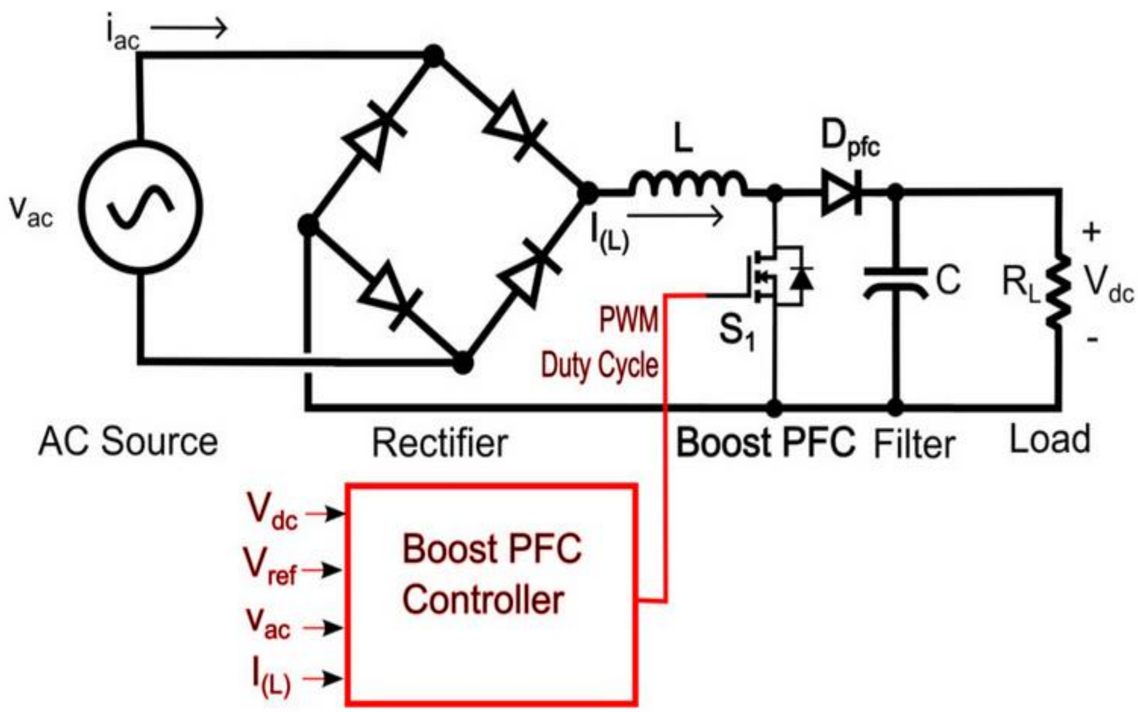


Figure 2.7: Boost PFC Converter Circuit with Feedback Control System

With proper feedback circuit designed in this thesis work, (Detail of the feedback circuit design is given in chapter 4) the improved performances of the typical waveforms of the conventional boost circuit are given in Figures 2.8 to 2.11.

2.3.1 Typical Results of Output Switched Boost PFC Converter with Feedback

Properly designed boost power factor corrected rectifier with feedback from output and input voltages, and inductor current maintains constant regulated output voltage with high input power factor and low input current total harmonic distortion. Typical waveforms of such an arrangement for a rectifier followed by boost DC-DC converter (between rectifier and load) of Figure 2.8 shows DC output voltage of low ripple, input voltage/current being in phase and the input current is of low THD (lower than 20%) as evident from the spectrum of the input current of Figure 2.9. Boost pfc circuit however does not allow lower than input voltage at output. Ĉuk converter can be used in place of boost converter in order to get both buck and boost voltage gain by varying duty cycle.

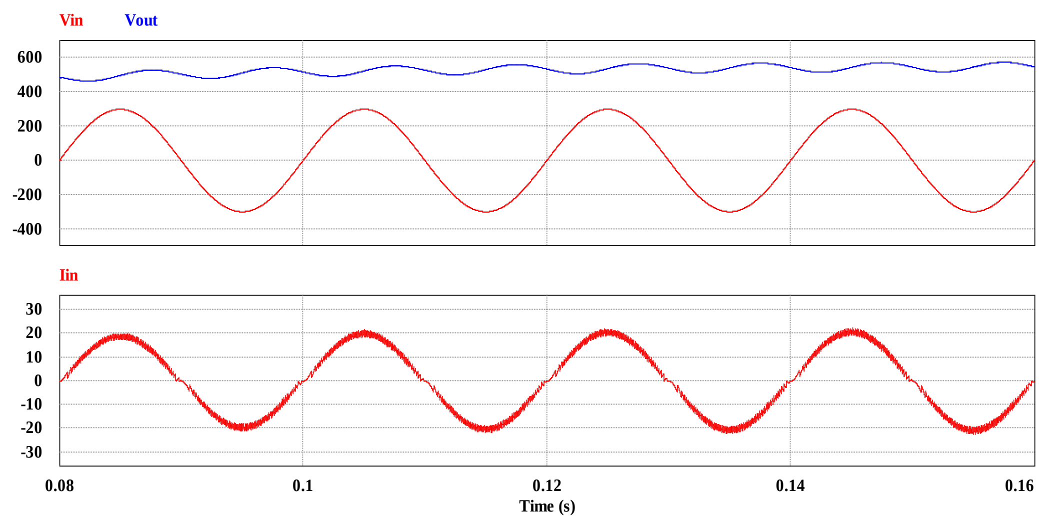


Figure 2.8: Input and output voltage (upper Figure) and input current (lower Figure) of the conventional output switched single phase boost rectifier

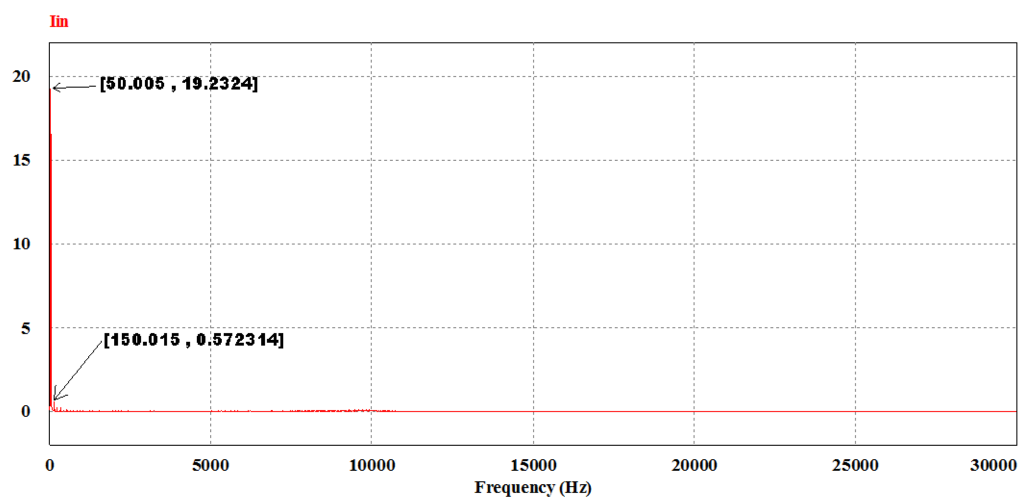


Figure 2.9: Spectrum of the input current of Figure 2.8 of the conventional output switched single phase boost rectifier

2.3.2 Typical Results of Input Switched Boost PFC Converter with Feedback

Similar to power factor correction stage between rectifier and load, the switching stage between input voltage and rectifier provides almost same performance as shown in the waveforms of Figures 2.10 and 2.11. Figures 2.10 and 2.11 are for single phase boost pfc circuit being switched at the input. Figure 2.10 shows the output voltage with low ripple maintaining almost unity input power factor as evident from the input voltage and current. The input current is almost sinusoidal with very low THD as apparent from the corresponding spectrum of Figure 2.11. Boost pfc circuit however does not allow lower than input voltage at the output load. Figures 2.10 and 2.11 are obtained by proper feedback control of output/input voltages and inductor current of the boost rectifier circuit.

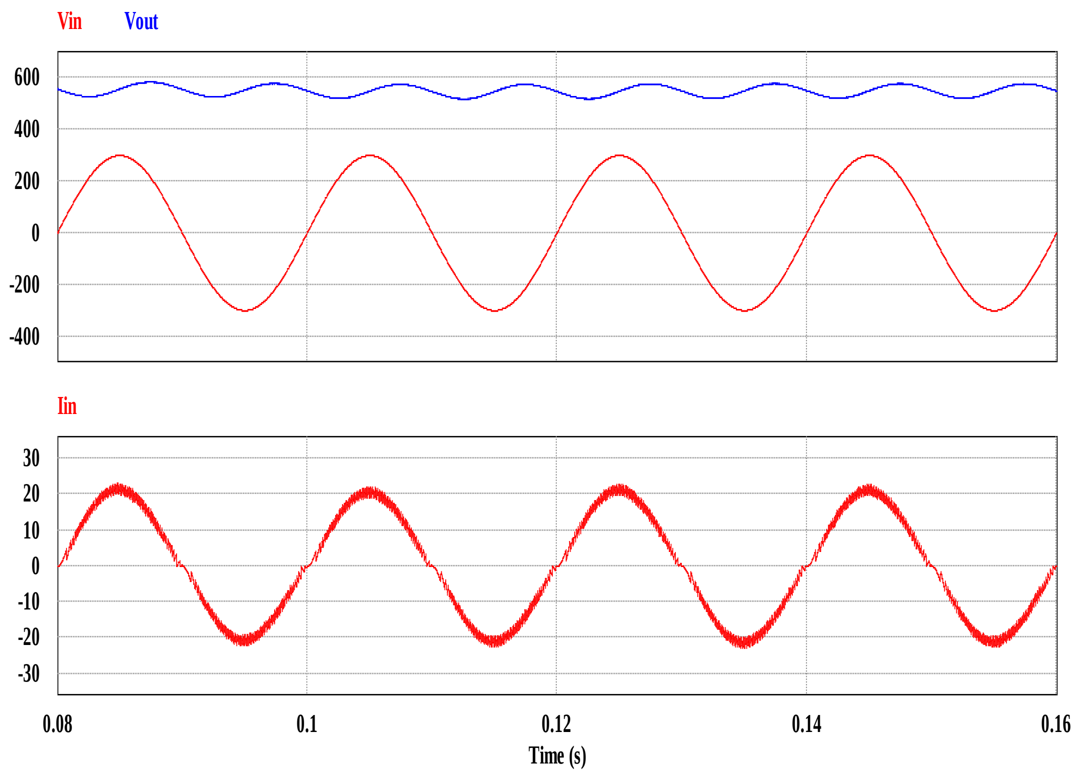


Figure 2.10: Input and output voltage (upper Figure) and input current (lower Figure) of the conventional input switched single phase boost rectifier

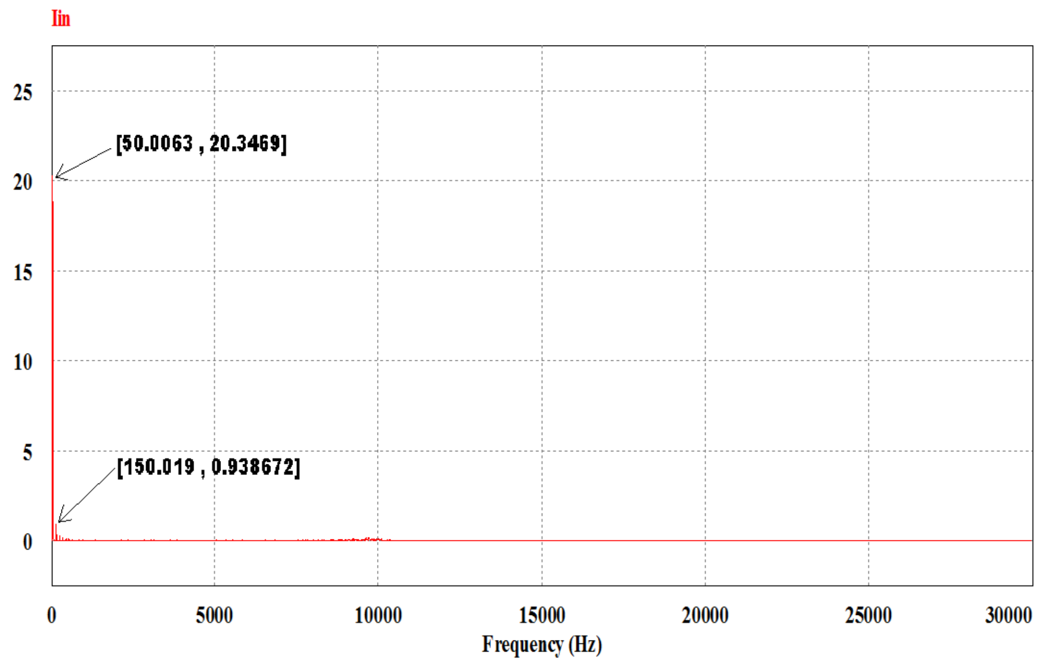


Figure 2.11: Spectrum of the input current of Figure 2.10 of the conventional input switched single phase boost rectifier

Chapter 3

Proposed Ĉuk Single Phase AC-DC Converter

3.1 Conventional Single Phase Output Switched Ĉuk AC-DC Converter

A conventional output regulated AC-DC converter with Ĉuk topology is shown in Figure 3.1, where input AC is converted to DC through bridge rectifier and then this DC voltage is fed to Ĉuk DC-DC Converter. The single-ended output capacitor of converter (Ĉuk) can produce an output voltage that is either greater or less than the input but with no polarity reversal by varying duty cycle of switch.

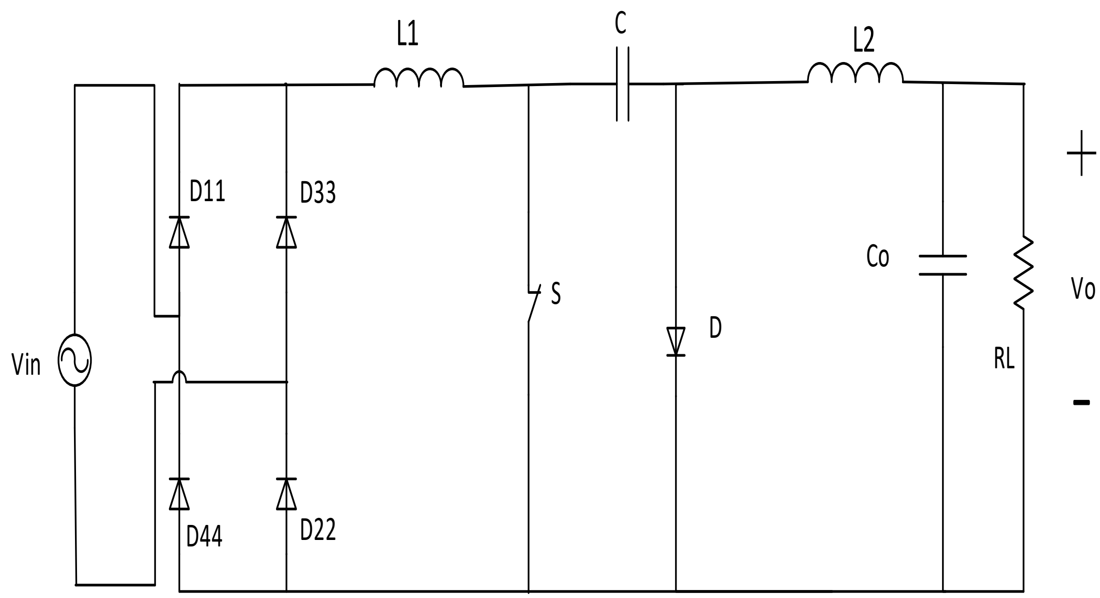


Figure 3.1: Conventional single phase Ĉuk output switched AC-DC converter

The relationship between input and output voltage of the DC-DC Ĉuk converter is,

$$V_o = \frac{D}{1-D} V_{in}$$

$$I_o = \frac{1-D}{D} I_{in}$$

Where, V_0, I_o and V_{in}, I_{in} are output voltage, current and input voltage, current respectively and D is duty cycle of gate pulses of switch.

The output switched Ĉuk topology has two operating states as shown in Figure 3.2 to Figure 3.5 which represent switch ON and OFF states. Figure 3.2 shows that when the switch is ON during positive cycle, the boost inductor charges and boost capacitor discharges through the path shown. Figure 3.3 indicates the path through which the top output capacitor charges from input and the capacitor voltage is higher than input voltage when the switch is OFF. During the negative supply, when the switch is ON current flows in the boost inductor through the path shown in Figure 3.4 and boost capacitor discharges. When the switch is OFF, the negative supply voltage charges the boost capacitor at a higher voltage than negative supply voltage shown in Figure 3.5.

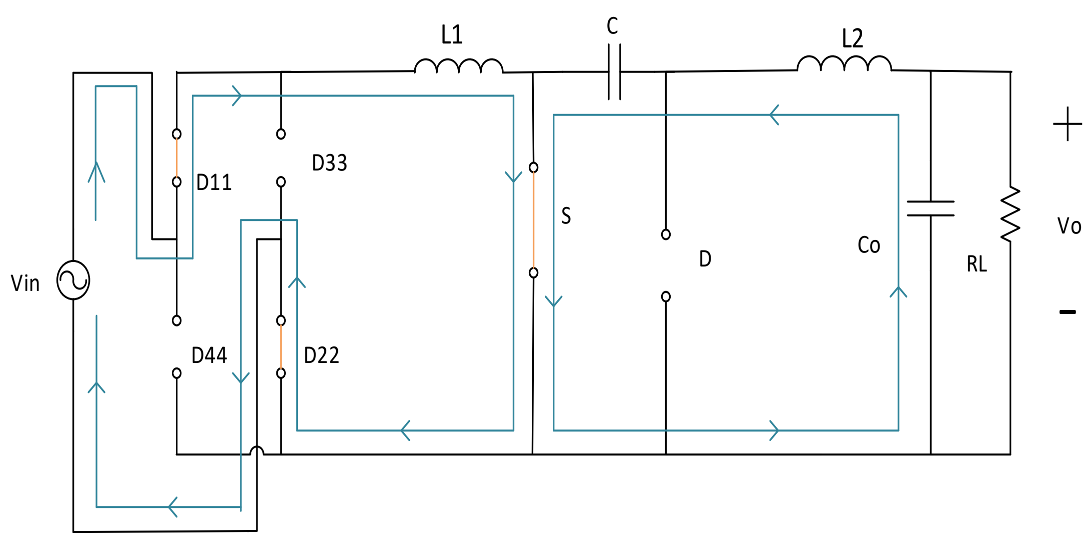


Figure 3.2: Output switched Ĉuk converter when switch is ON (During positive cycle of the source)

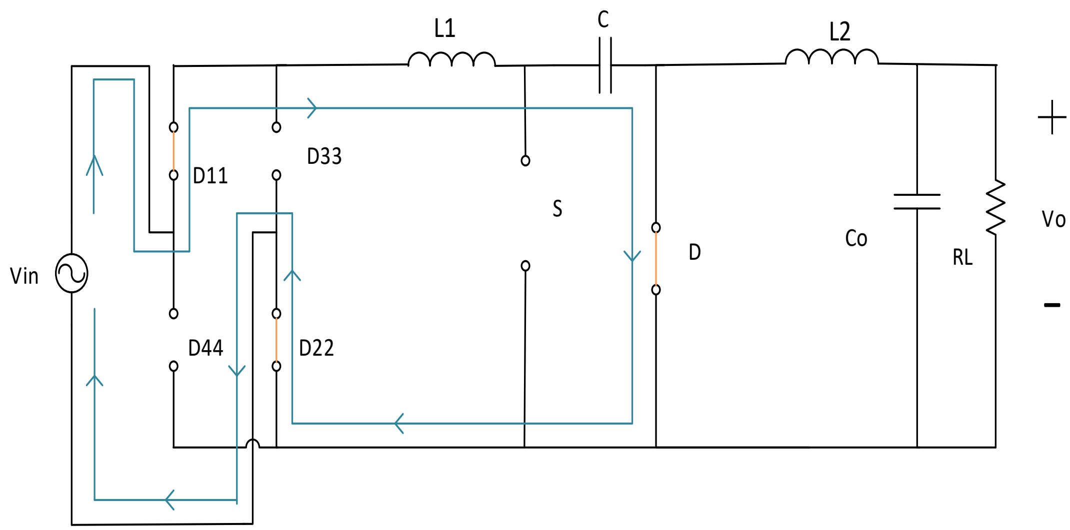


Figure 3.3: Output switched Ĉuk converter when switch is OFF (During positive cycle of the source)

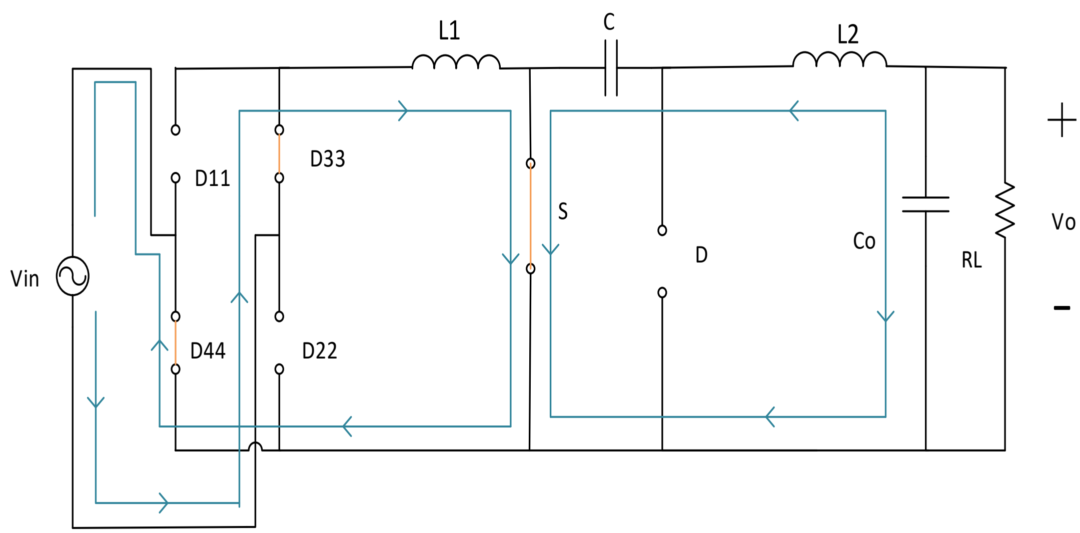


Figure 3.4: Output switched Ĉuk converter when switch is ON (During negative cycle of the source)

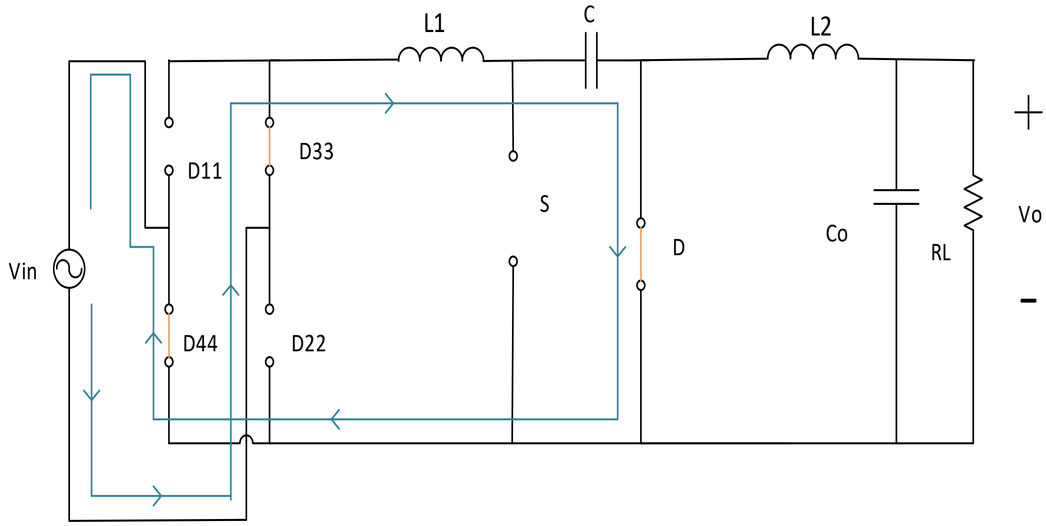


Figure 3.5: Output switched Ĉuk converter when switch is OFF (During negative cycle of the source)

3.2 Proposed Single Phase Ĉuk AC-DC Converters

In this thesis, four configurations of single phase Ĉuk converter has been proposed. They are Input Switched Ĉuk Converter (output full bridge), Input Switched Ĉuk Converter (output half bridge), Modified Ĉuk Converter-1 (Switch within a Diode Bridge), Modified Ĉuk Converter-2 (Switch within a Diode Bridge) configurations. MOSFET switch is used on the input side in first two proposed topology and in between a diode bridge rectifier in the last two topologies.

3.2.1 Input Switched Ĉuk Converter (Output Diode Bridge)

Input switched Ĉuk AC-DC converter (output bridge configuration) is shown in Figure 3.6. The basic operation of this converter has four states as shown in Figure 3.7 to Figure 3.10. Figure 3.7 and Figure 3.8 represent the positive half cycle operation with switch ON and OFF positions, whereas, Figure 3.9 and Figure 3.10 represent the negative half cycle with switch ON and OFF positions respectively.

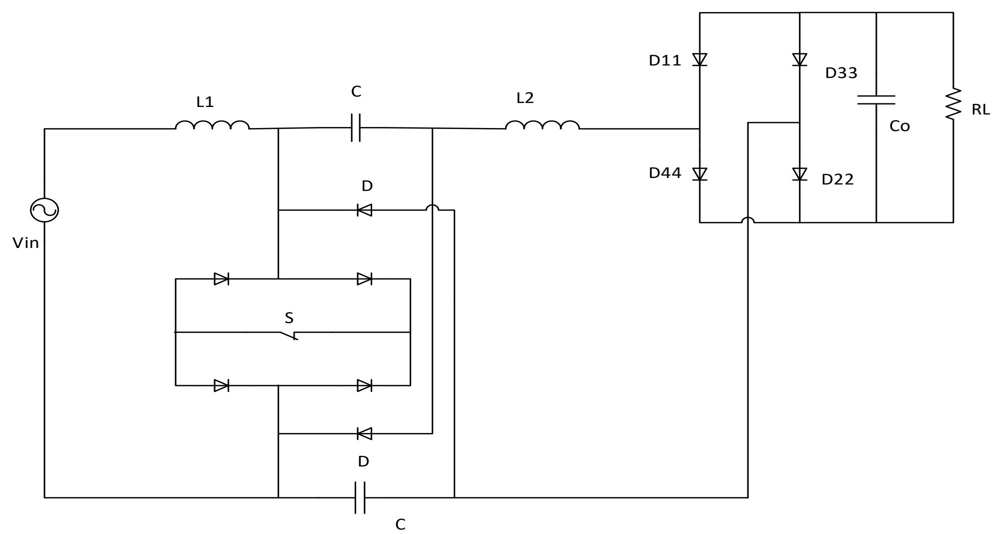


Figure 3.6: Input Switched Ĉuk converter-bridge Configuration

Figure 3.7 shows that when the switch is ON during positive cycle, the boost inductor charges and upper boost capacitor discharges through the paths shown. Figure 3.8 indicates the path through which the top boost capacitor charges from input and current flows to load when the switch is OFF. During the negative supply, when the switch is ON current flows in the boost inductor through the path shown in Figure 3.9 and lower boost capacitor discharges. When the switch is OFF, the negative supply voltage charges the lower boost capacitor at a higher voltage than negative supply voltage shown in Figure 3.10.

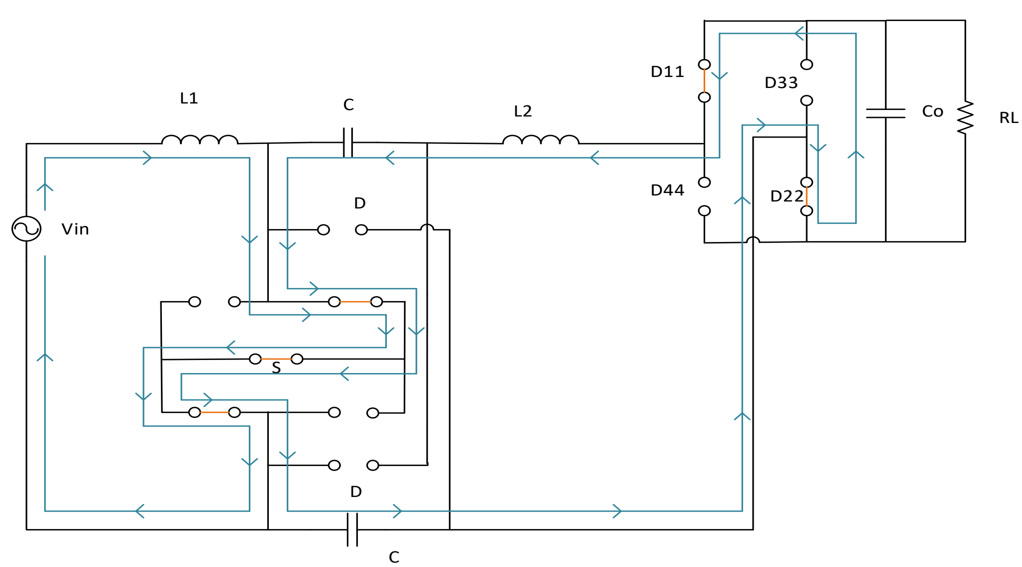


Figure 3.7: Current flow direction of input switched Ĉuk converter (Output Diode Bridge) (positive cycle switch ON)

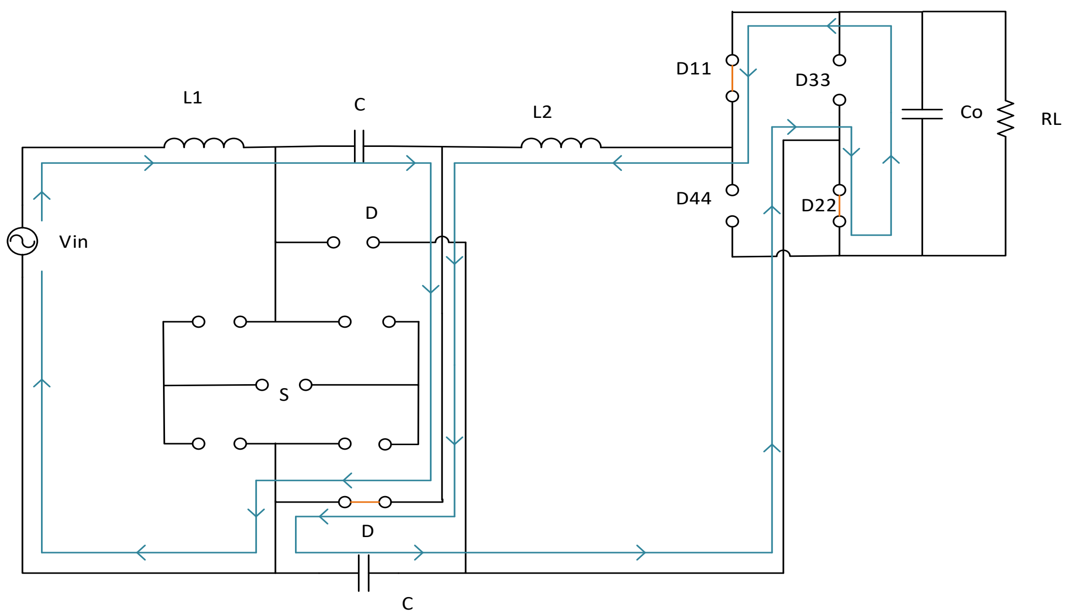


Figure 3.8: Current flow direction of input switched Ĉuk converter (Output Diode Bridge) (positive cycle switch OFF)

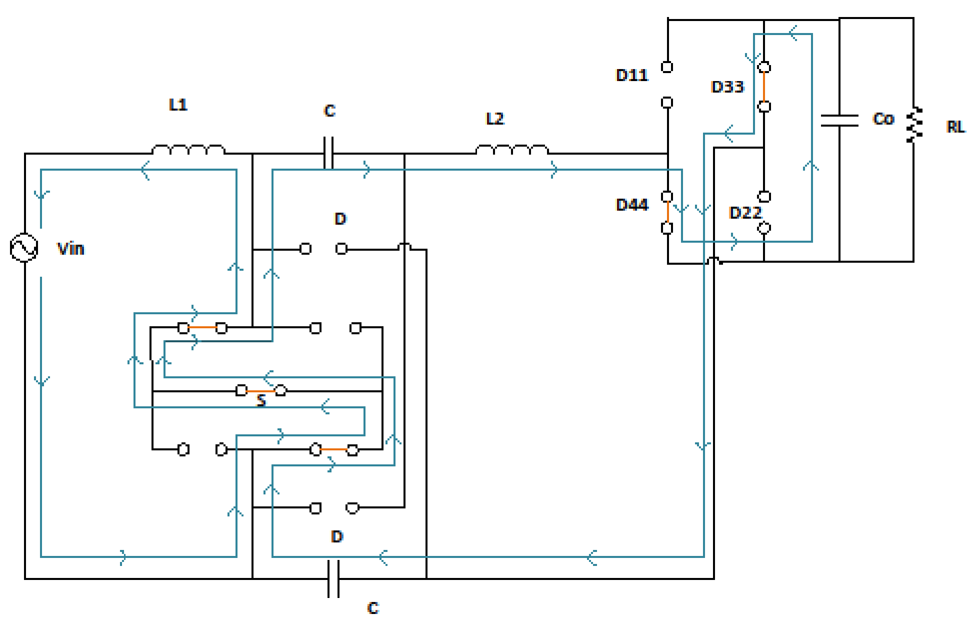


Figure 3.9: Current flow direction of input switched Ĉuk converter (Output Diode Bridge) (negative cycle switch ON)

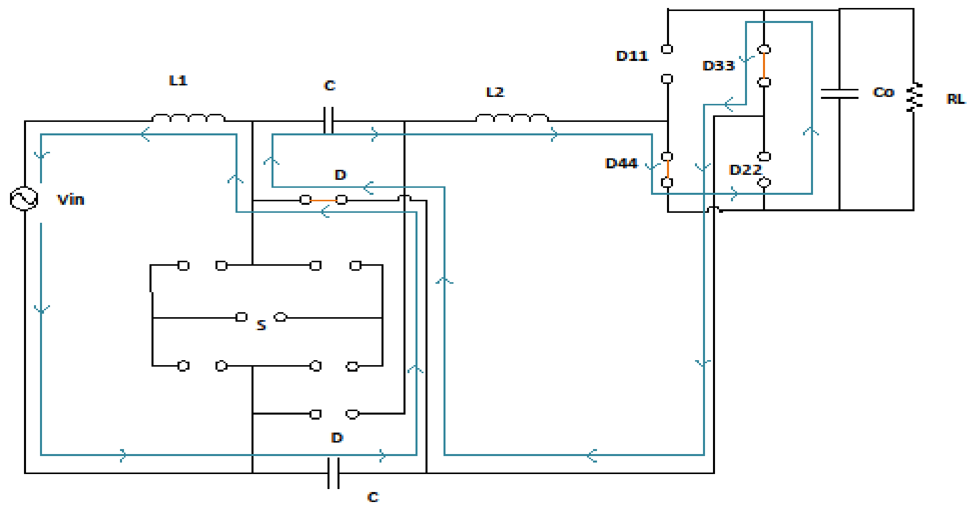


Figure 3.10: Current flow direction of input switched Ĉuk converter (Output Diode Bridge) (negative cycle switch OFF)

3.2.2 Input Switched Ĉuk Converter (Output Half Diode Bridge)

Input switched Ĉuk AC-DC converter (Output Half Diode Bridge) is shown in Figure 3.11. This type of converter has four states as shown in Figure 3.12 to Figure 3.15. Figure 3.12 and Figure 3.13 represent the positive half cycle operation with switch ON and OFF positions, whereas, Figure 3.14 and Figure 3.15 represent the negative half cycle with switch ON and OFF positions respectively.

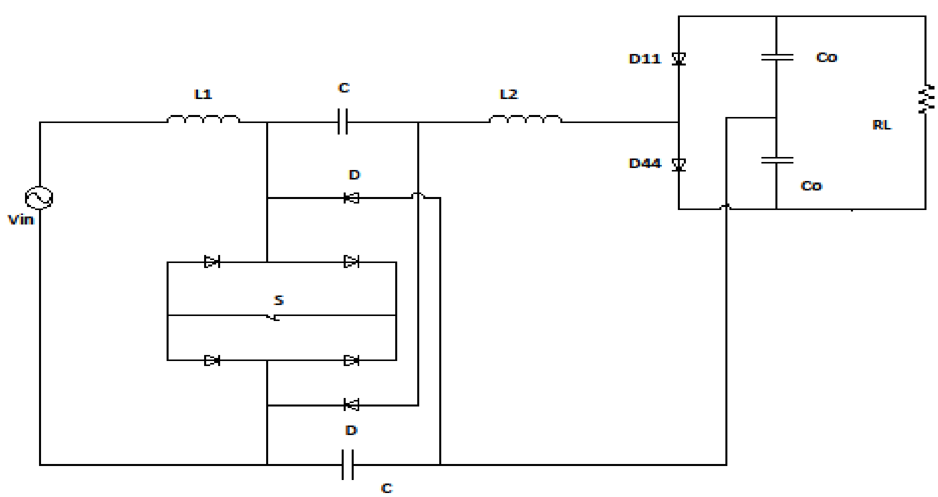


Figure 3.11: Input Switched Ĉuk Converter (Output Half Diode Bridge)

Figure 3.12 shows that when the switch is ON during positive cycle, the boost inductor charges and upper boost capacitor discharges through the paths shown. Figure 3.13 indicates the path through which the top boost capacitor charges from input and current flows to load when the switch is OFF. During the negative supply, when the switch is ON current flows in the boost inductor through the path shown in Figure 3.14 and lower boost capacitor discharges. When the switch is OFF, the negative supply voltage charges the lower boost capacitor at a higher voltage than negative supply voltage shown in Figure 3.15.

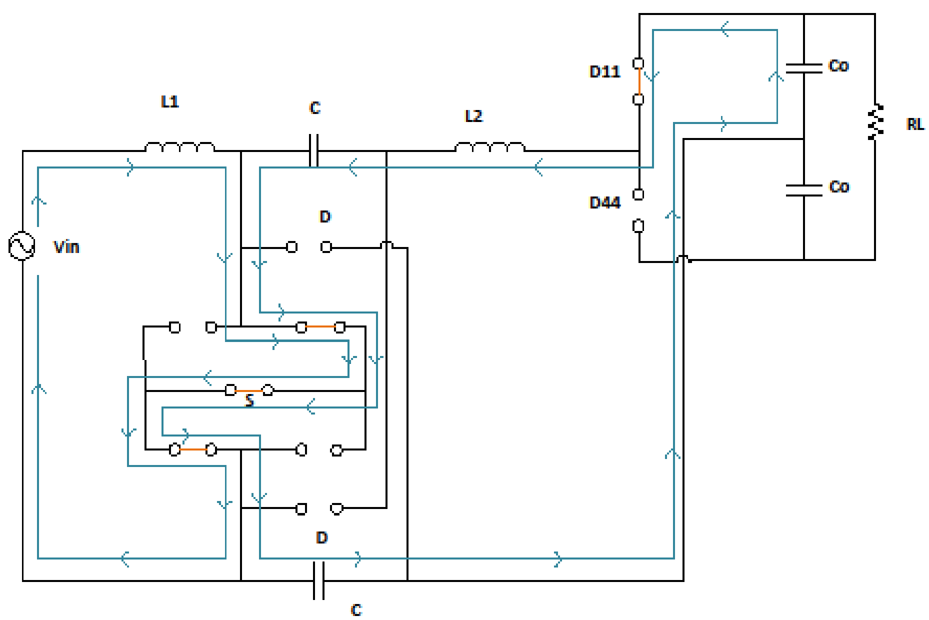


Figure 3.12: Current flow direction of input switched Ĉuk converter (Output Half Diode Bridge) (during positive supply cycle switch is ON)

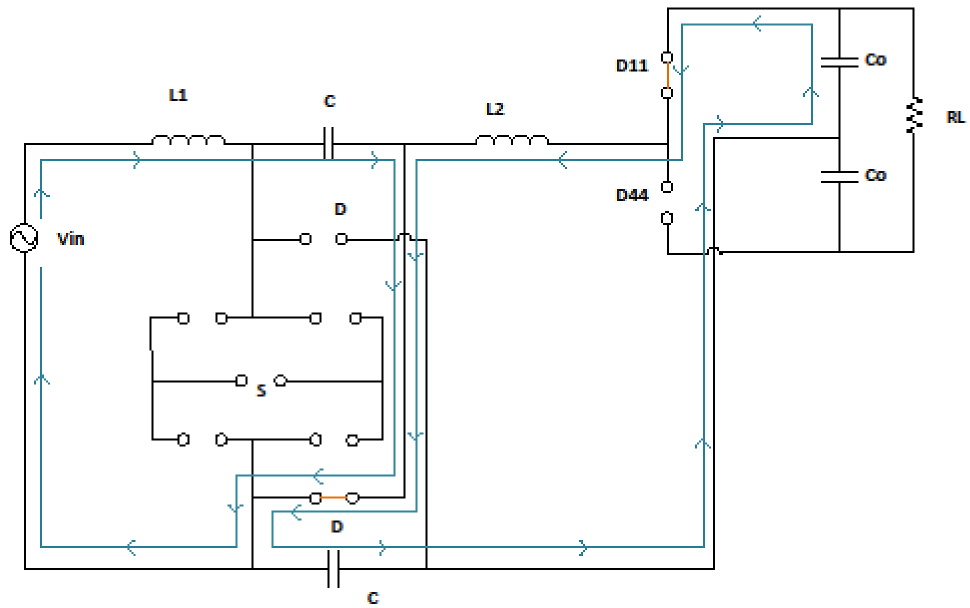


Figure 3.13: Current flow direction of input switched Ĉuk converter (Output Half Diode Bridge) (during positive supply cycle switch is OFF)

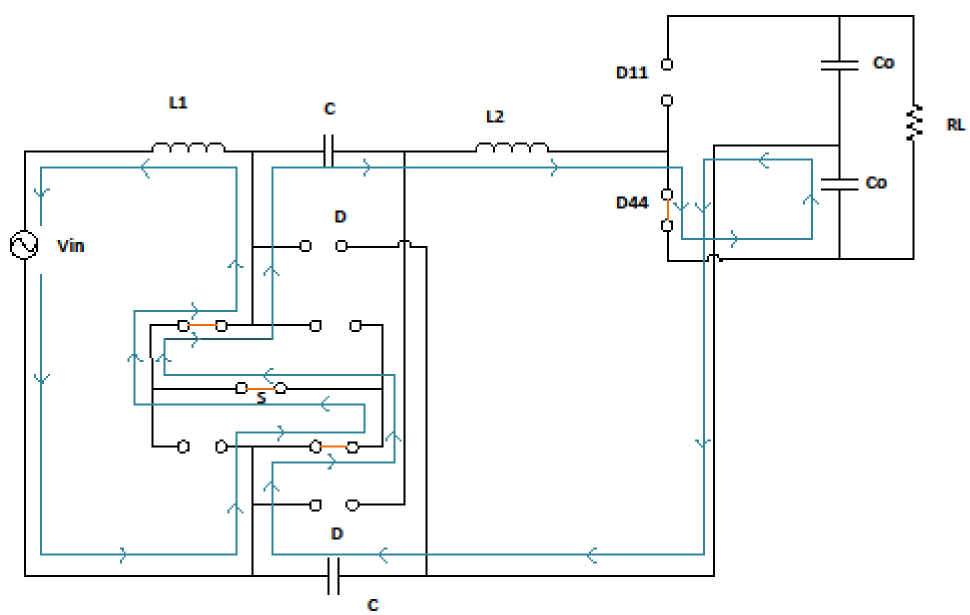


Figure 3.14: Current flow direction of input switched Ĉuk converter (Output Half Diode Bridge) (during negative supply cycle switch is ON)

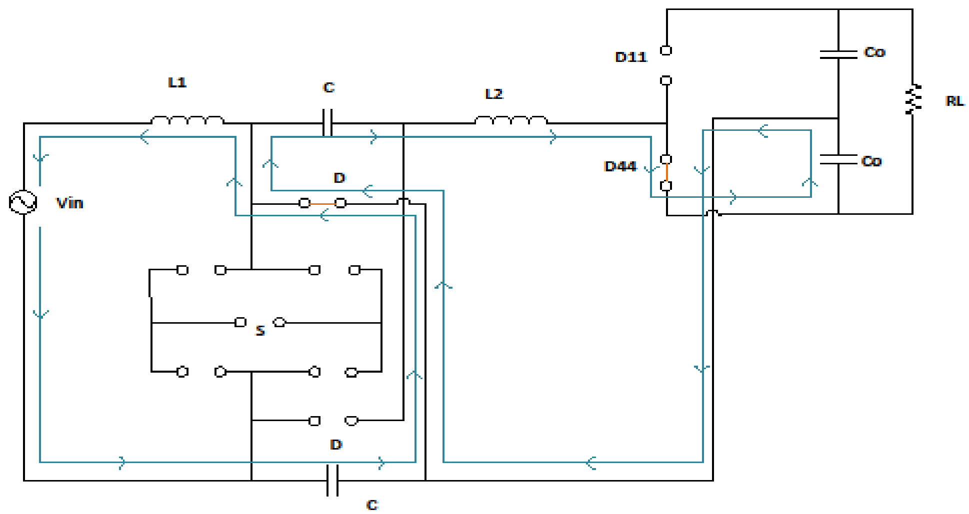


Figure 3.15: Current flow direction of input switched Ĉuk converter (Output Half Diode Bridge) (during negative supply cycle switch is OFF)

3.2.3 Modified Ĉuk Converter-1 Switched Within Bridge

Modified Ĉuk Converter-1 with switch within the diode bridge is shown in Figure 3.16. This type of converter also has four states as shown in Figure 3.17 to Figure 3.20. Figure 3.17 and Figure 3.18 represent the positive half cycle operation with switch ON and OFF positions, whereas, Figure 3.19 and Figure 3.20 represent the negative half cycle with switch ON and OFF positions respectively.

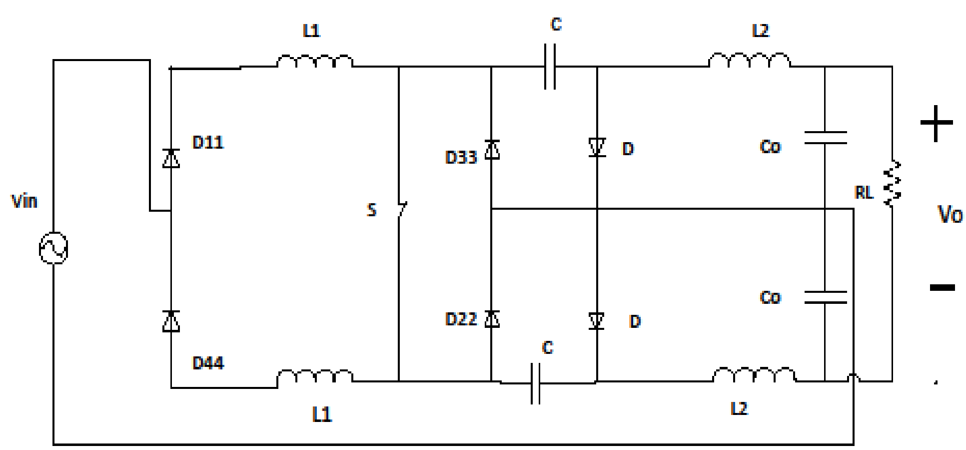


Figure 3.16: Modified Ĉuk Converter-1 switched within Diode Bridge

Figure 3.17 shows that when the switch is ON during positive cycle, the upper boost inductor charges and upper boost capacitor discharges through the paths shown. Figure 3.18 indicates the path through which the top boost capacitor charges from input when the switch is OFF. During the negative supply, when the switch is ON current flows in the lower boost inductor through the path shown in Figure 3.19 and lower boost capacitor discharges. When the switch is OFF, the negative supply voltage charges the lower boost capacitor at a higher voltage than negative supply voltage shown in Figure 3.20.

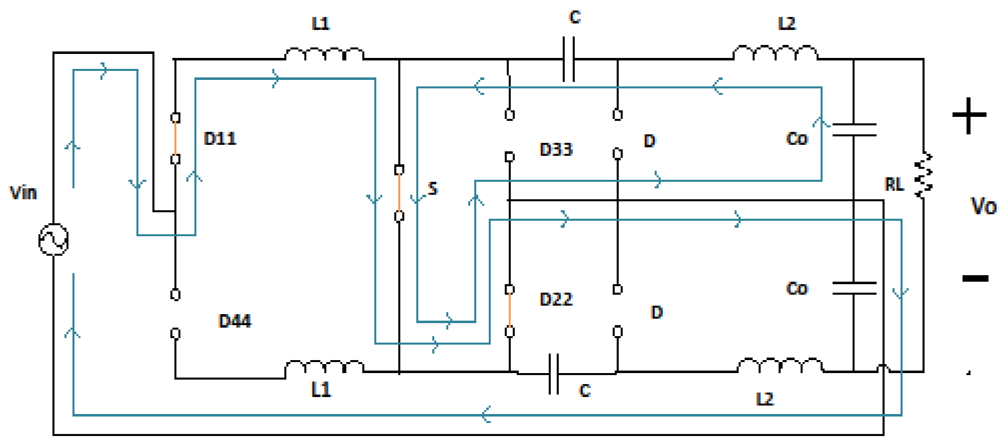


Figure 3.17: Current flow direction of Modified Ĉuk Converter-1 configuration (during positive supply cycle switch is ON)

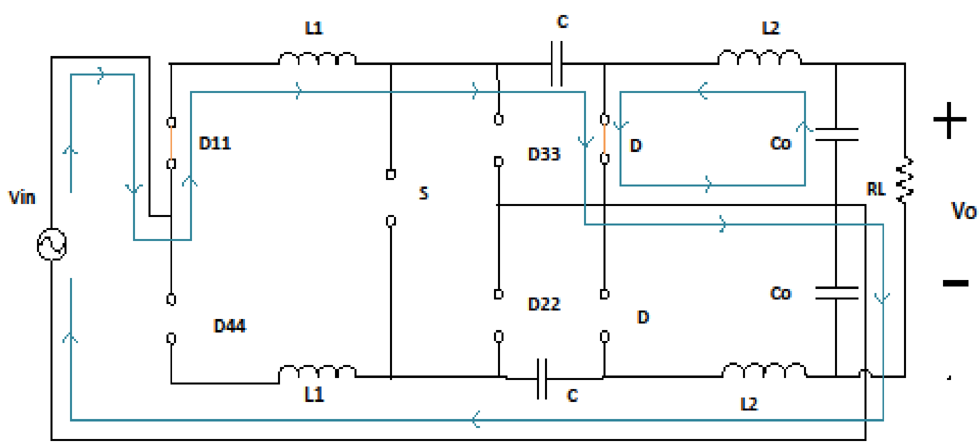


Figure 3.18: Current flow direction of Modified Ĉuk Converter-1 configuration (during positive supply cycle switch is OFF)

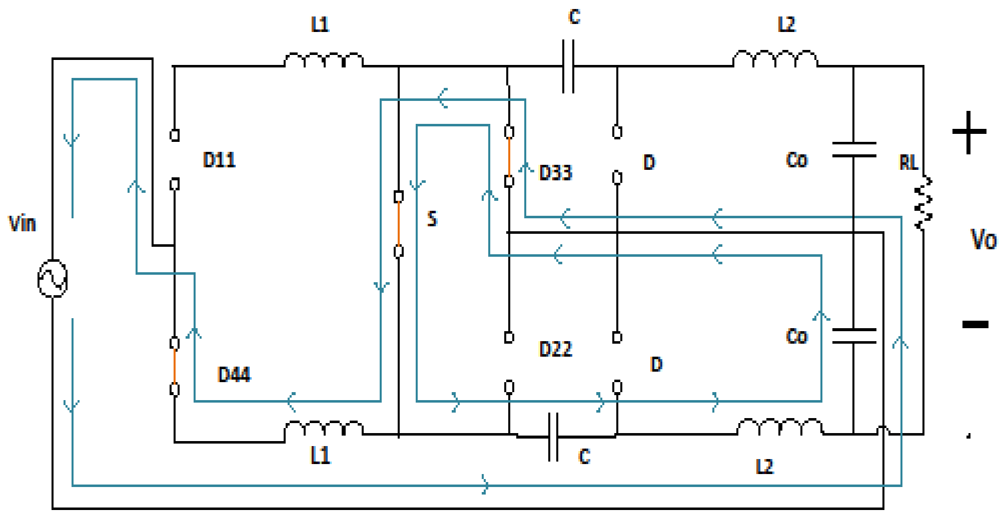


Figure 3.19: Current flow direction of Modified Ĉuk Converter-1 configuration (during negative supply cycle switch is ON)

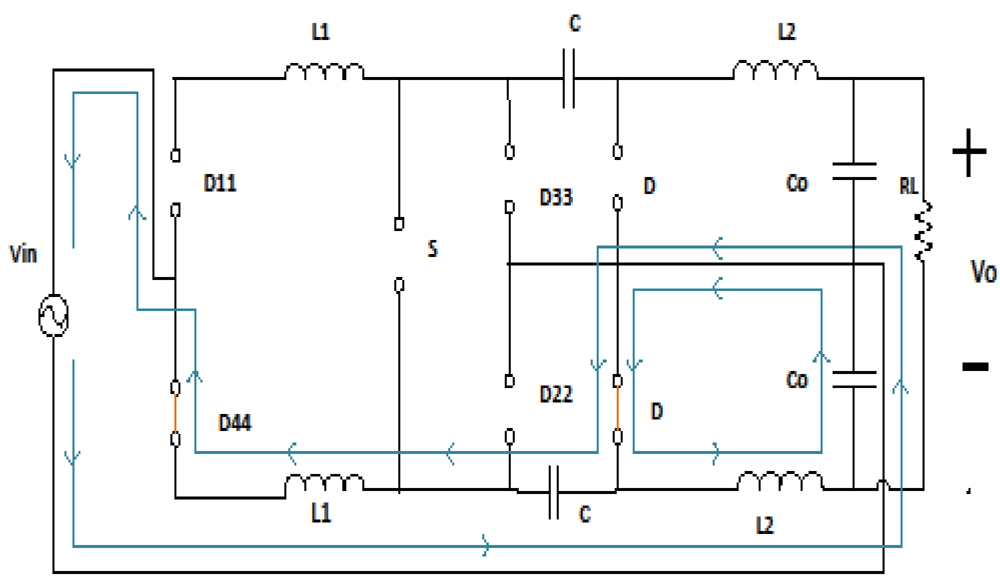


Figure 3.20: Current flow direction of Modified Ĉuk Converter-1 configuration (during negative supply cycle switch is OFF)

3.2.4 Modified Ĉuk Converter-2 Switched Within Bridge Configuration

Modified Ĉuk conveter-2 switched within bridge configuration is shown in Figure 3.21. In this type of converter configuration has four states as shown in Figure 3.22 to Figure 3.25. Figure 3.22 and Figure 3.23 represent the positive half cycle operation with switch ON and OFF positions, whereas, Figure 3.24 and Figure 3.25 represent the negative half cycle with switch ON and OFF positions respectively.

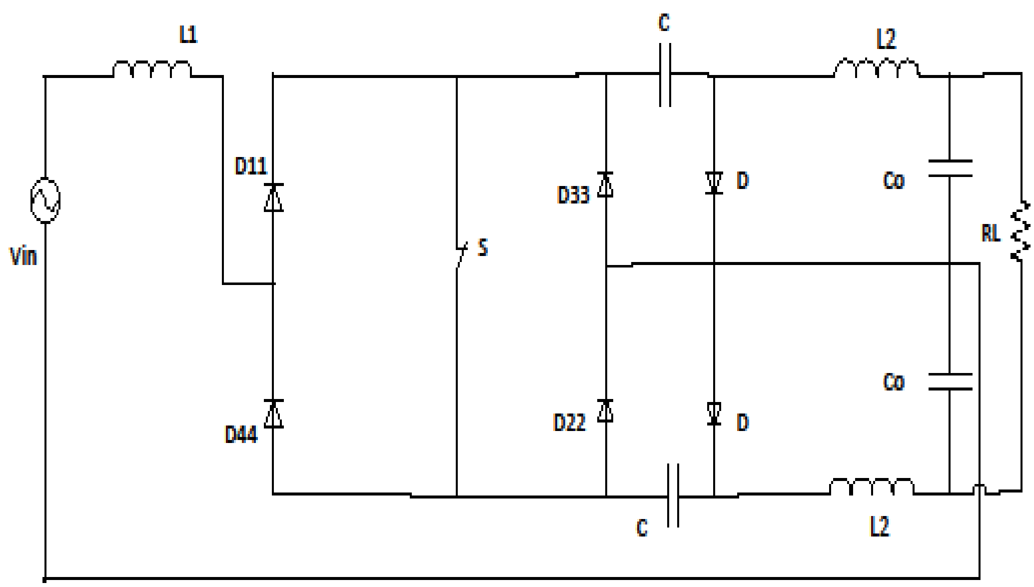


Figure 3.21: Modified Ĉuk Converter-2 Switched within Bridge Configuration

Figure 3.22 shows that when the switch is ON during positive cycle, the boost inductor charges and upper boost capacitor discharges through the paths shown. Figure 3.23 indicates the path through which the top boost capacitor charges from input when the switch is OFF. During the negative supply, when the switch is ON current flows in the boost inductor through the path shown in Figure 3.24 and lower boost capacitor discharges. When the switch is OFF, the negative supply voltage charges the lower boost capacitor at a higher voltage than negative supply voltage shown in Figure 3.25.

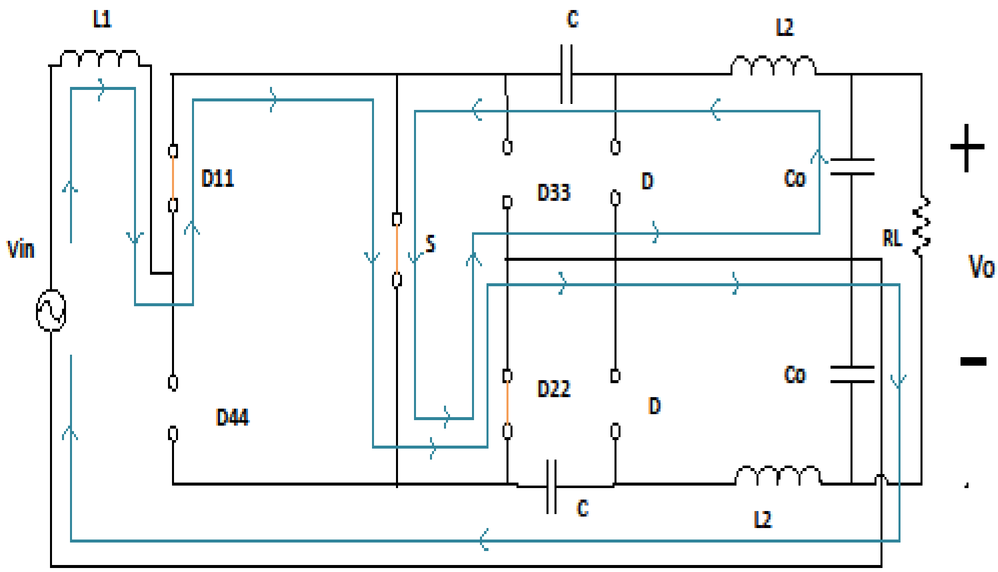


Figure 3.22: Current flow direction of Modified Ĉuk Converter-2 configuration (during positive supply cycle switch is ON)

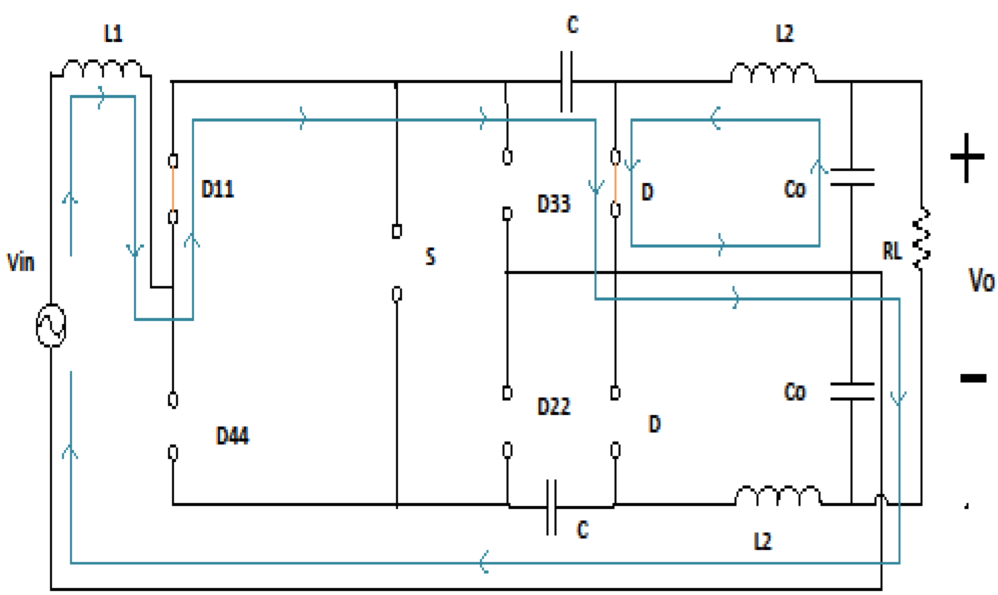


Figure 3.23: Current flow direction of Modified Ĉuk Converter-2 configuration (during positive supply cycle switch is OFF)

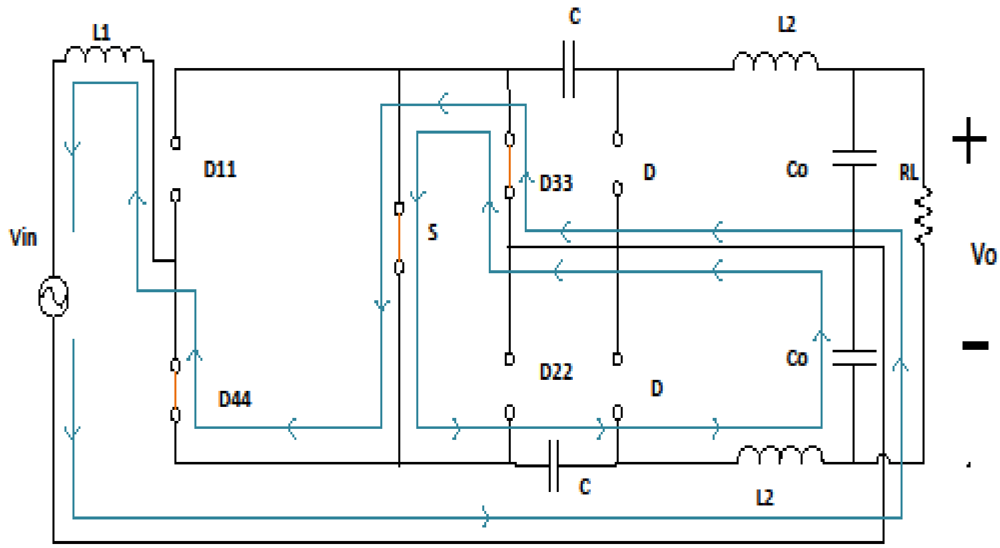


Figure 3.24: Current flow direction of Modified Ĉuk Converter-2 configuration (during negative supply cycle switch is ON)

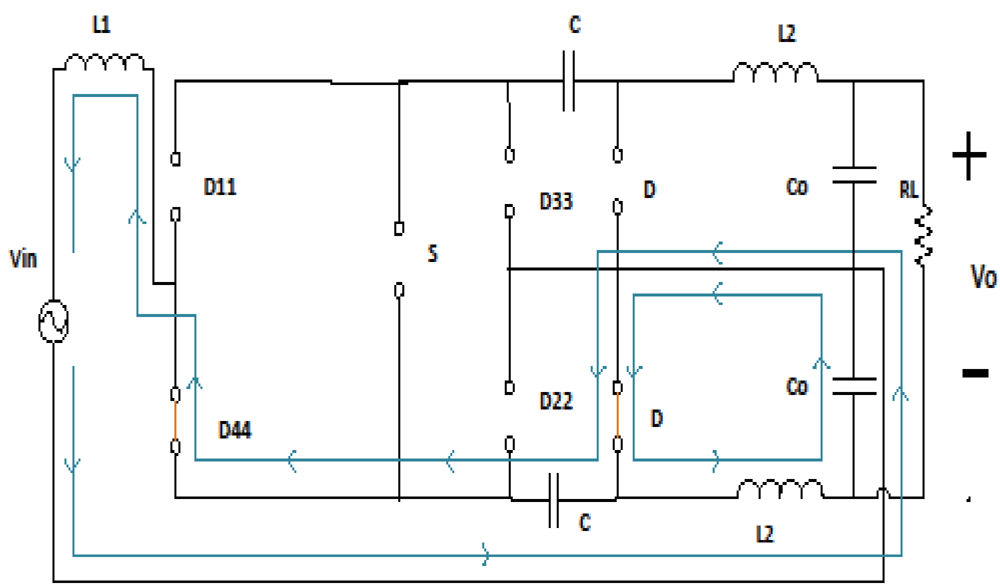


Figure 3.25: Current flow direction of Modified Ĉuk Converter-2 configuration (during negative supply cycle switch is OFF)

3.3 Voltage Gain of Input Switched Single Phase Ĉuk Rectifier (Output Diode Bridge Configuration)

The proposed input switched single phase **Ĉ**uk AC-DC converter (non-split output capacitor type) is shown in Figure 3.26. In the figure v_{in} is an input AC voltage and v_{oac} is an intermediate AC voltage between v_{in} and v_{odc} (DC voltage) of the circuit.

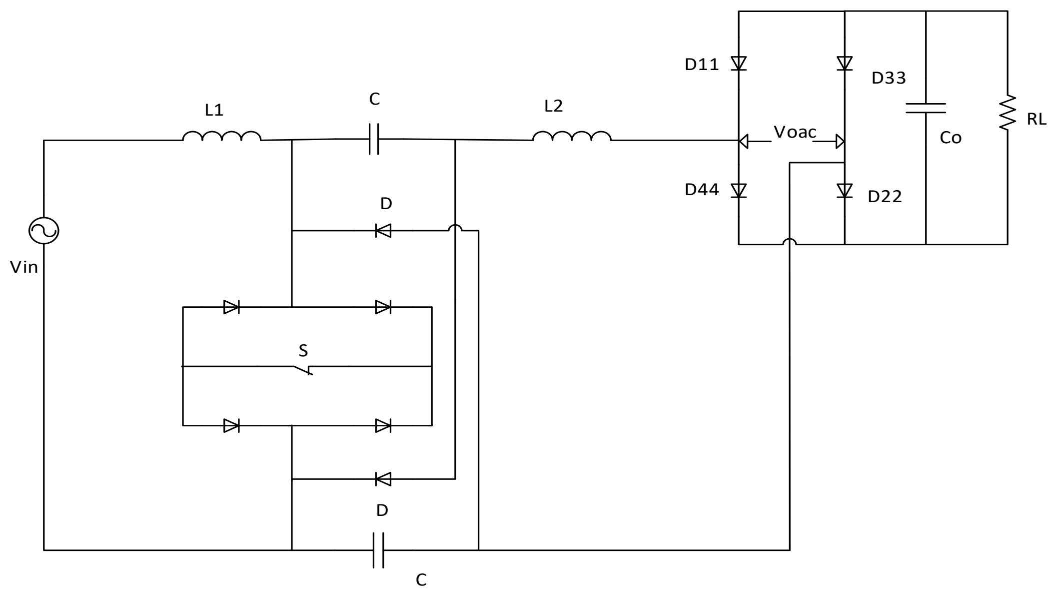


Figure 3.26: Input Switched **Ĉ**uk Converter- Output Diode Bridge Configuration

In the circuit, the inductor currents are AC, the typical shape of which is shown in Figure 3.27.

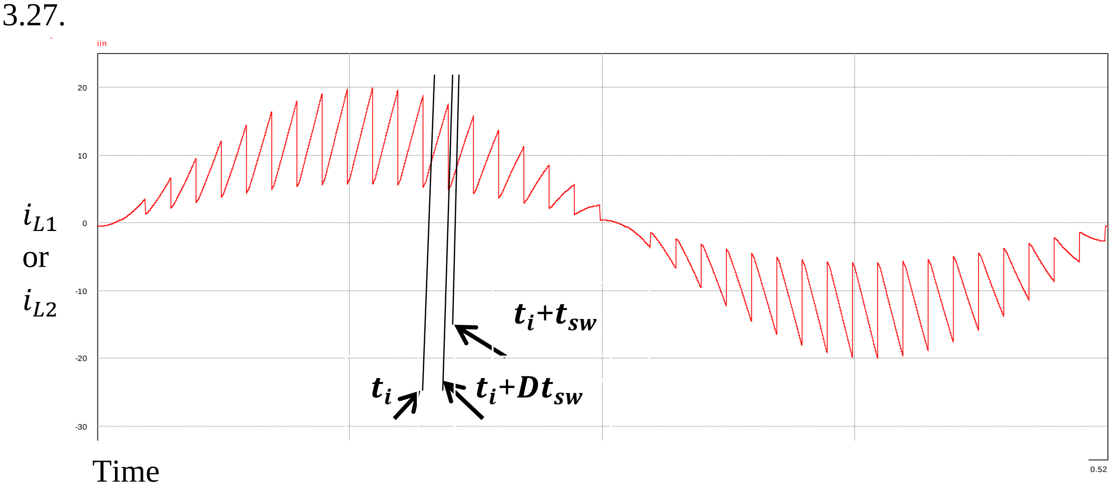


Figure 3.27: Typical Inductor Current i_{L1} or i_{L2} of Figure 3.3.1

In the input/ intermediate inductor current waveform shown in Figure 3.3.2 t_i is the start of any switching period, $T_{ON} = DT_{sw}$, T_{sw} is the switching period and T_{sup} is the period of the utility supply voltage. As ,

$$L\frac{di}{dt} = v_L$$

$$\Rightarrow \; di = \frac{1}{L} v_L dt$$

$$\Rightarrow \; \int di = 0 = \frac{1}{L} \int v_L dt$$

$$\Rightarrow \; \int v_L dt = 0,$$

for a complete period of T_{sup}, which is known as volt-sec balance of an inductor. The volt-second balance relationship can be used on inductors L_1 and L_2 to find the voltage gain relationship of ${v_{oac}}/{v_{in}}$ of the proposed **Ĉ**uk converter of Figure 3.3.1.

Output Stage

Applying volt-sec balance on L_2 over a 50Hz supply cycle,

When switch is ON,

$$-v_C - v_{0ac} = v_{L_2} \tag{3.1}$$

When switch is OFF,

$$-v_{oac} = v_{L_2} \tag{3.2}$$

For generalized switching cycle

$$\int_{t_i}^{t_i + T_{sw}} v_{L_2} dt = \int_{t_i}^{t_i + DT_{sw}} (-v_C - v_{oac}) dt + \int_{t_i + DT_{sw}}^{t_i + T_{sw}} -v_{oac} dt \tag{3.3}$$

For one supply cycle (N number of switching within the cycle),

$$\sum_{i=1}^{N} \int_{t_i}^{t_i + DT_{sw}} (-v_C - v_{oac}) dt + \sum_{i=1}^{N} \int_{t_i + DT_{sw}}^{t_i + T_{sw}} -v_{oac} dt = 0 \tag{3.4}$$

Assuming,

$$v_C = v_{Cm} \sin(\omega t - \theta_C)$$

and

$$v_{oac} = v_{om} \sin(\omega t - \theta_o)$$

Equation (3.4) can be written as,

$$- \sum_{i=1}^{N} \int_{t_i}^{t_i + DT_{sw}} v_{Cm} \sin(\omega t - \theta_C)\, dt = \sum_{i=1}^{N} \int_{t_i}^{t_i + T_{sw}} v_{om} \sin(\omega t - \theta_o)\, dt \tag{3.5}$$

Which becomes,

$$- \sum_{i=1}^{N} \frac{v_{Cm}}{\omega} \{\cos[\omega(t_i + DT_{sw}) - \theta_C] - \cos(\omega t_i - \theta_C)\}$$

$$= \sum_{i=1}^{N} \frac{v_{om}}{\omega} \{\cos[\omega(t_i + T_{sw}) - \theta_o] - \cos[\omega t_i - \theta_o]\} \tag{3.6}$$

Using the following indentity,

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

Equation (3.6) becomes,

$$\sum_{i=1}^{N} v_{Cm} \left\{ \sin\left(\omega t_i - \theta_C + \frac{\omega DT_{sw}}{2}\right) \sin \frac{\omega DT_{sw}}{2} \right\}$$

$$= - \sum_{i=1}^{N} v_{om} \left\{ \sin\left(\omega t_i - \theta_o + \frac{\omega T_{sw}}{2}\right) \sin \frac{\omega T_{sw}}{2} \right\} \tag{3.7}$$

Dividing both side of the equation (3.7) by $\sin \frac{\omega T_{sw}}{2}$ one obtains,

$$\frac{\sin \frac{\omega DT_{sw}}{2}}{\sin \frac{\omega T_{sw}}{2}} \sum_{i=1}^{N} v_{Cm} \left\{ \sin\left(\omega t_i - \theta_C + \frac{\omega DT_{sw}}{2}\right) \right\}$$

$$= -\sum_{i=1}^{N} v_{om} \left\{ \sin\left(\omega t_i - \theta_o + \frac{\omega T_{sw}}{2} \right) \right\} \quad (3.8)$$

But,

$$\lim_{\theta \to 0} \frac{\sin\theta}{\theta} = 1 \text{ and since } \begin{cases} \frac{\omega D T_{sw}}{2} \to 0 \; as \; T_{sw} \to 0 \\ \frac{\omega T_{sw}}{2} \to 0 \; as \; T_{sw} \to 0 \end{cases}$$

Simplification of equation (3.8) leads to,

$$\frac{\frac{\omega D T_{sw}}{2}}{\frac{\omega T_{sw}}{2}} \sum_{i=1}^{N} v_{Cm}\{\sin(\omega t_i - \theta_C)\} = -\sum_{i=1}^{N} v_{om}\{\sin(\omega t_i - \theta_o)\}$$

$$\Rightarrow D \sum_{i=1}^{N} v_{Cm}\{\sin(\omega t_i - \theta_C)\} = -\sum_{i=1}^{N} v_{om}\{\sin(\omega t_i - \theta_o)\} \quad (3.9)$$

Input Stage

To apply Volt-Sec balance of L_1 over a 50Hz supply cycle,

When switch is ON,

$$v_{L_1} = v_{in} \quad (3.10)$$

When switch is OFF,

$$v_{L_1} = v_{in} - v_C \quad (3.11)$$

For generalized switching cycle

$$\int_{t_i}^{t_i + T_{sw}} v_{L_1} dt = 0$$

$$\int_{t_i}^{t_i + DT_{sw}} v_{in} dt + \int_{t_i + DT_{sw}}^{t_i + T_{sw}} (v_{in} - v_C) dt = 0 \quad (3.12)$$

Let us assume,

$$v_{in} = v_m \sin \omega t$$
$$v_C = v_{Cm} \sin(\omega t - \theta_C)$$

and

$$v_{oac} = v_{om} \sin(\omega t - \theta_o)$$

Over a supply cycle of period $T_{sup} = NT_{sw}$ (where T_{sup} is period of the supply ac and the T_{sw} is the period of switching frequency of the switch and N is the number of switching within a period of supply signal).

$$\sum_{i=1}^{N} \int_{t_i}^{t_i + T_{sw}} v_{L_1} dt = 0$$

$$\sum_{i=1}^{N} \int_{t_i}^{t_i + DT_{sw}} v_{in} dt + \int_{t_i + DT_{sw}}^{t_i + T_{sw}} (v_{in} - v_C) dt = 0$$

$$\Rightarrow \sum_{i=1}^{N} \int_{t_i + DT_{sw}}^{t_i + T_{sw}} -v_{Cm} \sin(\omega t - \theta_C)\, dt + \sum_{i=1}^{N} \int_{t_i}^{t_i + T_{sw}} v_m \sin \omega t\, dt = 0$$

which after integration can be written as,

$$\sum_{i=1}^{N} v_{Cm}[\cos(\omega t_i + \omega T_{sw} - \theta_C) - \cos(\omega t_i + \omega DT_{sw} - \theta_C)] = \sum_{i=1}^{N} v_m[\cos(\omega t_i + \omega T_{sw}) - \cos(\omega t_i)] \quad (3.13)$$

Using ideally,

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

Equation (3.13) can be rearranged as below,

$$\sum_{i=1}^{N} v_{Cm} \sin\{\omega t_i - \theta_C + \frac{\omega(1+D)T_{sw}}{2}\} \sin\frac{\omega(D-1)T_{sw}}{2}$$

$$= -\sum_{i=1}^{N} v_m \left\{\sin\left(\omega t_i + \frac{\omega T_{sw}}{2}\right) \sin\frac{\omega T_{sw}}{2}\right\} \qquad (3.14)$$

$$\Rightarrow \frac{[\sin\frac{\omega(D-1)T_{sw}}{2}][\frac{\omega(D-1)T_{sw}}{2}]}{\frac{\omega(D-1)T_{sw}}{2}} \sum_{i=1}^{N} v_{Cm} \sin\{\omega t_i - \theta_C + \frac{\omega(1+D)T_{sw}}{2}\}$$

$$= -\frac{[\sin\frac{\omega T_{sw}}{2}][\frac{\omega T_{sw}}{2}]}{\frac{\omega T_{sw}}{2}} \sum_{i=1}^{N} v_m \left\{\sin\left(\omega t_i + \frac{\omega T_{sw}}{2}\right)\right\} \qquad (3.15)$$

As,

$$\lim_{\theta \to 0} \frac{\sin\theta}{\theta} = 1 \text{ and since } \omega T_{sw} \to 0 \; as \; T_{sw} \to 0$$

Equation (3.15) can be written as,

$$\left[\frac{\omega(D-1)T_{sw}}{2}\right] \sum_{i=1}^{N} v_{Cm} \sin(\omega t_i - \theta_C)$$

$$= -\left[\frac{\omega T_{sw}}{2}\right] \sum_{i=1}^{N} v_m \{\sin(\omega t_i)\}$$

$$= (D-1) \sum_{i=1}^{N} v_{Cm} \sin(\omega t_i - \theta_C)$$

$$= -\sum_{i=1}^{N} v_m \{\sin(\omega t_i)\}$$

$$\Rightarrow \quad \sum_{i=1}^{N} v_{Cm} \sin(\omega t_i - \theta_C) = \frac{1}{1-D} \sum_{i=1}^{N} v_m \sin \omega t_i \qquad (3.16)$$

⇨

Equating (3.9) and (3.16),

$$\frac{1}{D} \sum_{i=1}^{N} v_{om} \{\sin(\omega t_i - \theta_o)\}$$

$$= \frac{1}{1-D} \sum_{i=1}^{N} v_m \sin \omega t_i$$

$$\Rightarrow \sum_{i=1}^{N} v_{om} \sin(\omega t_i - \theta_o) = \frac{D}{1-D} \sum_{i=1}^{N} v_m \sin \omega t_i$$

$$\Rightarrow \sum_{i=1}^{N} v_{oac} = \frac{D}{1-D} \sum_{i=1}^{N} v_{inac}$$

v_{odc} is the rectified v_{oac}

$$\sum_{i=1}^{N} v_{oac} = \frac{D}{1-D} \sum_{i=1}^{N} v_{inac}$$

The output capacitor of the proposed input switched output-bridge rectifier charges every half cycle of the full rectified AC voltage. Therefore the output of the rectifier becomes as follow:

$$v_{odc} = \frac{D}{1-D} \frac{V_m}{\sqrt{2}}$$

For proposed Input Switched **Ĉ**uk Converter Output Diode Half Bridge Configuration of Figure 3.11, the rectified value will be approximately $\frac{D}{1-D} V_m$ where V_m is the maximum value of the input ac voltage, as each capacitor charges itself at only a half cycle of the AC input and the r.m.s. of voltage across each capacitor becomes $\frac{V_m}{2}$. Summing the voltage across each output capacitor the rectifier voltage across the load is $\frac{D}{1-D} V_m$. [37]

3.4 Performance of the Conventional and Proposed Ĉuk AC-DC Converters without PFC Feedback Controller

Performance of the conventional and proposed **Ĉ**uk AC-DC Converters without PFC Feedback Controller in terms efficiency, total harmonic distortion, power factor, gain of the circuit are shown in detail in the following subsections.

3.4.1 Conventional Single Phase Ĉuk output switched Rectifier

A conventional output switched Ĉuk topology based power factor corrected (PFC) rectifier of Figure 3.28 has been simulated with following circuit parameters,

L_1 = 5mH, L_2 = 5mH,

C = 5µF (Coupling capacitor)

C_0 = 330µF (Output capacitor)

EDR = 100Ω (Equivalent Cuk Resistor/output resistor)

V_{in} = 300$V_{p\text{-}p}$, 50 Hz

f_{switch} = 5KHz

Simulation has been initially carried out without any feedback and pfc, output voltage regulation and input current harmonic distortion are calculated. The performance parameters were observed with variation of duty cycle, D from 0.1 to 0.9. The observations have been recorded as shown in Table 3.1 and graphically represented in Figure 3.29. It is evident that the converter has buck-boost voltage gain, high efficiency for a wide range of duty cycle variation and power factor above 0.7 for D above 0.2. The total harmonic distortion is however above 45 percent. The voltage gain calculated from simulation and theoretical equation (discussed in section 3.3) are close for duty cycle above 0.5. To attain THD of input current less than 10 percent and improve power factor further, proper feedbacks are necessary.

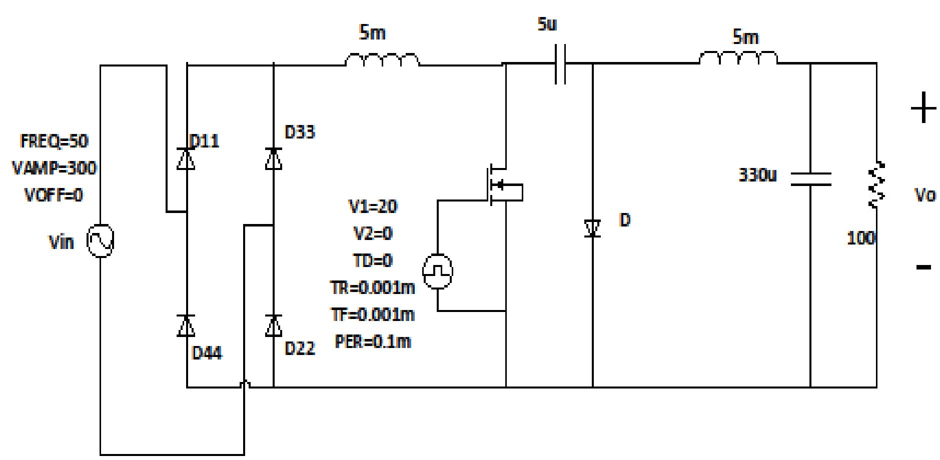
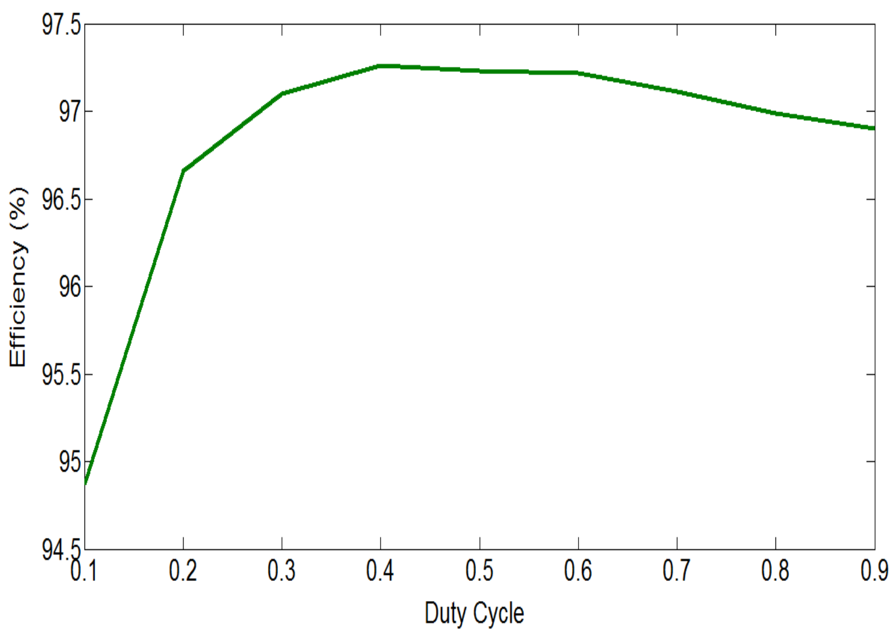


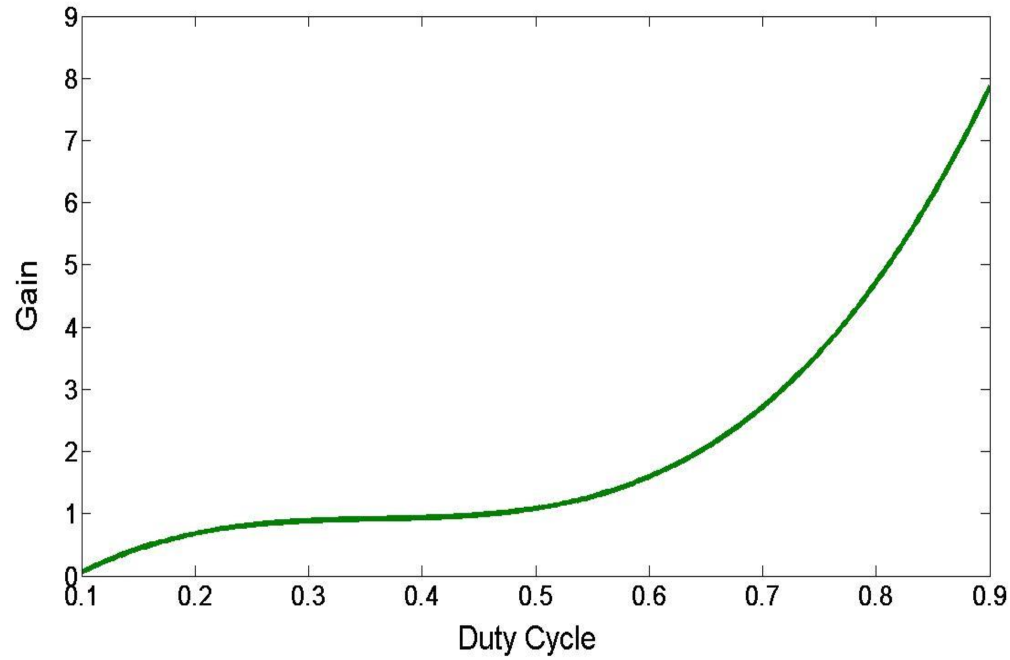
Figure 3.28: Conventional Single Phase Ĉuk output switched Rectifier

Table 3.1: Performance of Conventional Single Phase Ĉuk output switched Rectifier (Without Feedback Control)

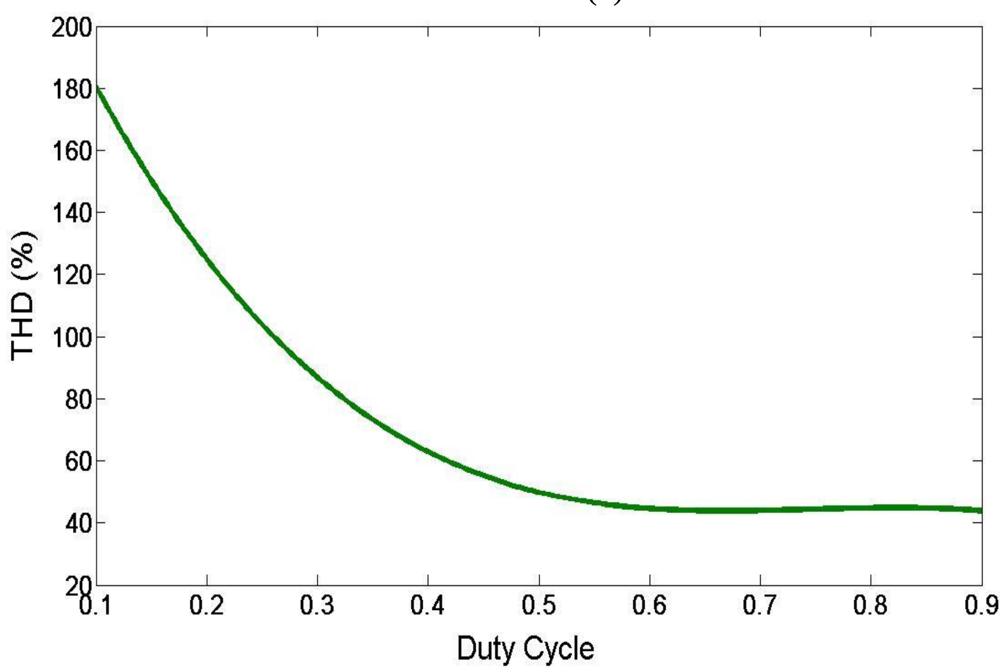
Duty Cycle	Vout	Efficiency (%)	Gain (Simulation)	Gain (Theoretical)	THD (%)	P.F.
0.1	52.11	94.87	0.25	0.11	183.78	0.4784
0.2	99.43	96.66	0.47	0.25	119.7	0.6310
0.3	145.36	97.1	0.68	0.43	87.68	0.7071
0.4	197.76	97.26	0.93	0.67	61.93	0.7357
0.5	285.9	97.23	1.35	1.0	52.27	0.7482
0.6	410.35	97.22	1.93	1.5	49.93	0.7705
0.7	585.83	97.11	2.76	2.33	43.39	0.7787
0.8	846.8	96.99	3.99	4.0	36.71	0.7445
0.9	1749.2	96.9	8.25	9.0	48.44	0.8376



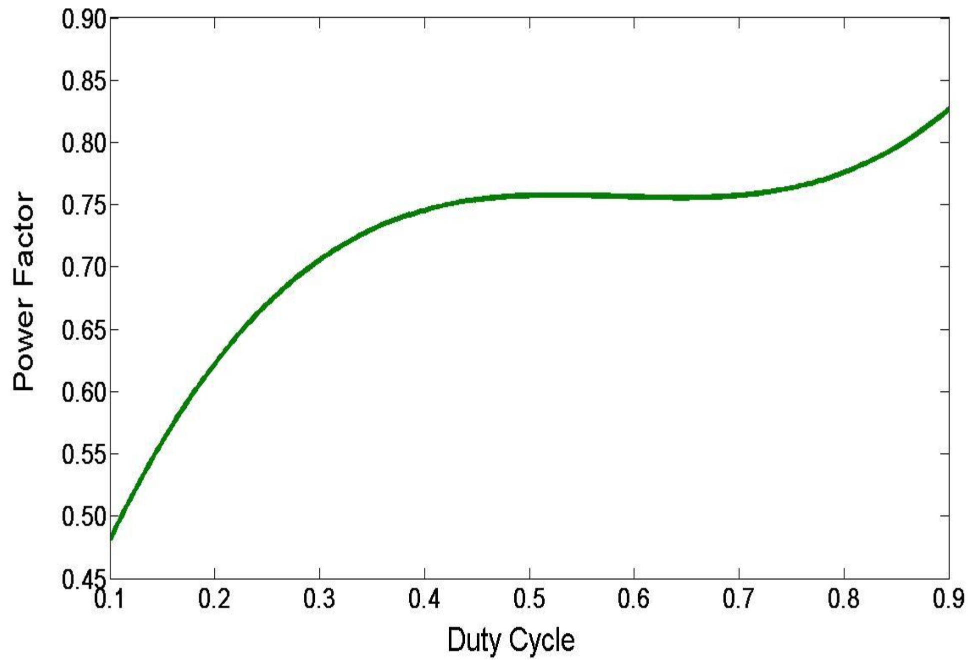
(a)


Gain
Duty Cycle
0
1
2
3
4
5
6
7
8
9
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9

(b)


THD (%)
Duty Cycle
20
40
60
80
100
120
140
160
180
200
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9

(c)



(d)

Figure 3.29: Conventional output switched Ĉuk AC-DC Converter (a) Efficiency, (b) Gain, (c) THD and (d) power factor

3.4.2 Single Phase Input Switched Ĉuk AC-DC Converter Output Diode Bridge Configuration without feedback

In input switched Ĉuk topology based single phase AC-DC converters, the circuit works at both buck gain region and boost gain region without feedback control. In the following simulation results, Figure 3.30 circuit is simulated for buck and boost gain operations with same circuit parameters listed in following.

L_1 = 1mH, L_2 = 0.1mH,

C = 1µF (Coupling capacitor)

C_o = 220µF (Output capacitor)

ECR = 100Ω (Equivalent Cuk Resistor/output resistor)

V_{in} = 300$V_{p\text{-}p}$, 50 Hz

f_{switch} = 5KHz

Simulation has been initially carried out without any feedback and pfc, output voltage regulation and input current harmonic distortion are calculated. The performance parameters were observed with variation of duty cycle D from 0.1 to 0.9. The observations have been recorded as shown in Table 3.2 and graphically represented in Figures 3.31 for single phase input switched Ĉuk AC-DC converter output diode bridge configuration. It is evident that the converter has buck-boost voltage gain and power factor above 0.7 for D above 0.5 to 0.9 but lower efficiency compared to conventional output switched Ĉuk AC-DC converter. The total harmonic distortion is however above 40 percent. The voltage gain calculated from simulation and theoretical equation (discussed in section 3.3) are close for duty cycle 0.7-0.8 range. To attain THD of input current less than 10 percent and improved power factor further, proper feedbacks are necessary.

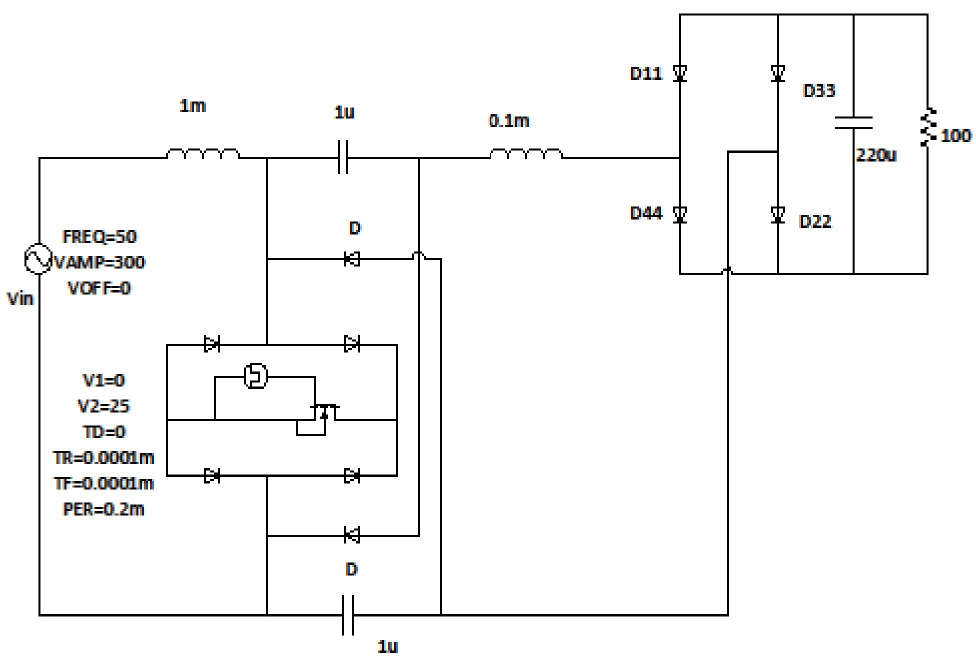
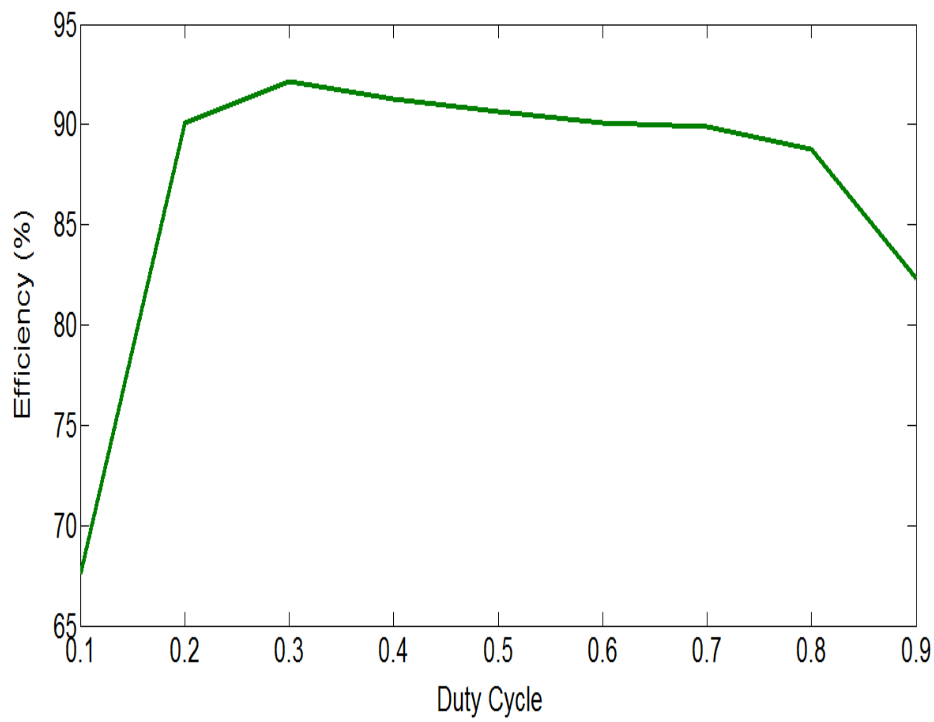


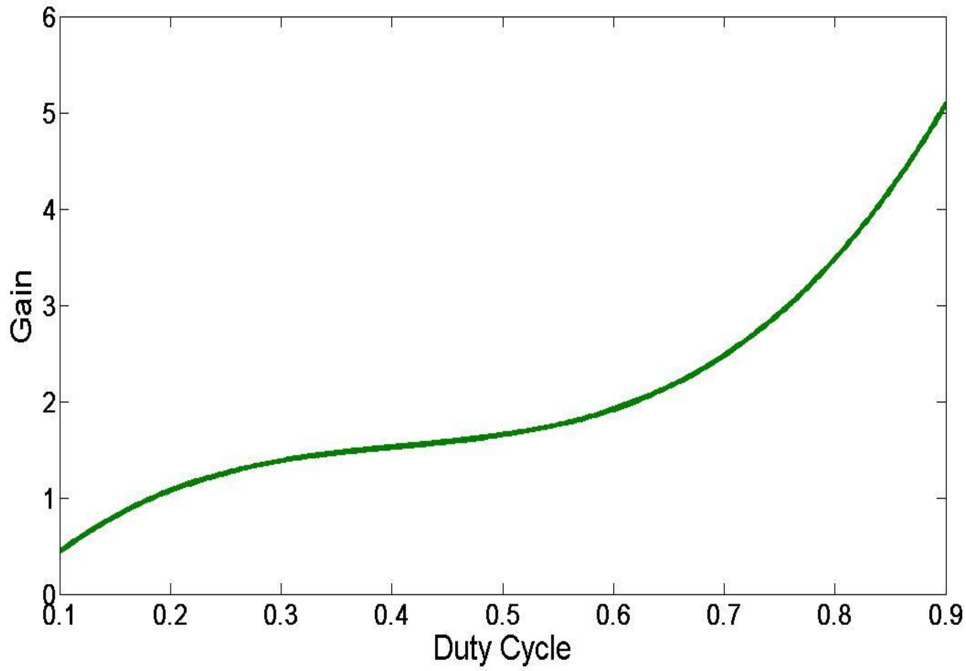
Figure 3.30: Single Phase Input Switched Ĉuk AC-DC Converter Output Diode Bridge Configuration without feedback control

Table 3.2: Performance of Single Phase Input Switched Ĉuk AC-DC Converter Output Diode Bridge Configuration (without feedback control)

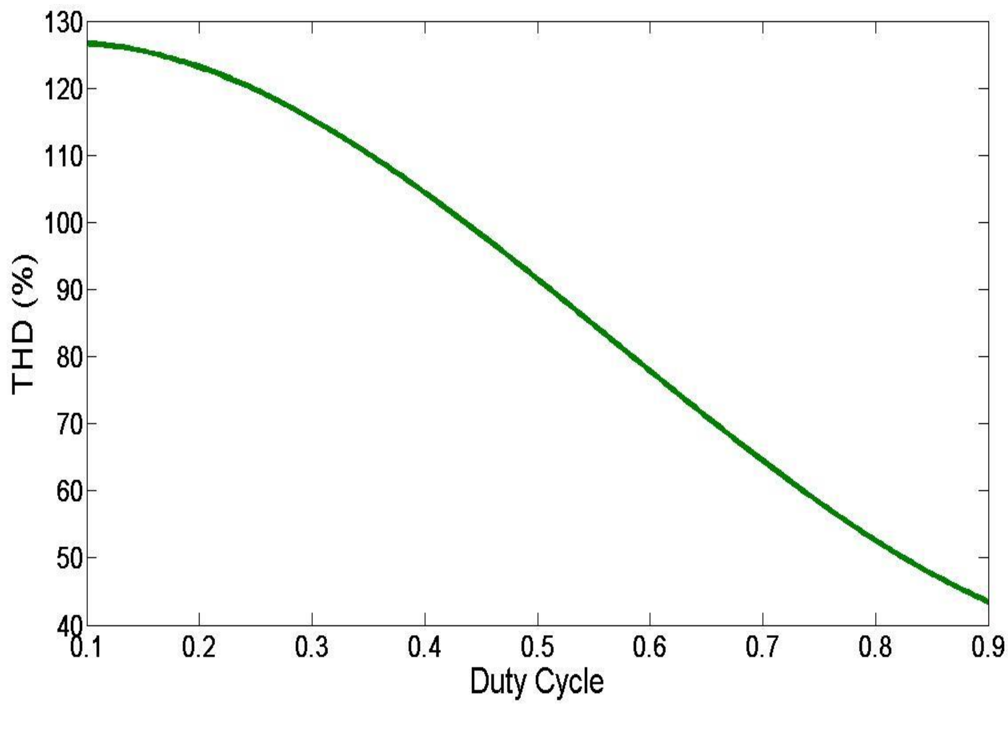
Duty Cycle	Vout	Efficiency (%)	Gain (Simulation)	Gain (Theoretical)	THD (%)	PF
0.1	117.6	67.59	0.55	0.11	125	0.6196
0.2	204.23	90.07	0.96	0.25	126.39	0.6176
0.3	266.61	92.14	1.25	0.43	115.9	0.6546
0.4	326.11	91.28	1.54	0.67	102.71	0.6997
0.5	387.06	90.65	1.82	1.0	89.93	0.7456
0.6	449.41	90.10	2.11	1.5	77.93	0.7902
0.7	513.75	89.89	2.42	2.33	66.55	0.8283
0.8	669.6	88.77	3.16	4.0	52.79	0.8662
0.9	1120.7	82.32	5.28	9.0	42.88	0.8952



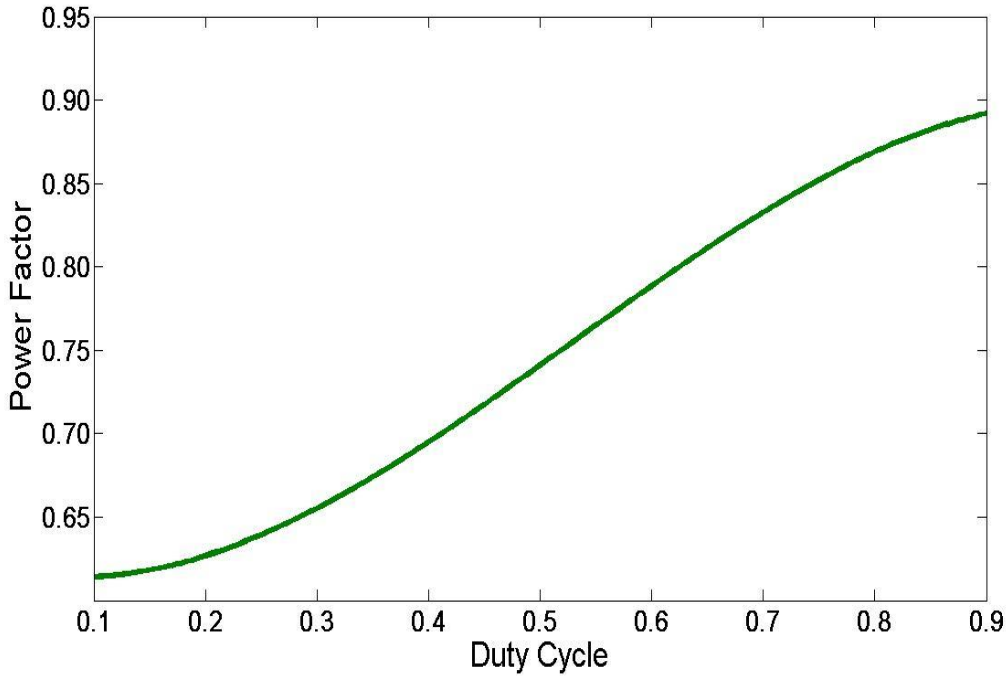
(a)


6
5
4
3
2
1
0
Gain
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
Duty Cycle

(b)


130
120
110
100
90
80
70
60
50
40
THD (%)
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
Duty Cycle

(c)



(d)

Figure 3.31: Single Phase Input Switched Ĉuk AC-DC Converter-Bridge Configuration without feedback (a) Efficiency, (b) Gain, (c) THD and (d) power factor

3.4.3 Single Phase Input Switched Ĉuk AC-DC Converter Output Half Diode Bridge Configuration without feedback

In input switched Ĉuk topology based single phase AC-DC converters, the circuit works at both buck gain region and boost gain region without feedback control. In the following simulation results, Figure 3.32 circuit is simulated for buck and boost gain operations with same circuit parameters listed in following.

L_1 = 1mH, L_2 = 0.1mH,

C = 4.4µF (Coupling capacitor)

C_o = 220µF (Output capacitor)

ECR = 100Ω (Equivalent Cuk Resistor/output resistor)

V_{in} = 300V_{p-p} , 50 Hz

f_{switch} = 5KHz

Simulation has been initially carried out without any feedback and pfc, output voltage regulation and input current harmonic distortion are calculated. The performance parameters were observed with variation of duty cycle D from 0.1 to 0.9. The observations have been recorded as shown in Table 3.3 and graphically represented in Figures 3.33 for single phase input switched Ĉuk AC-DC converter output half diode bridge configuration. It is evident that the converter has buck-boost voltage gain and power factor above 0.7 but lower efficiency compared to conventional output switched Ĉuk AC-DC converter. The total harmonic distortion is however above 25 percent. The voltage gain calculated from simulation and theoretical equation (discussed in section 3.3) are close for duty cycle within 0.6-0.8 range. To attain THD of input current less than 10 percent and improved power factor further, proper feedbacks are necessary.

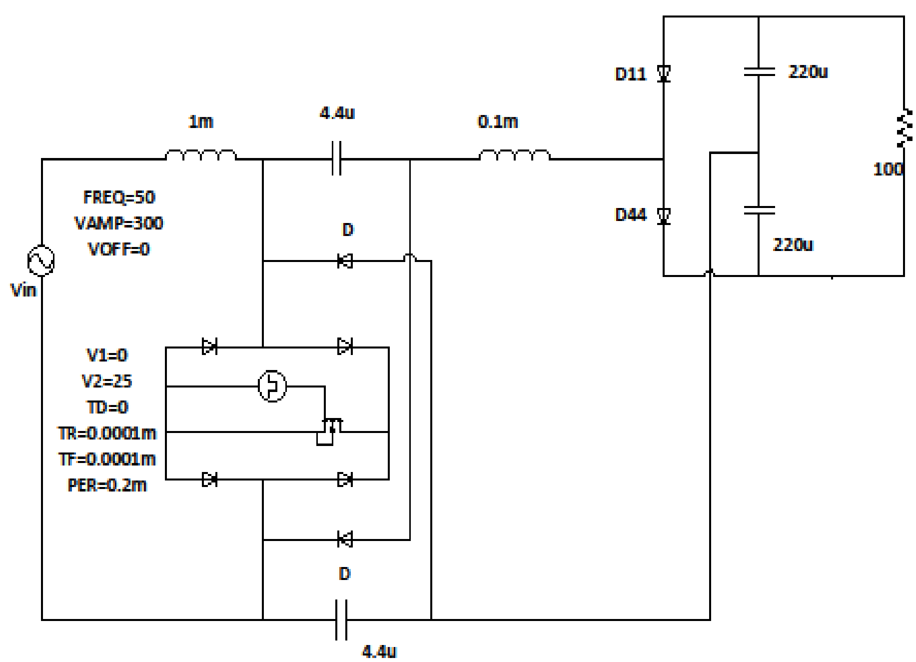
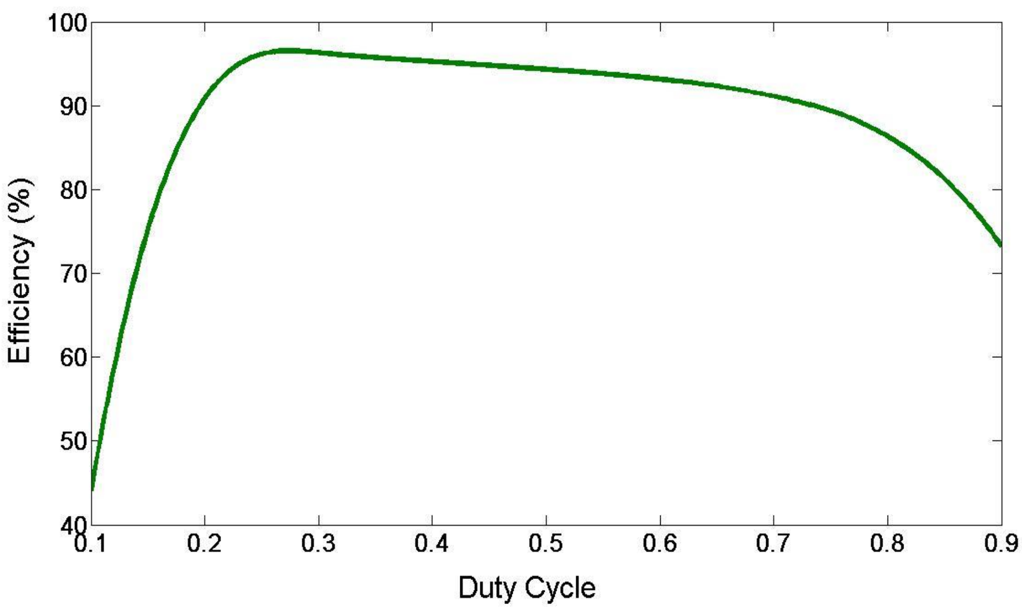


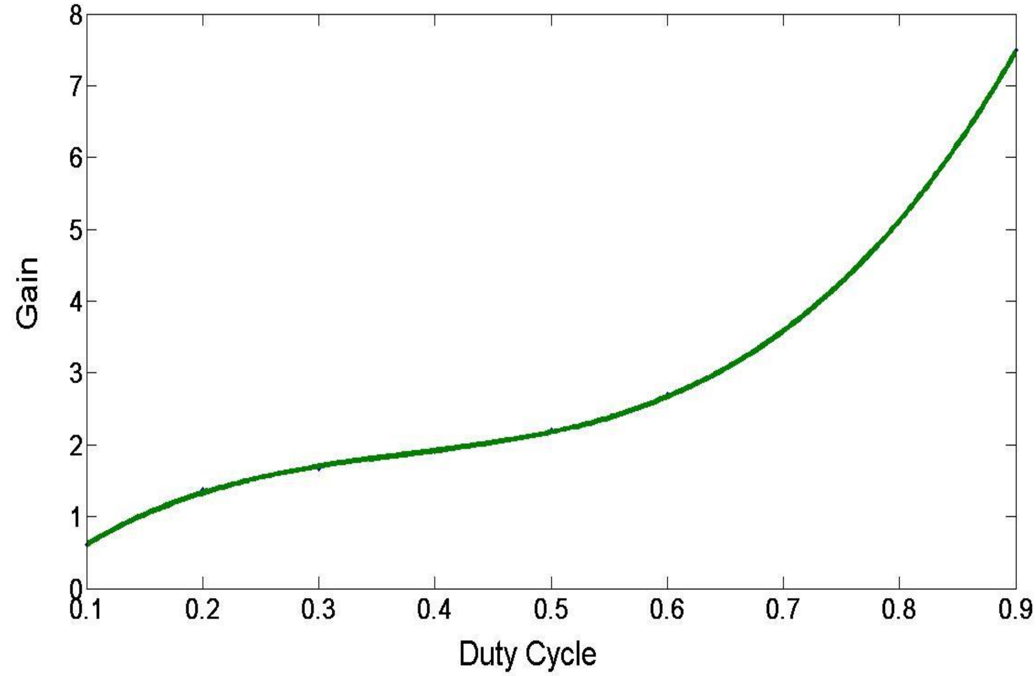
Figure 3.32: Single Phase Input Switched Ĉuk AC-DC Converter Output Half Diode Bridge Configuration without feedback control

Table 3.3: Performance of Single Phase Input Switched Ĉuk AC-DC Converter Output Half Diode Bridge Configuration without feedback control

Duty Cycle	Vout	Efficiency (%)	Gain (Simulation)	Gain (Theoretical)	THD (%)	PF
0.1	128.88	44.18	0.61	0.16	78.01	0.7818
0.2	293.21	90.97	1.38	0.35	90.05	0.7319
0.3	352.8	96.36	1.66	0.61	83.71	0.7648
0.4	404.34	95.31	1.91	0.94	74.24	0.8016
0.5	467.31	94.38	2.20	1.41	63.76	0.8429
0.6	575.00	93.21	2.71	2.12	52.72	0.8845
0.7	758.38	91.17	3.58	3.30	45.77	0.9094
0.8	1081.7	86.4	5.1	5.66	41.09	0.9174
0.9	1591.08	73.32	7.5	12.73	25.37	0.9192

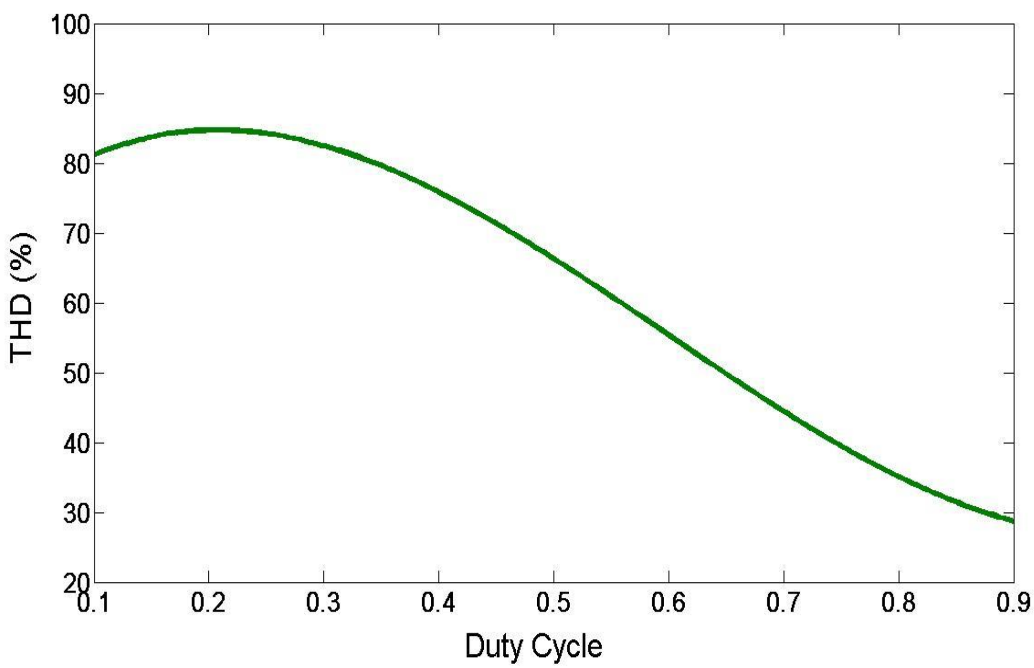


(a)



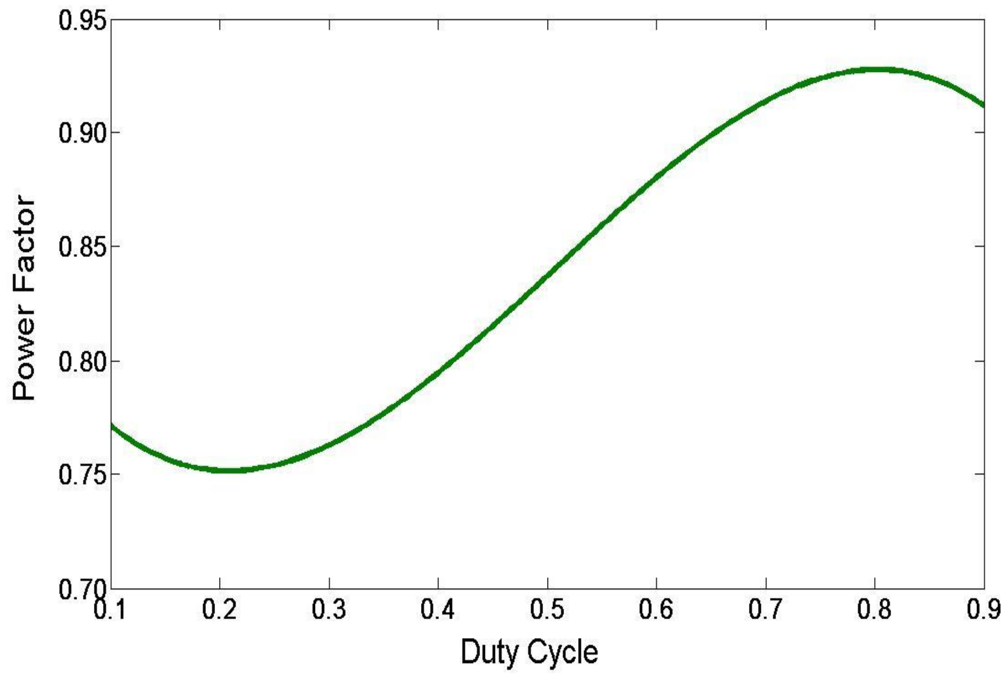
8
7
6
5
4
3
2
1
0
Gain
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
Duty Cycle

(b)



100
90
80
70
60
50
40
30
20
THD (%)
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
Duty Cycle

(c)



(d)

Figure 3.33: Single Phase Input Switched Ĉuk AC-DC Converter Output Half Diode Bridge Configuration without feedback control (a) Efficiency, (b) Gain, (c) THD and (d) power factor

3.4.4 Single Phase Modified Ĉuk AC-DC Converter – 1 Switch Within Diode Bridge without feedback

In Modified Ĉuk topology based single phase AC-DC converter Configuration - 1, the circuit works at both buck gain region and boost gain region without feedback control. In the following simulation results, Figure 3.34 circuit is simulated for buck and boost gain operations with same circuit parameters listed in following.

L_1 = 5mH, L_2 = 5mH,

C = 5µF (Coupling capacitor)

C_o = 330µF (Output capacitor)

ECR = 100Ω (Equivalent Cuk Resistor/output resistor)

V_{in} = 300V_{p-p} , 50 Hz

f_{switch} = 5KHz

Simulation has been initially carried out without any feedback and pfc, output voltage regulation and input current harmonic distortion are calculated. The performance parameters were observed with variation of duty cycle D from 0.1 to 0.9. The observations have been recorded as shown in Table 3.4 and graphically represented in Figures 3.35 for single phase modified Ĉuk AC-DC converter configuration - 1. It is evident that the converter has buck-boost voltage gain and power factor above 0.8 for a wide duty cycle and higher efficiency compared to conventional output switched Ĉuk AC-DC converter. The total harmonic distortion is however above 10 percent. The voltage gain calculated from simulation and theoretical equation (discussed in section 3.3) are close for duty cycle above 0.5. To attain THD of input current less than 10 percent and improved power factor further, proper feedbacks are necessary.

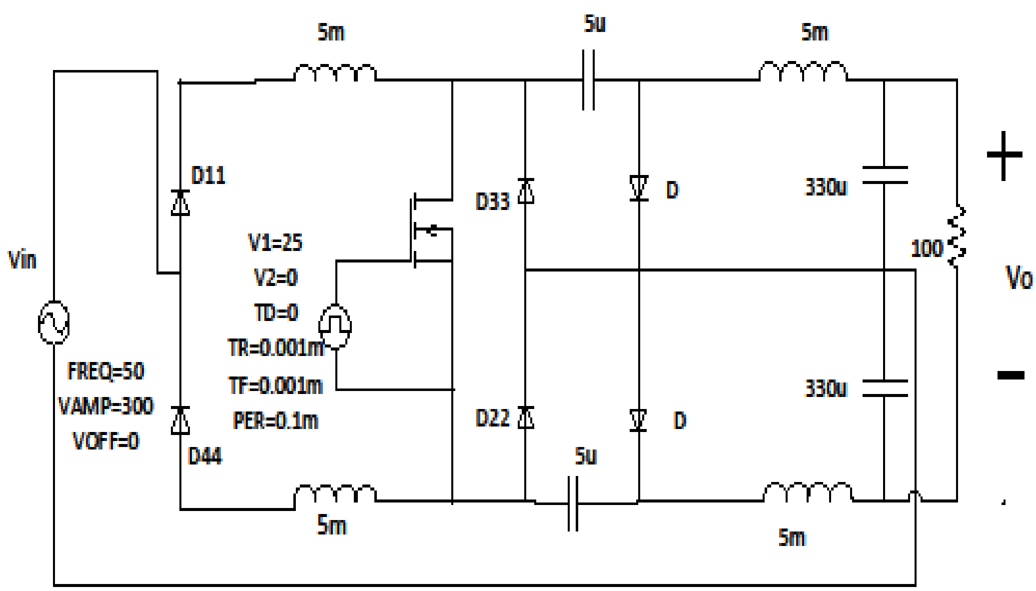
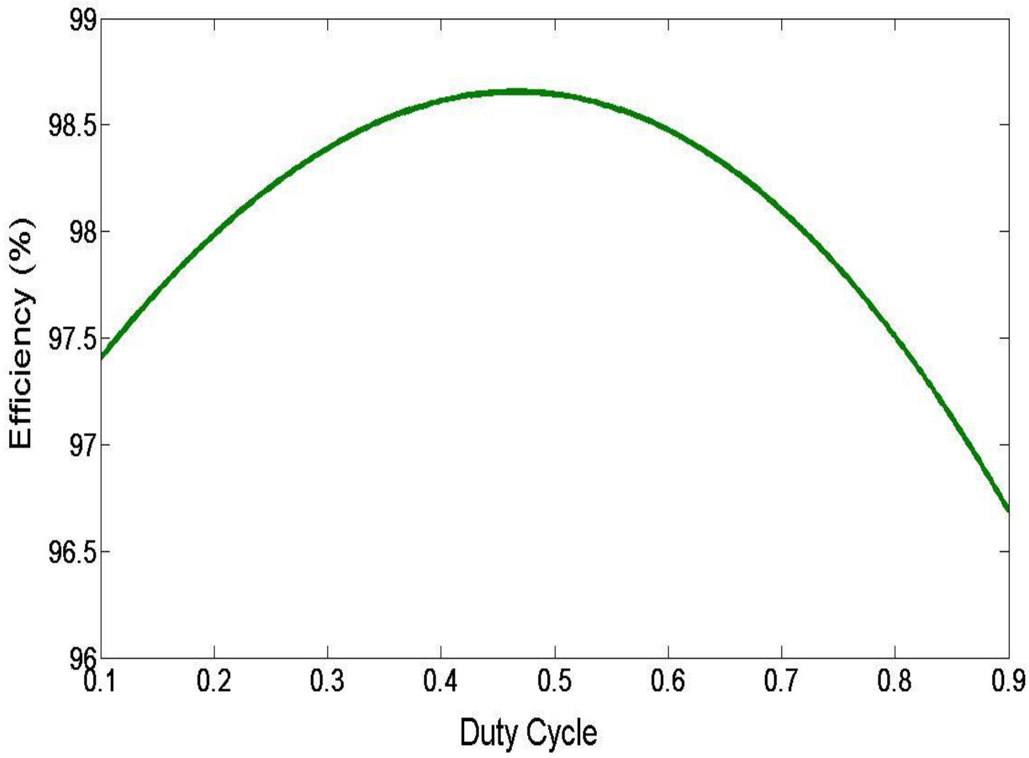


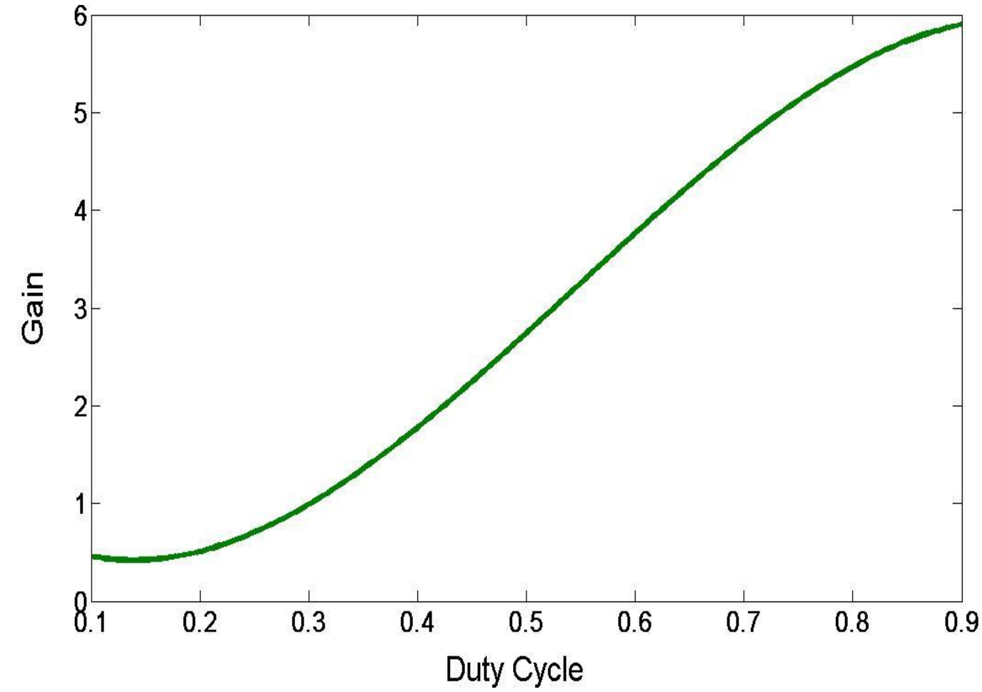
Figure 3.34: Single Phase Modified Ĉuk AC-DC Converter Switched Within Bridge Configuration-1 without feedback control

Table 3.4: Performance of Single Phase Modified Ĉuk AC-DC Converter Switch Within Diode Bridge Configuration-1 without feedback control

Duty Cycle	Vout	Efficiency (%)	Gain (Simulation)	Gain (Theoretical)	THD (%)	PF
0.1	70.97	97.19	0.33	0.16	115.6	0.6385
0.2	144.48	98.35	0.68	0.35	61.26	0.8323
0.3	242.61	98.48	1.14	0.61	52.93	0.8711
0.4	372.09	98.49	1.76	0.94	50.86	0.8803
0.5	543.47	98.44	2.56	1.41	46.16	0.8863
0.6	760.11	98.34	3.58	2.12	36.99	0.8816
0.7	1012.16	98.19	4.77	3.30	24.05	0.8217
0.8	1244.6	97.88	5.87	5.66	10.46	0.6586
0.9	1207.28	96.47	5.69	12.73	8.26	0.3435

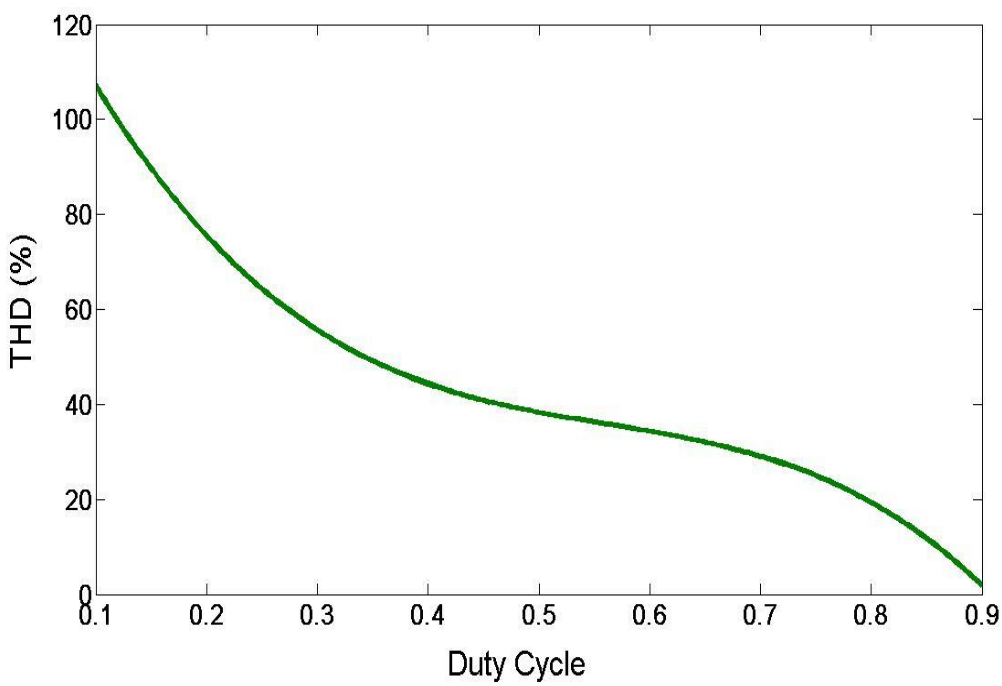


(a)



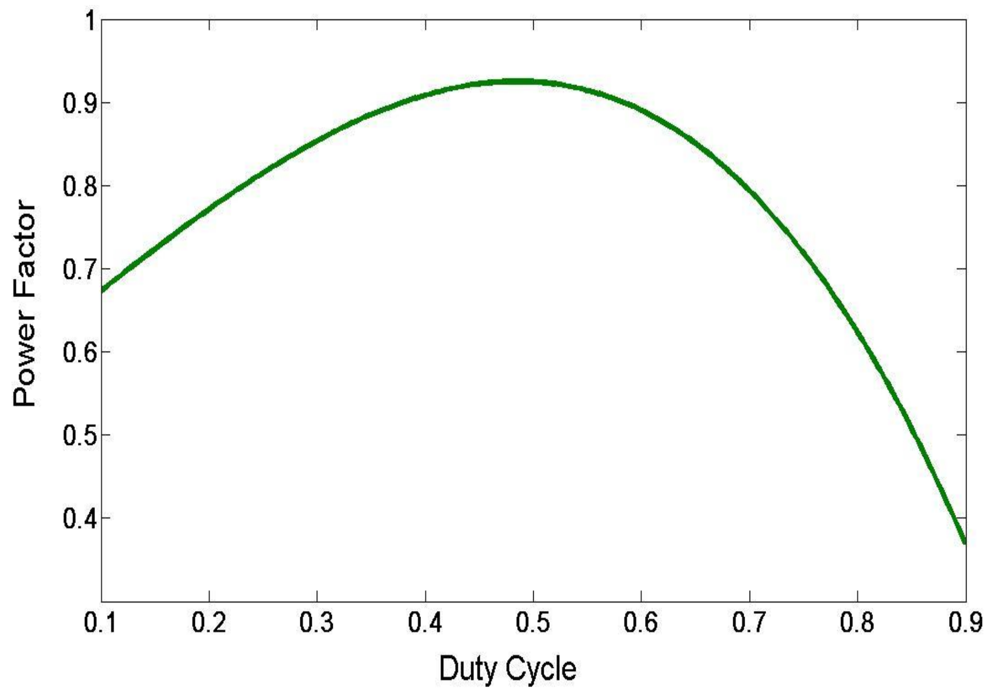
Gain
Duty Cycle
0
1
2
3
4
5
6
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9

(b)



THD (%)
Duty Cycle
0
20
40
60
80
100
120
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9

(c)



(d)

Figure 3.35: Single Phase Modified Ĉuk AC-DC Converter Switch Within Diode Bridge Configuration-1 without feedback control (a) Efficiency, (b) Gain, (c) THD and (d) power factor

3.4.5 Single Phase Modified Ĉuk AC-DC Converter Switch within Diode Bridge Configuration -2 without feedback

In modified Ĉuk topology based single phase AC-DC converter configuration -2, the circuit works both in buck gain region and boost gain region without feedback control. In the following simulation results, Figure 3.36 circuit is simulated for buck and boost gain operations with same circuit parameters listed in following.

L_1 = 5mH, L_2 = 5mH,

C = 5µF (Coupling capacitor)

C_o = 330µF (Output capacitor)

ECR = 100Ω (Equivalent Cuk Resistor/output resistor)

V_{in} = 300V_{p-p} , 50 Hz

f_{switch} = 5KHz

Simulation has been initially carried out without any feedback and pfc, output voltage regulation and input current harmonic distortion are calculated. The performance parameters were observed with variation of duty cycle D from 0.1 to 0.9. The observations have been recorded as shown in Table 3.5 and graphically represented in Figures 3.37 for single phase modified Ĉuk AC-DC converter configuration -2. It is evident that the converter has buck-boost voltage gain and higher efficiency compared to conventional output switched Ĉuk AC-DC converter. Its power factor is above 0.8 for wide range of duty cycle. The total harmonic distortion is also high. The voltage gain calculated from simulation and theoretical equation (discussed in section 3.3) are close for duty cycle within 0.7-0.8 range. To attain THD of input current less than 10 percent and improved power factor further, proper feedbacks are necessary.

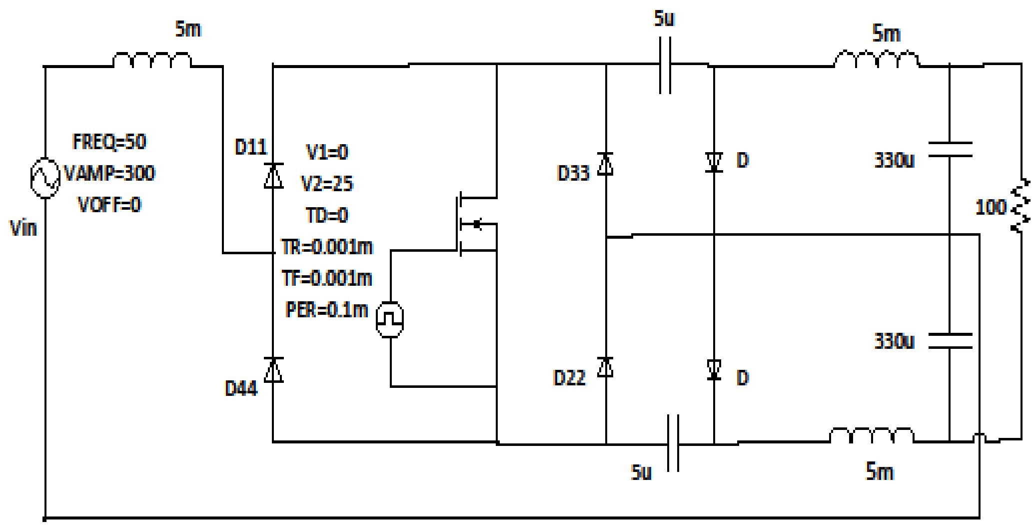
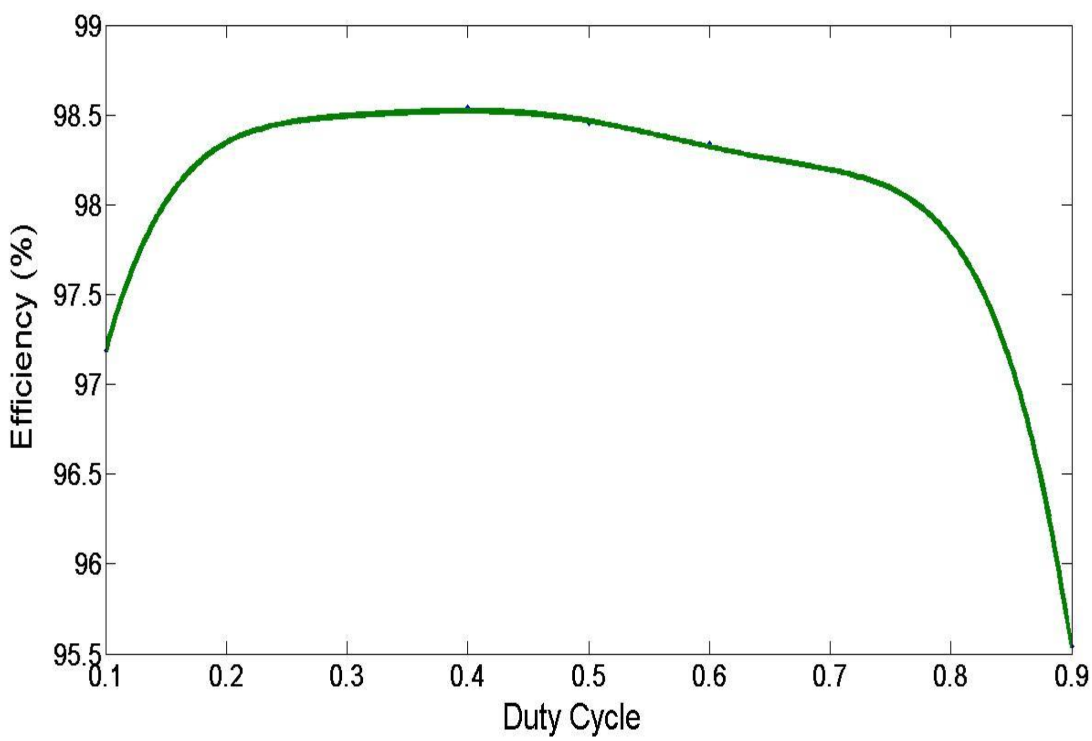


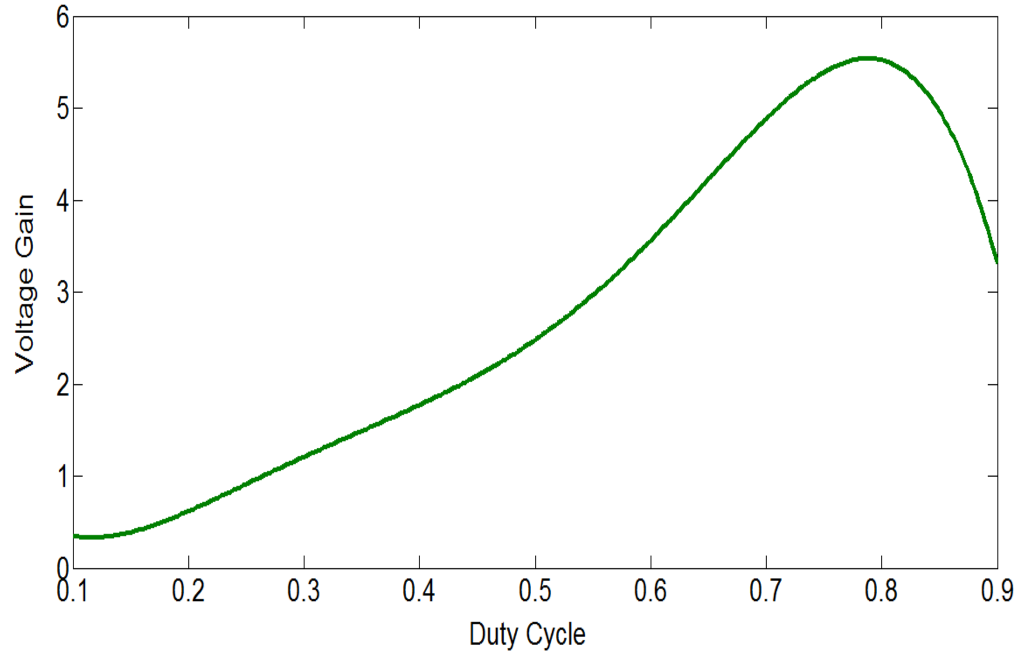
Figure 3.36: Single Phase Modified Ĉuk AC-DC Converter Switch Within Diode Bridge Configuration-2 without feedback control

Table 3.5: Performance of Single Phase Modified Ĉuk AC-DC Converter Switch Within Diode Bridge Configuration-2 (without feedback control)

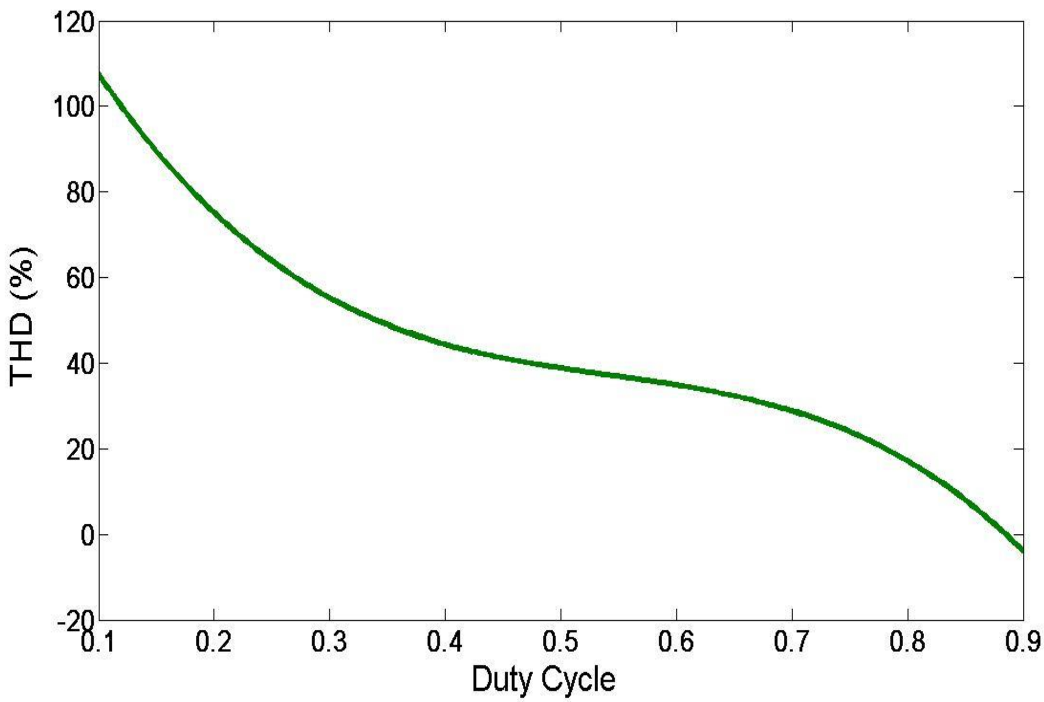
Duty Cycle	Vout	Efficiency (%)	Gain (Simulation)	Gain (Theoretical)	THD (%)	PF
0.1	70.97	97.19	0.33	0.16	115.64	0.6385
0.2	144.48	98.35	0.68	0.35	61.26	0.8323
0.3	242.61	98.49	1.14	0.61	52.93	0.8711
0.4	372.09	98.54	1.75	0.94	50.86	0.8803
0.5	543.47	98.45	2.56	1.41	46.16	0.8863
0.6	760.11	98.34	3.58	2.12	36.99	0.8816
0.7	1012.17	98.19	4.77	3.30	23.94	0.8217
0.8	1188.13	97.82	5.6	5.66	9.34	0.6152
0.9	698.13	95.54	3.29	12.73	1.89	0.1736



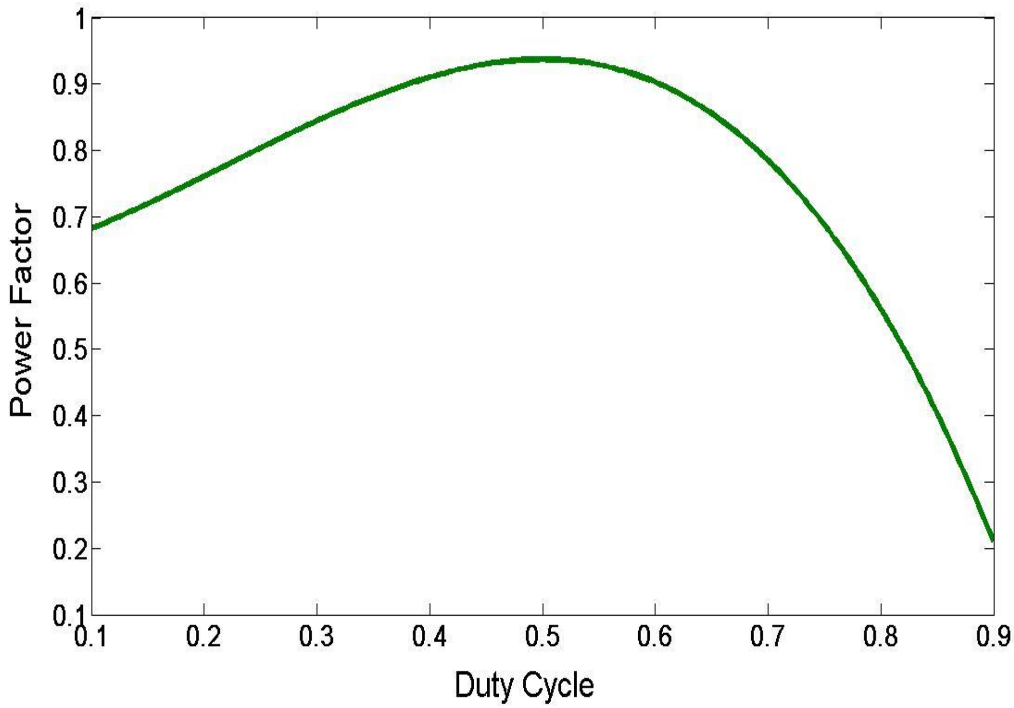
(a)


6
5
4
3
2
1
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
Voltage Gain
Duty Cycle

(b)


120
100
80
60
40
20
0
-20
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
THD (%)
Duty Cycle

(c)



(d)

Figure 3.37: Single Phase Modified Ĉuk AC-DC Converter Switched Within Bridge Configuration-2 without feedback control (a) Efficiency, (b) Gain, (c) THD and (d) power factor

3.5 Observations

Ĉuk topology based single phase AC-DC converters provide step-up/down voltage gain, output voltage control and regulation. In the open loop control, the power factor and efficiency of the proposed circuits are reasonably good for a wide range of duty cycle variation. Though input switch output diode bridge and output half diode bridge configurations show poor efficiency than other two proposed models and conventional circuit, due to loss of using extra circuit components in the design, these configurations will be useful for three phase AC-DC converter design. Extra circuitry is also used in proposed modified designs but they are regenerative in nature. It is observed in the previous section that theoretical and simulated voltage gain are close in mid-range duty cycle (0.4 - 0.7) and at high duty cycle (0.8 – 0.9) power factor gradually decreases. The main reason behind those problem is due to lack of proper design and switching behavior. In an open loop control, voltage and current are not in the same phase. As a result, it takes high input current and degrade output performance.

The input current total harmonic distortions (THD) are not in acceptable range in open loop control. It is therefore necessary that appropriate feedbacks are adopted in the circuit for all performance parameters to be in the acceptable range. Feedback is also necessary for output voltage regulation around a constant value where necessary. Chapter 4 describes the required PFC controller design of proposed **Ĉ**uk topology based single phase rectifiers.

Chapter 4

PFC Controller Design

Technical solutions to the problem of distortion in the input current have been known for a long time. However, recently it has the concern about deleterious effects of harmonics led to the formulation of guidelines and standards, which in turn have focused attention on ways of limiting current distortion. In the following sections, power factor corrected (PFC) interface are briefly explained for single phase rectification where it is assumed that the power needs to flow only in one direction, such as in dc power supplies.

4.1 Operating Principle of Single Phase PFC

Operating principle of a single phase PFC is shown in Figure 4.1, where a Boost DC/DC converter is introduced between the utility supply and the dc-bus capacitor. The boost converter consists of a switch, a diode and a small inductor L_d. By pulse width modulating the switch at a constant switching frequency, the current i_L through the inductor L_d is shaped to have the full wave rectified waveform |sinωt|, similar to $|v_s(t)|$. The inductor current contains high switching frequency ripples which is removed by a small filter and the input current i_s will be sinusoidal and in phase with supply voltage. Ĉuk converter is used in place of boost converter in our present work. As the input side of Ĉuk converter is similar to boost converter, PFC design technique is same for both.

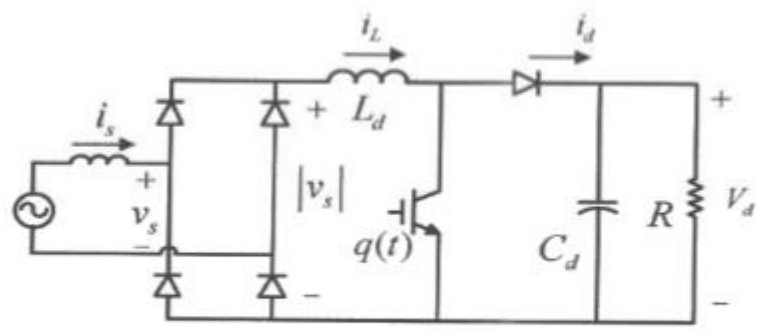


Figure 4.1 Power Factor Corrected Circuit

4.2 Control of PFC

In controlling a PFC rectifier, the main objective is to draw a sinusoidal current, in-phase with the utility voltage. The reference inductor current $i_L^*(t)$ should be of the full wave rectified form. The requirements on the form and the amplitude of the inductor current lead to two control loops [1], as shown in Figure 4.2, to pulse-width modulate the switch of the switching converter:

- The average inner current control loop ensures the form of $i_L^*(t)$ based on the template sin|ωt| provided by measuring the rectifier output voltage $|v_s(t)|$.
- The outer voltage control loop determines the amplitude I_L of $i_L^*(t)$ based on the output voltage feedback. If the inductor current is insufficient for a given load supplied by the PFC, the output voltage will drop below its preselected reference value V_d^*. By measuring the output voltage and using it as the feedback signal, the voltage control loop adjusts the inductor current amplitude to bring the output voltage to its reference value. In addition to determining the inductor current amplitude, this voltage feedback control acts to regulate the output voltage of the PFC to the pre-selected dc voltage.

In Figure 4.2, the inner current-control loop is required to have a very high bandwidth compared to the outer voltage-control loop. Hence, each loop can be designed separately.

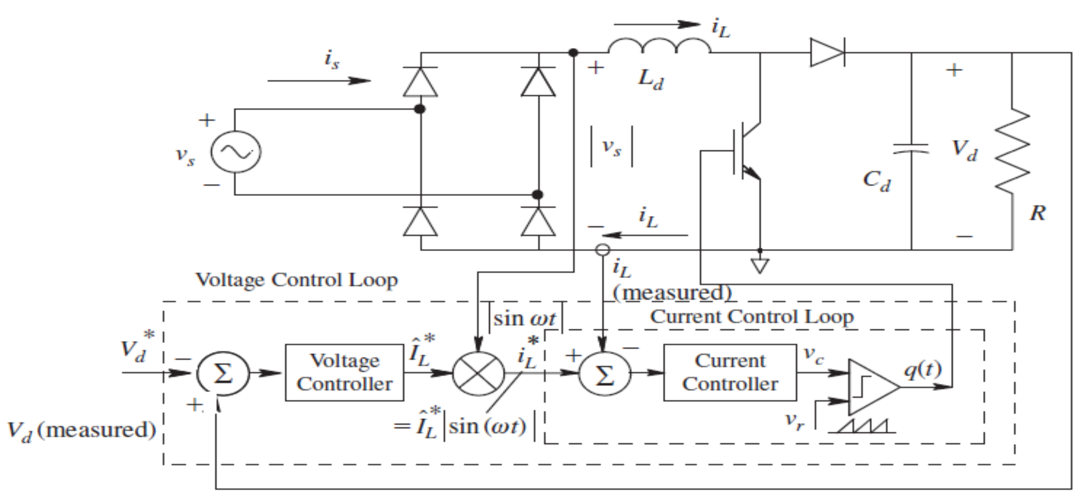


Figure 4.2: PFC control loop

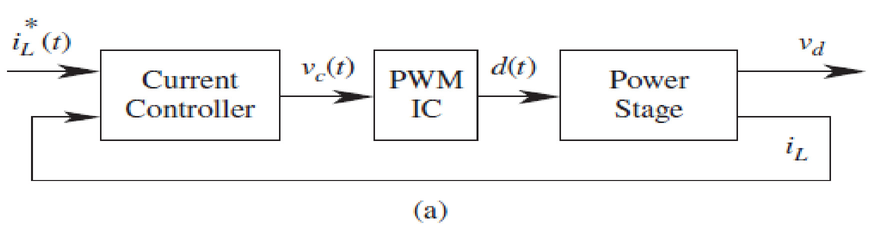
4.3 Design the Inner Average Current Control Loop

The inner current control loop is shown within the inner dotted box in Figure 4.2. In order to follow the reference with as little THD as possible, an average-current-mode control is used with a high bandwidth, where the error between the reference $i_L^*(t)$ and the measured inductor current $i_L(t)$ is amplified by a current controller to produce the control voltage $v_c(t)$.

This control voltage is compared with a ramp signal $v_r(t)$, with a peak of V_r at the switching frequency *fs* in the PWM controller IC, to produce the switching signal *q(t)*.

Just the inner current control loop of Figure 4.2 can be simplified, as shown in 4.3(a). The reference input $i_L^*(t)$, $|v_s(t)|$ vary much more slowly with time compared to the current control-loop bandwidth. Therefore, at each instant of time can be considered as a "dc" steady state.

This equilibrium condition varies slowly with time, compared to the current-control-loop bandwidth, which is designed to be much larger. In Laplace domain, this current loop is shown in Figure 4.3(b), as discussed below, where "~" on top represents small signal perturbations at very high frequencies in the range of the current-control-loop bandwidth.



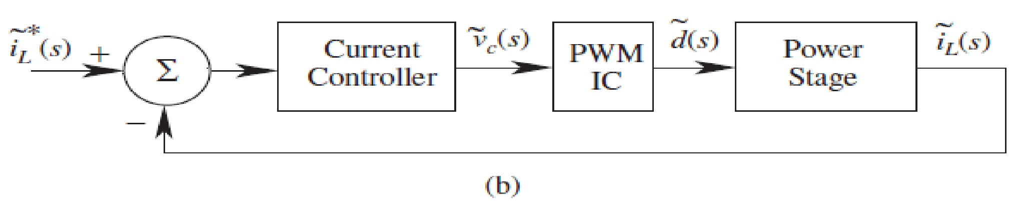


Figure 4.3: PFC current control loop

4.3.1 d(s)/v_c(s) for the PWM controller

If V_r is the difference between the peak and the valley of the ramp voltage in the PWM-IC, then the small signal transfer function of the PWM controller is,

$$\frac{\tilde{d}(s)}{\tilde{v}_C(s)} = \frac{1}{V_r} \tag{4.1}$$

4.3.2 $\frac{\tilde{i}_L(s)}{\tilde{d}(s)}$ for the Ĉuk converter in the power stage

To design the PFC feedback controller to the Ĉuk DC-DC converter, a small-signal model of the converter is required. This is obtained by linearizing system of Figure 3.1.1 around the static operating point.

The state equation at ON period of Ĉuk DC-DC converter can be derived as follows:

$$L_1 \frac{d}{dt} i_{L1} = v_{in}$$

$$L_2 \frac{d}{dt} i_{L2} = -v_C - v_o$$

$$C \frac{d}{dt} v_C = i_{L2}$$

$$C_o \frac{d}{dt} v_o = i_{L2} - \frac{v_o}{R_o}$$

The state equation at OFF period of Ĉuk DC-DC converter can be derived as follows:

$$L_1 \frac{d}{dt} i_{L1} = v_{in} - v_C$$

$$L_2 \frac{d}{dt} i_{L2} = -v_o$$

$$C \frac{d}{dt} v_C = i_{L1}$$

$$C_o \frac{d}{dt} v_o = i_{L2} - \frac{v_o}{R_o}$$

Applying the state space averaging modeling technique [32] in CCM/CVM mode yields the following averaged model of the converter [33, 34]:

$$L_1 \frac{d}{dt} i_{L1} = v_{in} - (1-d) v_C \tag{4.2.a}$$

$$L_2 \frac{d}{dt} i_{L2} = -d v_C - v_o \tag{4.2.b}$$

$$C \frac{d}{dt} v_C = (1-d) i_{L1} + d i_{L2} \tag{4.2.c}$$

$$C_o \frac{d}{dt} v_o = i_{L2} - \frac{v_o}{R_o} \tag{4.2.d}$$

Small Signal Model and Transfer Function

For the design of linear control system based on PI regulators, a small signal model of the converter is required. This is obtained by linearizing system (4.2) around the static operating point defined by:

$$V_C = \frac{1}{1-D} V_{in} \tag{4.3.a}$$

$$V_o = -D V_C \tag{4.3.b}$$

$$I_{L2} = \frac{V_o}{R_o} = I_o \tag{4.3.c}$$

$$I_{L1} = \frac{-1}{1-D} I_{L2} \tag{4.3.d}$$

Where, D, $I_{L1}, I_{L2}, I_o, V_{in}, V_o, V_C$ are the static or DC values of duty cycle, current through inductor L_1 and L_2, the DC load current, input voltage, output voltage and voltage across capacitor C.

Applying the small signal model linearization technique to system (4.2) around the static point (4.3) and choosing i_{L1} and v_o the system's output yields [35] :

$$\frac{d}{dt}\begin{bmatrix} \tilde{i}_{L1} \\ \tilde{i}_{L2} \\ \tilde{v}_C \\ \tilde{v}_o \end{bmatrix} = A.\begin{bmatrix} \tilde{i}_{L1} \\ \tilde{i}_{L2} \\ \tilde{v}_C \\ \tilde{v}_o \end{bmatrix} + B.\tilde{d} + P.\tilde{v}_{in} \tag{4.4}$$

$$\begin{bmatrix}\tilde{\imath}_{L1}\\ \tilde{v}_o\end{bmatrix} = C\begin{bmatrix}\tilde{\imath}_{L1}\\ \tilde{\imath}_{L2}\\ \tilde{v}_C\\ \tilde{v}_o\end{bmatrix} \tag{4.5}$$

Where,

$$A=\begin{bmatrix} 0 & 0 & \frac{-(1-D)}{L1} & 0\\ 0 & 0 & \frac{-D}{L2} & \frac{1}{L1}\\ \frac{1-D}{C} & \frac{D}{C} & 0 & 0\\ 0 & \frac{1}{Co} & 0 & \frac{-1}{RoCo}\end{bmatrix};\ B=\begin{bmatrix}\frac{-V_o}{L1D}\\ \frac{V_o}{L2D}\\ \frac{DV_o}{R_oC(1-D)}\\ 0\end{bmatrix};\ P=\begin{bmatrix}\frac{1}{L1}\\ 0\\ 0\\ 0\end{bmatrix};$$

$$C=\begin{bmatrix}1 & 0 & 0 & 0\\ 0 & 0 & 0 & 1\end{bmatrix}$$

In equation (4.4), A defines the state matrix, B the control matrix, P the disturbance matrix and C the output matrix. For any state variable $z \in \{i_{L1},\ i_{L2},\ v_C,\ v_o\}$ and $\tilde{z}$ is small-variation around its static value Z that is,

$$\tilde{z} = z - Z$$

The frequency domain representation of the converter is obtained by applying the Laplace transform to state equations (4.4, 4.5). It gives [35]:

$$Y(s)=C(sI_4 - A)^{-1}B.D(s) + C(sI_4 - A)^{-1}P.V_{in}(s) \tag{4.6}$$

Where, I_4 denotes the 4× 4 identity matrix and $Y(s)=[I_{L1}(s), V_o(s)]^T$

4.3.3 Designing the Current Controller $G_i(s)$

To have a high loop dc gain and a zero dc steady state error in Figure 4.3(b), the current controller transfer function must have a pole at the origin. The inner current-control loop is required to have a very high bandwidth compared to the outer voltage-control loop. To make the inner current loop's transient response faster in the time response a zero is introduced to the controller at corner frequency k_i/k_p. The transfer function of the current controller becomes as follows:

$$G_i(s) = k_{pc}\frac{s+\frac{k_{ic}}{k_{pc}}}{s} \tag{4.7}$$

The above transfer function of the current controller can be realized by a single operational amplifier working a PI regulator.

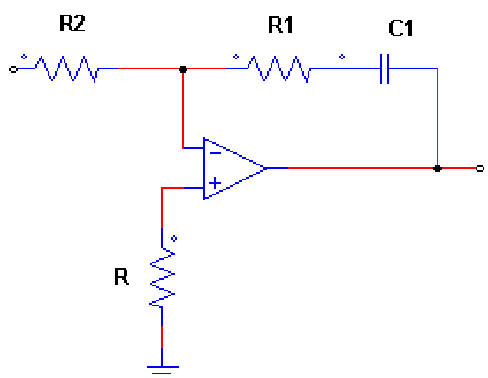


Figure 4.4: PI controller

Here,

$$k_{ic} = \frac{1}{R_2C_1} \tag{4.8}$$

$$k_{pc} = \frac{R_1}{R_2} \tag{4.9}$$

Where, k_i is the integrator gain and k_p is the proportional gain.

4.4 Designing the Outer Voltage Control Loop

The outer voltage loop is needed to determine the peak, I_L of the inductor current. In this voltage loop, bandwidth is kept low due to avoid third harmonic distortion in the input current. In view of such a low bandwidth of the voltage loop, it is perfectly reasonable to assume the current loop ideal at low frequencies. Therefore in the voltage control block diagram shown in Figure 4.5 (a) the closed current loop produces I_L equal to its reference value I_L^*. In addition to a large dc component, I_L^* contains an unwanted second harmonic component in the input results a third harmonic distortion in the current from the utility. Therefore in the output of the voltage controller block is limited to approximately 1.5% of the dc component in I_L^*.

The voltage control loop for low frequency perturbations, in the range of the voltage loop bandwidth is shown in Figure 4.5 (b)

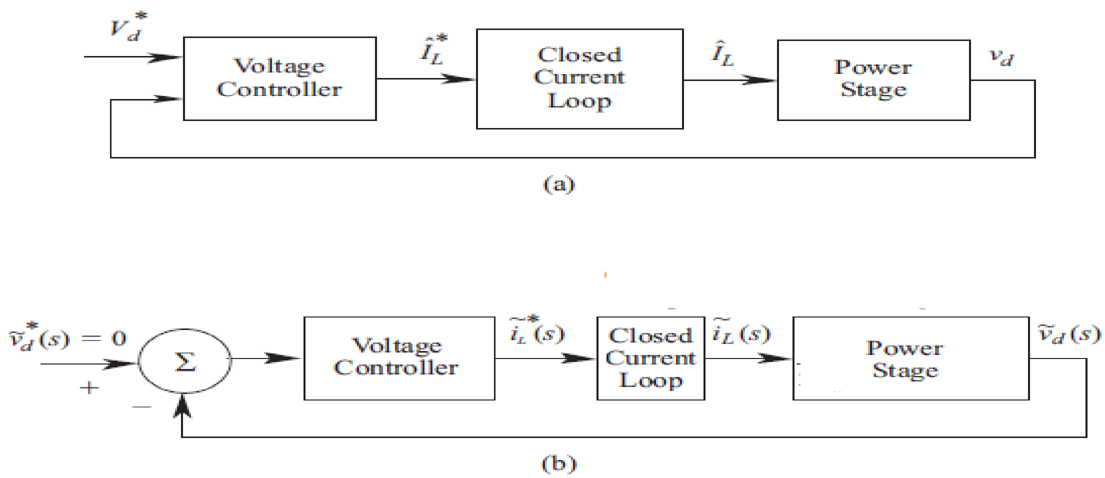


Figure 4.5: Voltage loop control

To achieve a zero steady state error, the voltage-controller transfer function should have a pole at the origin and a zero at corner frequency of k_{iv}/k_{pv} to make the loop's time response faster. The following simple transfer function is often used for the voltage controller as below:

$$G_v(s) = k_{pv}\frac{s+\frac{k_{iv}}{k_{pv}}}{s} \tag{4.10}$$

The above transfer function can be realized as Figure 4.4

Here,

$$k_{iv} = \frac{1}{R_2C_1} \tag{4.11}$$

$$k_{pv} = \frac{R_1}{R_2} \tag{4.12}$$

Where, k_{iv} is the integrator gain and k_{pv} is the proportional gain.

4.5 Implementation of Controller Design

Controller design parameters for single phase Ĉuk AC-DC converter of all configurations are given in the following Table no. 4.1.

Table 4.1: Circuit Parameters of the Ĉuk AC-DC converter and PFC controller

Circuit	Parameter Name	Parameter Value
Power Circuit	L_1	5mH
	L_2	5mH
	C	5µF
	C_0	330µF
	R_0	100 Ω
Current Controller Circuit	R_1	220k
	R_2	100 Ω
	C_1	0.022µF
Voltage Controller Circuit	R_1	15kΩ
	R_2	10kΩ
	C_1	0.01µF
Controller Gain	K_{ic}	4.54×10^5
	K_{pc}	2200
	K_{iv}	6666.67
	K_{pv}	0.67

This Power Factor Corrected feedback controller can be used to improve the performance of the conventional single phase output switched Ĉuk configuration and can also be implemented to improve efficiency, THD below 10% and power factor above 0.9 of the proposed input switched and switched within bridge Ĉuk configurations for both buck and boost operations. The results of these configurations with feedback controller circuit are given below in detail.

4.5.1 $\hat{C}$uk Topology Based Conventional Output Switched Single Phase AC-DC Converter with PFC Controller

Figure 4.6 shows the conventional way of power factor correction (PFC) control of a single phase rectifier through $\hat{C}$uk topology. The switch circuit is placed between the rectifier and load at the load side. Feedbacks are taken from input voltage (which may also be taken from rectifier output), output voltage and input current (which may also be taken from the inductor after the rectifier).

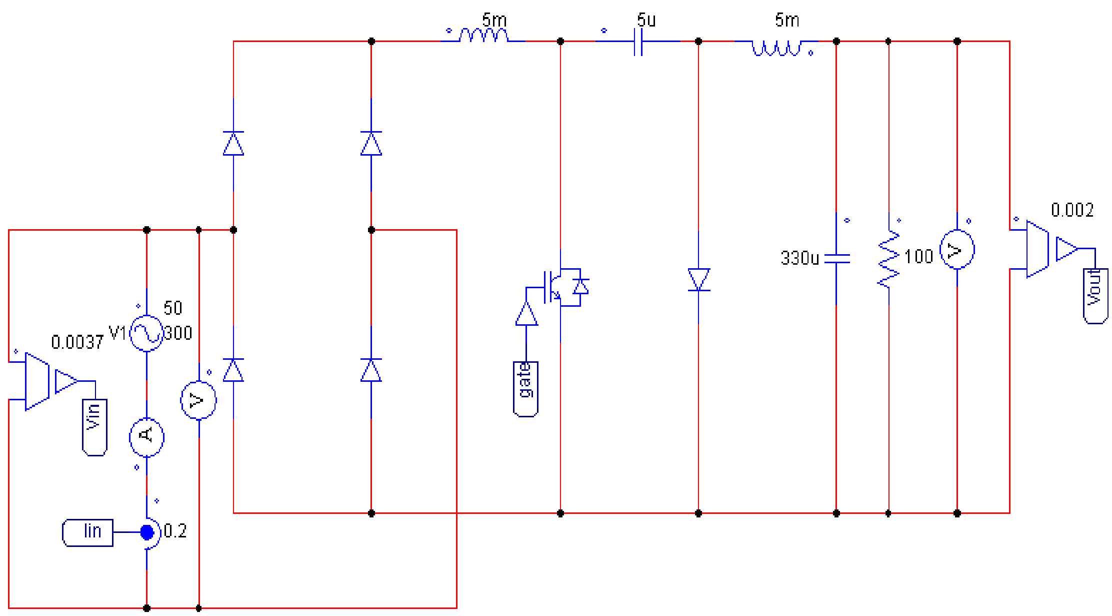


Figure 4.6: Conventional $\hat{C}$uk Output Switched-Bridge AC-DC Converter

Buck Operation:

$\hat{C}$uk Topology Based Conventional Output Switched Single Phase AC-DC Converter has both buck and boost gain characteristics. The control pulse of the switch of the converter for buck operation is produced by the control circuit as shown in Figure 4.7.

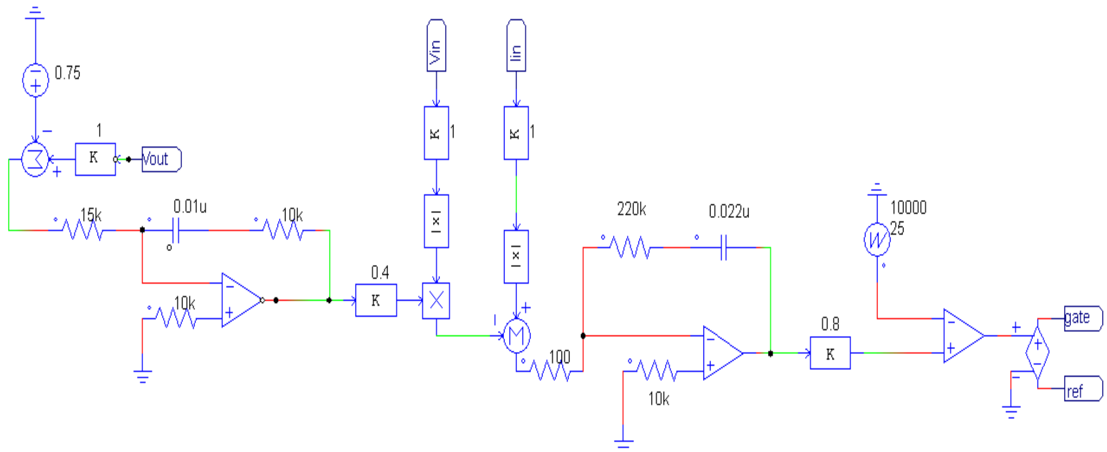
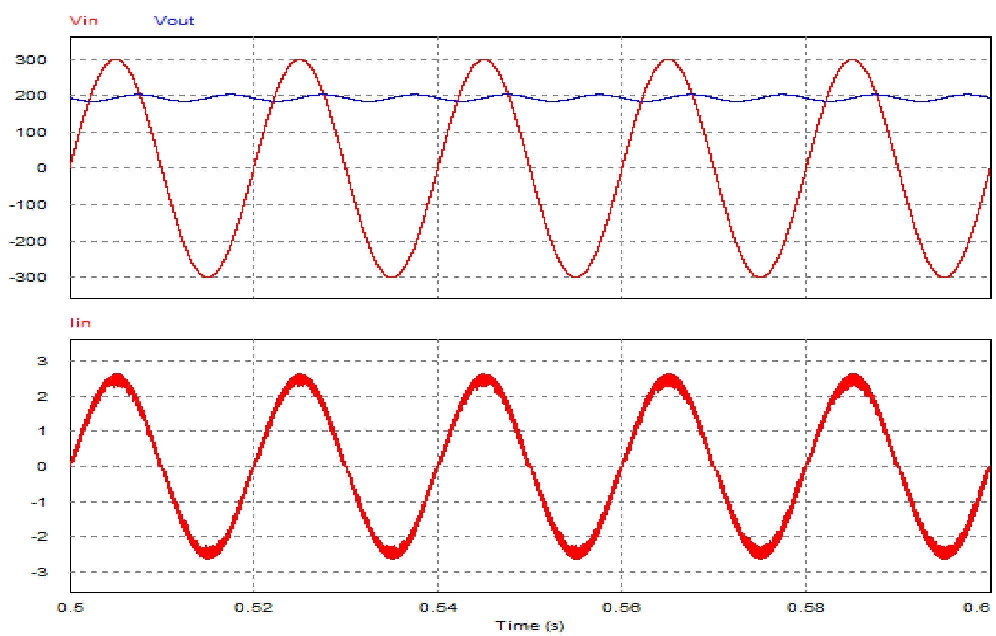
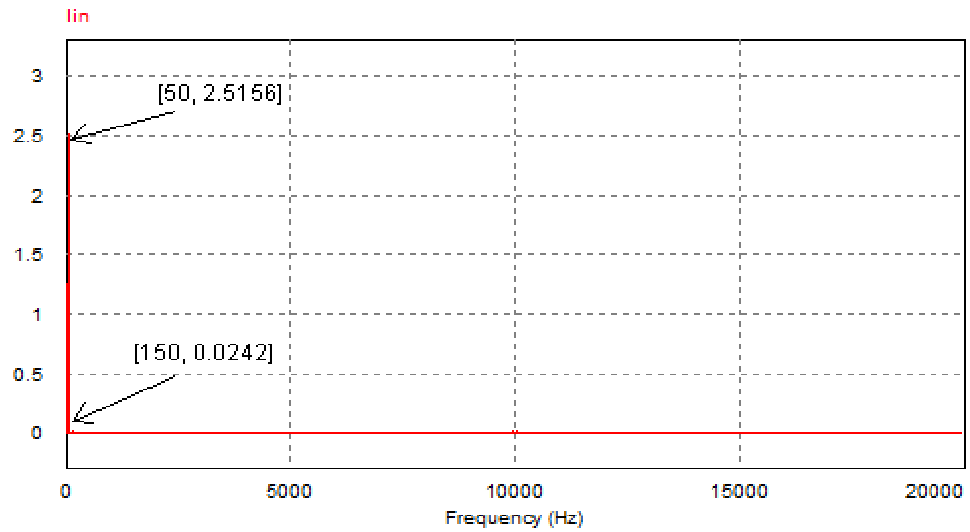


Figure 4.7: Feedback for Conventional $\hat{C}$uk Output AC-DC Converter (Buck Operation)

In this subsection, the circuits are designed for power factor correction for Conventional $\hat{C}$uk Output Switched-Bridge Configuration AC-DC Converter. The typical results of which are shown in Figure 4.8. Figure 4.8 (a) and (b) show the input/output voltages, input current and the input current spectrum respectively. Input power factor is reasonably high and the input current total harmonic distortion is considerably low (less than 10 percent).



(a)



(b)

Figure 4.8: (a) Input-output voltage and input current
(b) Spectrum of input current wave shape
(Control voltage set for regulated output voltage of 200V DC)

Boost Operation:

The control pulse of the switch of the converter for boost operation is produced by the control circuit as shown in Figure 4.9. The typical results of which are shown from Figure 4.10. Figure 4.10 (a) and (b) show the input/output voltages, input current and the input current spectrum. Input power factor is reasonably high and the input current total harmonic distortion is considerably low (less than 15 percent).

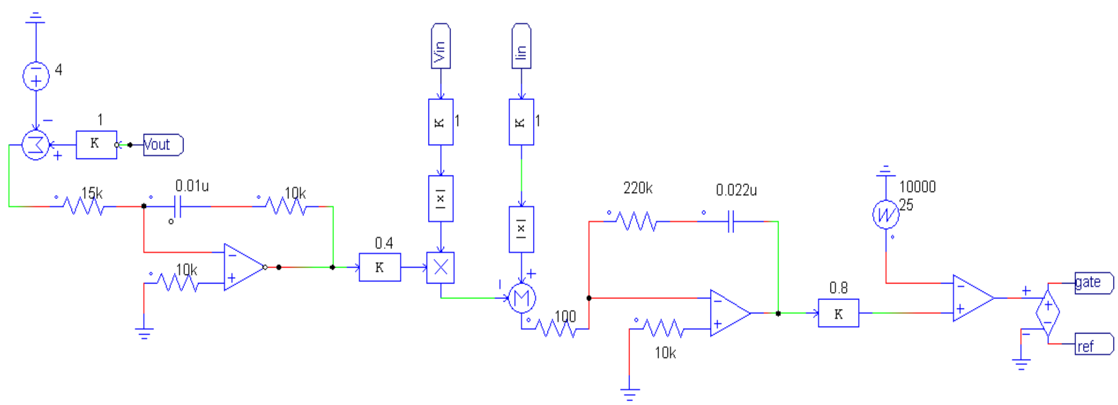
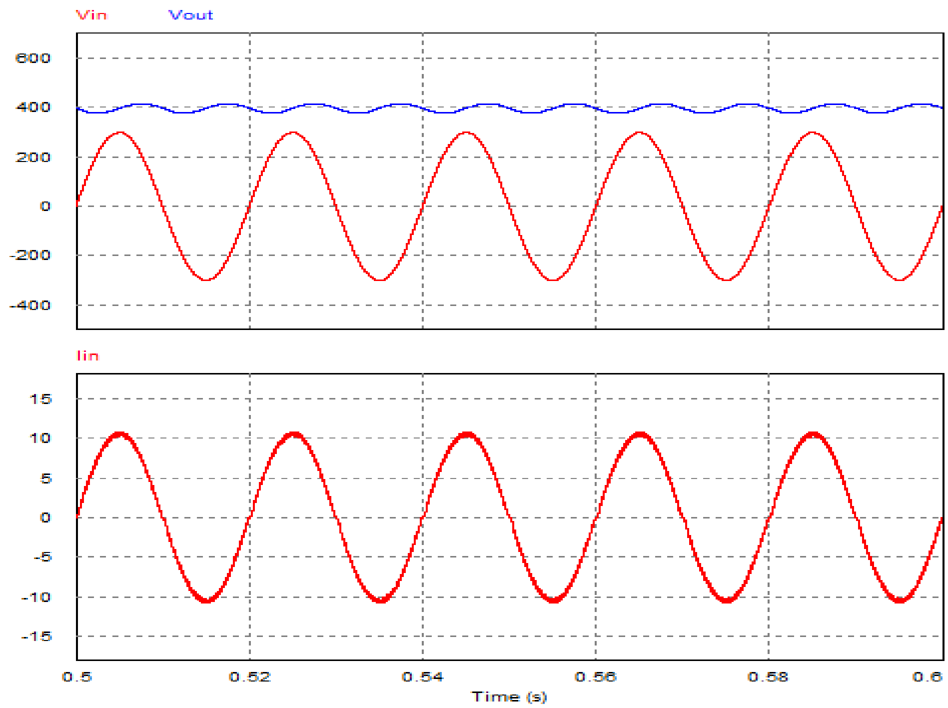
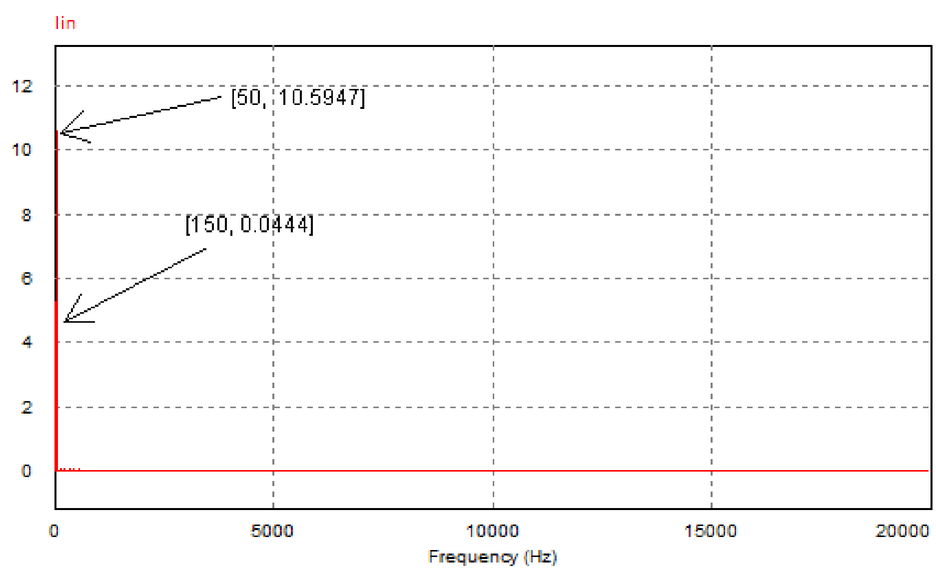


Figure 4.9: Feedback for Conventional Ĉuk Output AC-DC Converter (Boost Operation)



(a)



(b)

Figure 4.10: (a) Input-output voltage and input current
(b) Spectrum of input current wave shape
(Control voltage set for regulated output voltage of 400V DC)

4.5.2 Proposed Input Switched Single Phase $\hat{C}$uk Topology Based Rectifier With PFC Controller-Output Diode Bridge Configuration

Proposed input switched $\hat{C}$uk topology based single phase power factor corrected (PFC) rectifier of output bridge configuration is shown in Figure 4.11. Feedbacks are taken from input voltage (which may also be taken from rectifier output), output voltage and input current (which may also be taken from the inductor after the rectifier).

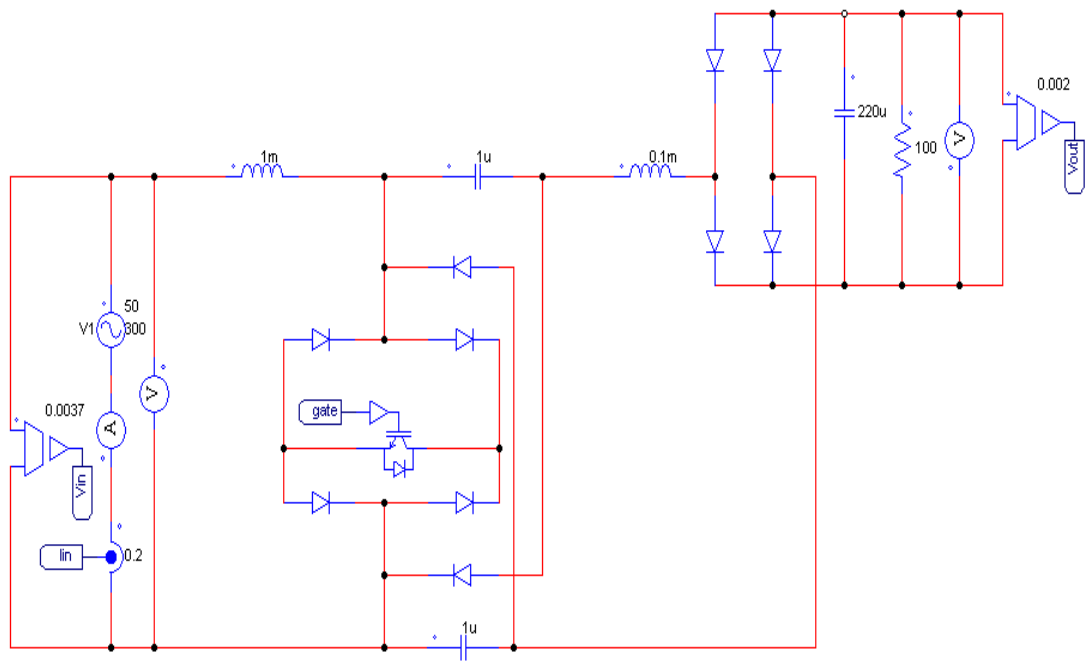


Figure 4.11: Proposed Input Switched $\hat{C}$uk Topology based AC-DC converter – Output Diode Bridge Configuration

Buck Operation

Proposed Input Switched $\hat{C}$uk Topology based AC-DC converter – Bridge Configuration has both buck and boost gain characteristics. The control pulse of the switch of the converter for buck operation is produced by the control circuit as shown in Figure 4.12. The typical results of which are shown from Figure 4.13. Figure 4.13 (a) and (b) show the input/output voltages, input current and the input current spectrum. Input power factor is reasonably high and the input current total harmonic distortion is considerably low (less than 10 percent).

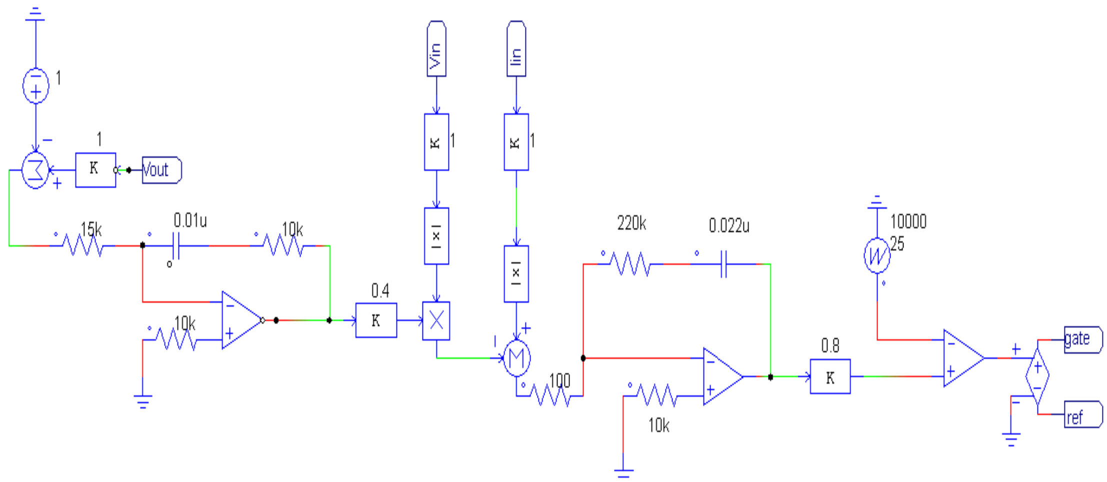
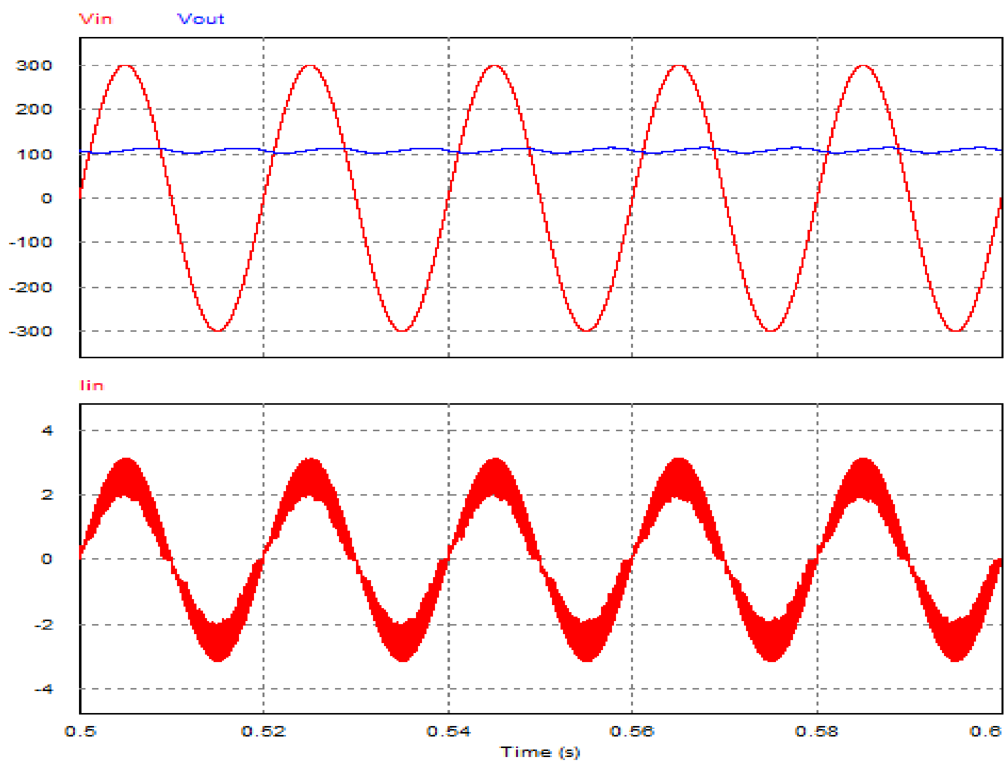


Figure 4.12: Feedback Circuit for Proposed Input Switched $\hat{C}$uk Topology based AC-DC converter – Output Diode Bridge Configuration



(a)

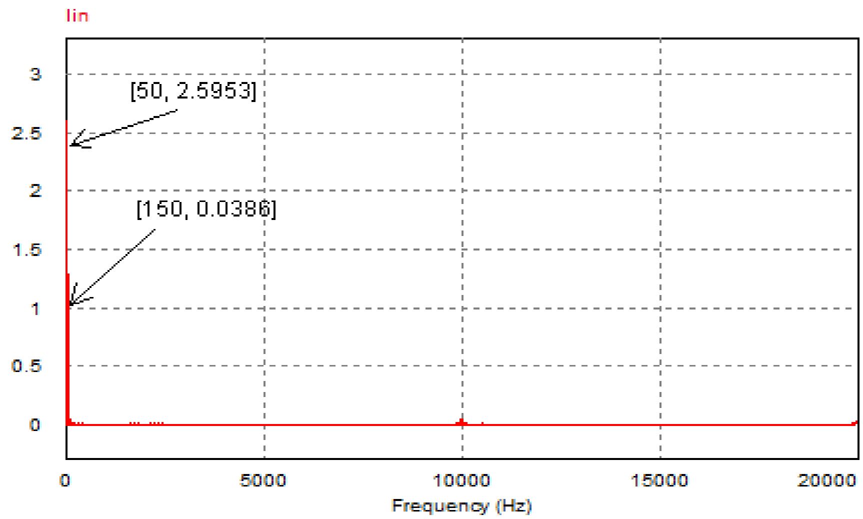


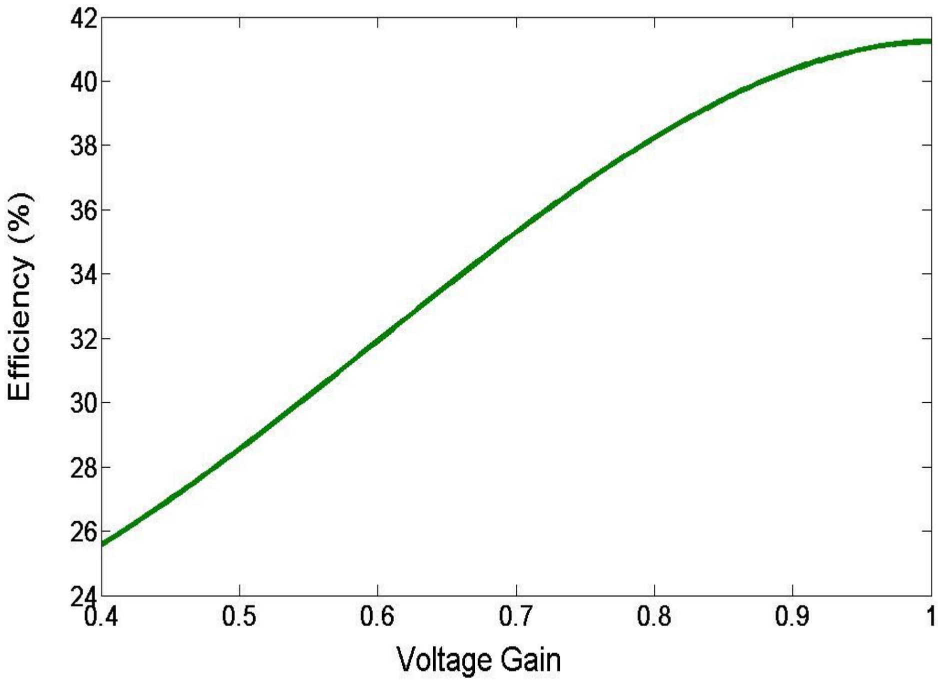
Figure 4.13: (a) Input-output voltage and input current
(b) Spectrum of input current wave shape
(Control voltage set for regulated output voltage of 110V DC)

In this subsection, the power and controller circuit with feedbacks are designed for buck operation of the converter. Table 4.2 shows that for voltage gain between 0.42 and 0.98, the power factor of the circuit remains above 0.9925 and input current THD is below 15 percent. However, the efficiency is too low compared to Conventional output switched $\hat{C}$uk topology based AC-DC converter. Variation of Efficiency, THD and power factor with respect to voltage gain are shown in Figure 4.14 (a), (b) and (c). Simulated results indicate the ability of the circuit of voltage regulation maintaining the good power factor and input current THD of the rectifier but provides lower efficiency.

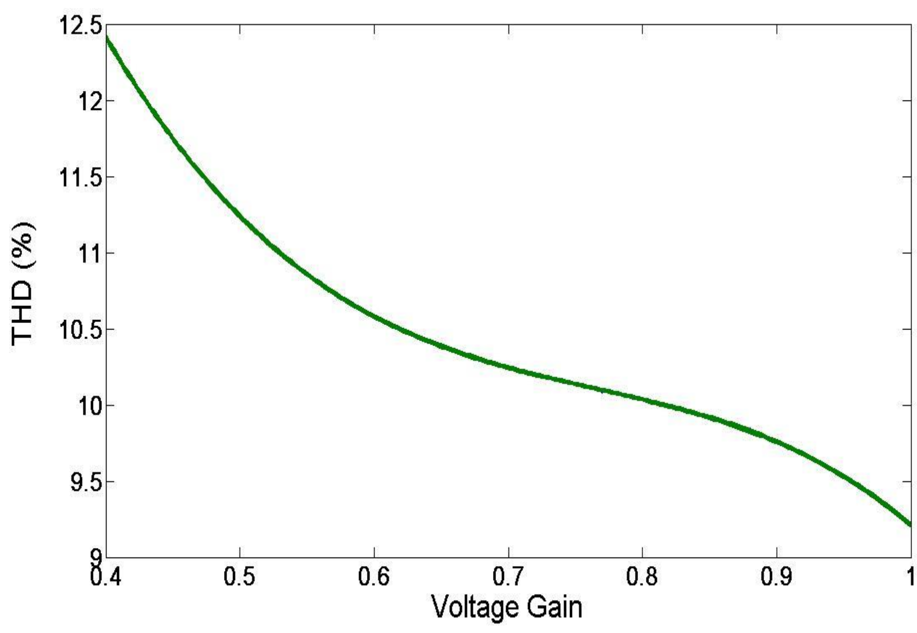
Performance of the proposed circuit shown above is listed in the Table 4.2.

Table 4.2: Performance of input switched single phase $\hat{C}$uk converter –Output Diode Bridge configuration operating as buck converter

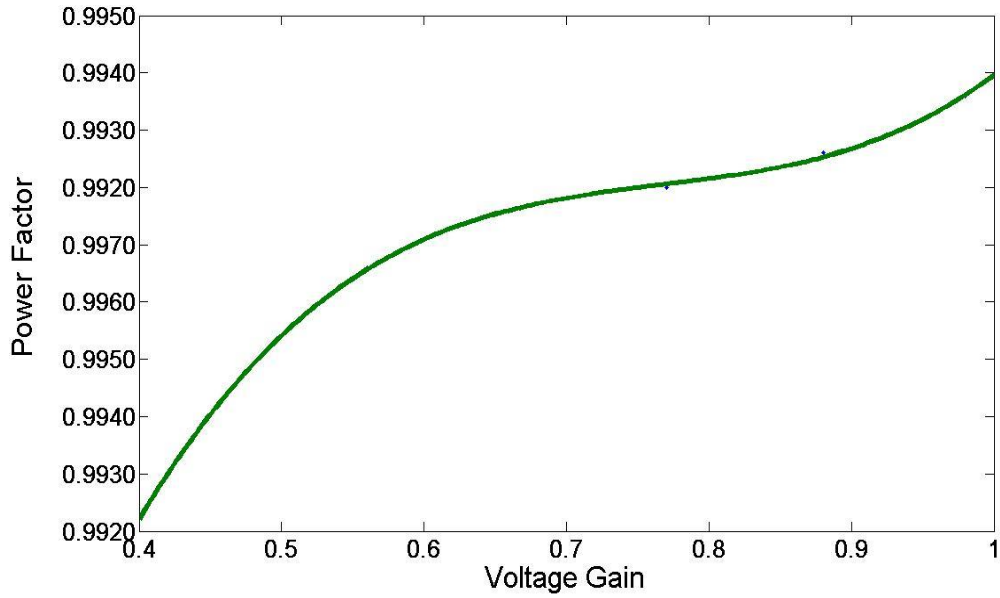
Vin	Vout	Gain	Efficiency (%)	THD(%)	PF
212	88.92	0.42	26.14	12.13	0.9925
212	119.75	0.56	30.57	10.80	0.9943
212	164.06	0.77	37.44	10.09	0.9950
212	187.8	0.88	40.04	9.84	0.9953
212	207.5	0.98	41.2	9.35	0.9958


42
40
38
36
34
32
30
28
26
24
Efficiency (%)
0.4
0.5
0.6
0.7
0.8
0.9
1
Voltage Gain

(a)


12.5
12
11.5
11
10.5
10
9.5
9
THD (%)
0.4
0.5
0.6
0.7
0.8
0.9
1
Voltage Gain

(b)



(c)

Figure 4.14: Input switched single phase $\hat{C}$uk AC-DC Converter –Output Diode Bridge configuration operating as buck converter (a) Efficiency, (b) THD and (c) power factor

Boost Operation:

The control pulse of the switch of the converter for boost operation is produced by the control circuit as shown in Figure 4.15. The typical results of which are shown from Figure 4.16. Figure 4.16 (a) and (b) show the input/output voltages, input current and the input current spectrum. Input power factor is reasonably high and the input current total harmonic distortion is considerably low (less than 10 percent).

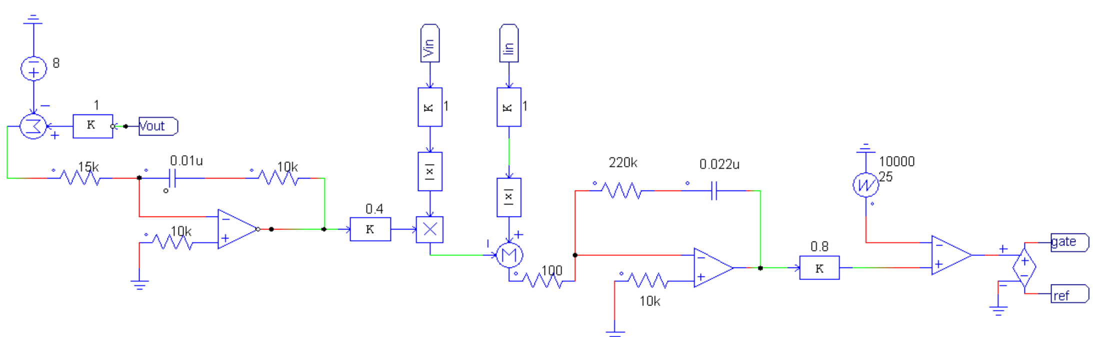
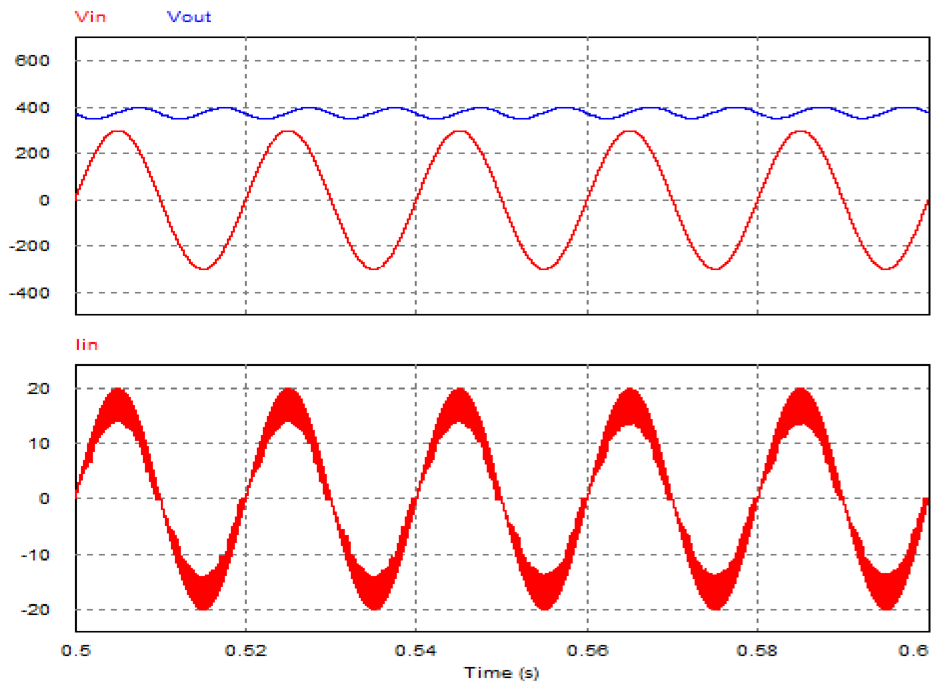
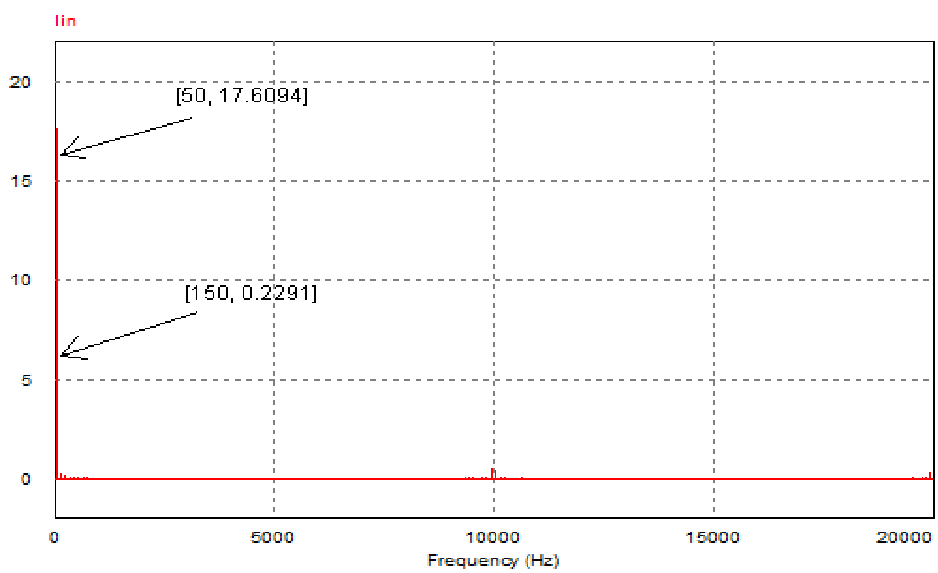


Figure 4.15: Feedback Circuit for Proposed Input Switched $\hat{C}$uk Topology based AC-DC converter- Output Diode Bridge Configuration (Boost Operation)



(a)



(b)

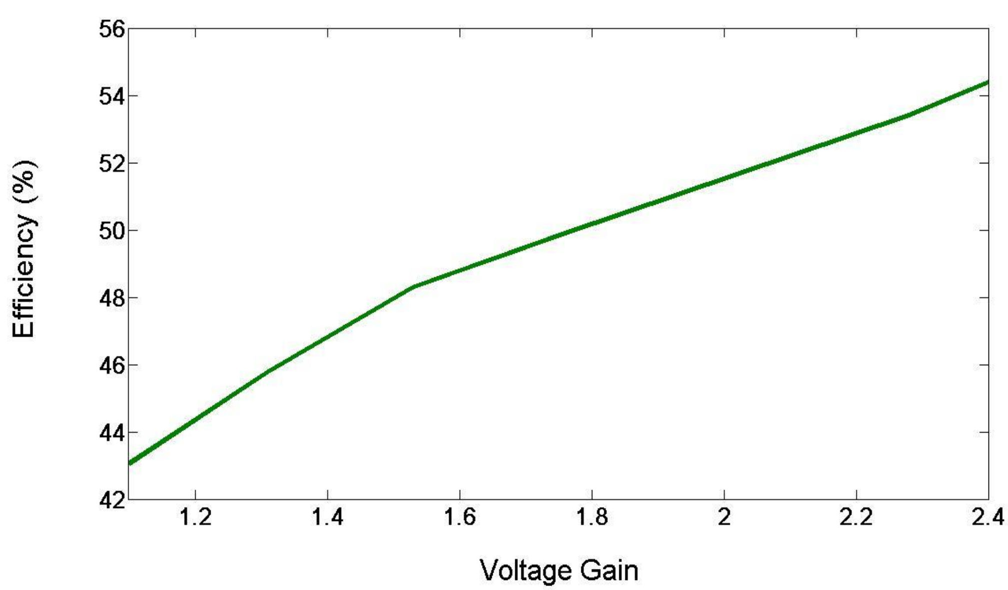
Figure 4.16: (a) Input-output voltage and input current
(b) Spectrum of input current wave shape
(Control voltage set for regulated output voltage of 400V DC)

In this subsection, the power and controller circuit with feedbacks are designed for boost operation of the converter. Table 4.3 shows that for voltage gain between 1.07 and 2.43, the power factor of the circuit remains above 0.9959 and input current THD is below 10 percent. However, the efficiency is low compared to Conventional output switched $\hat{C}$uk topology based AC-DC converter. Variation of Efficiency, THD and power factor with respect to voltage gain are shown in Figure 4.17 (a), (b) and (c). Simulated results indicate the ability of the circuit of voltage regulation maintaining the good power factor and input current THD of the rectifier but provides lower efficiency.

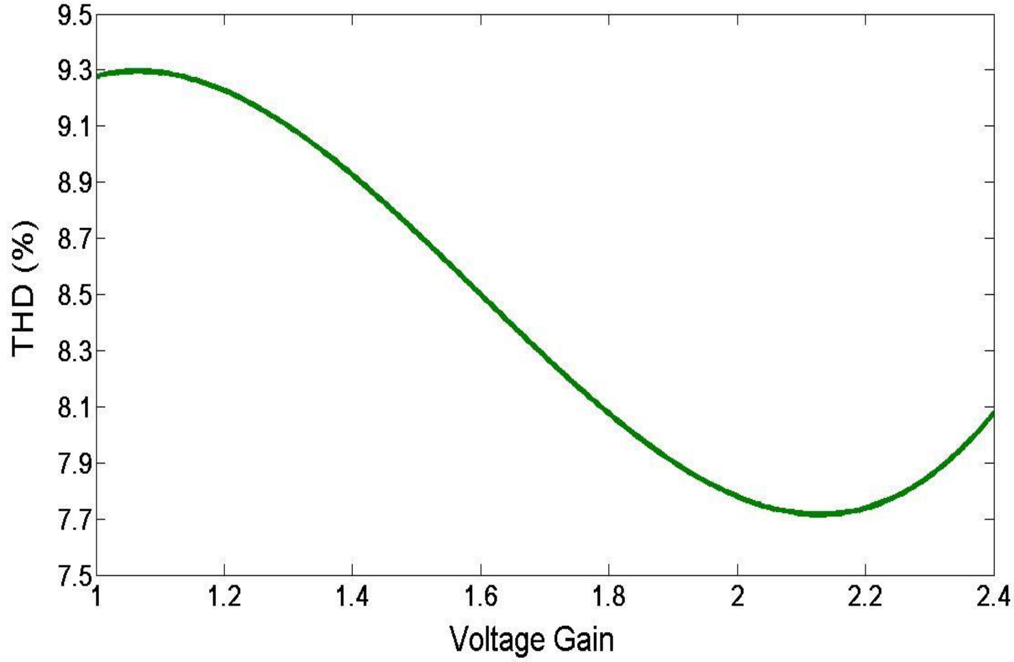
Performance of the proposed circuit shown above is listed in the Table 4.3.

Table 4.3: Performance of input switched single phase $\widehat{C}$uk converter – Output Diode Bridge configuration operating as boost converter

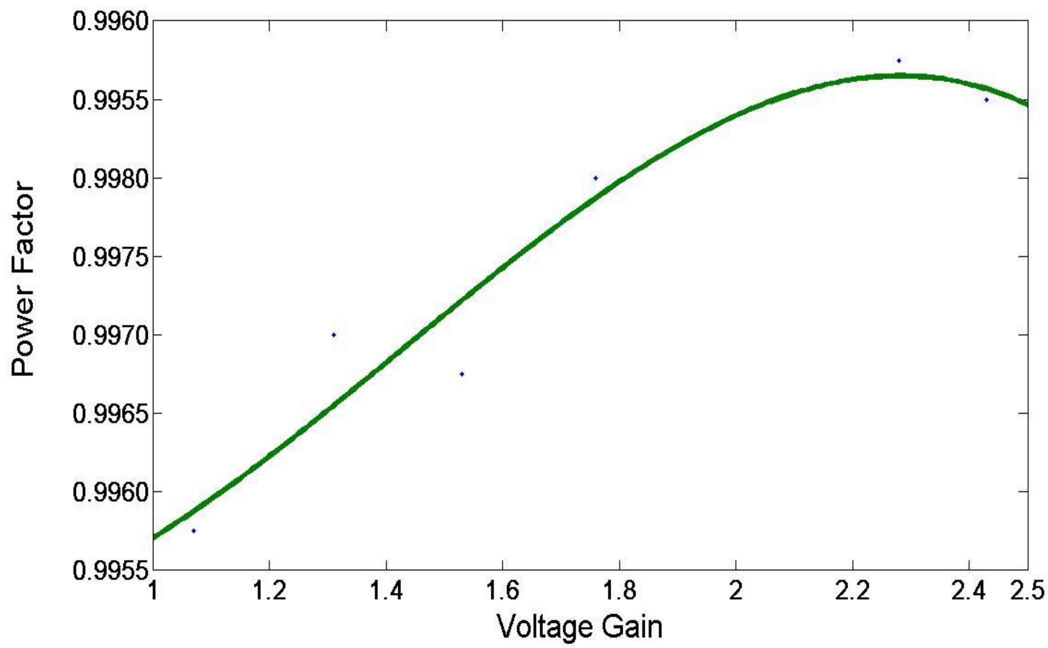
Vin	Vout	Gain	Efficiency (%)	THD (%)	PF
212	226.85	1.07	42.67	9.42	0.9959
212	278.25	1.31	45.78	8.68	0.9964
212	323.3	1.53	48.3	9.04	0.9963
212	374.5	1.76	49.9	8.10	0.9968
212	484.7	2.28	53.4	7.69	0.9971
212	514.8	2.43	54.64	8.26	0.9970



(a)



(b)

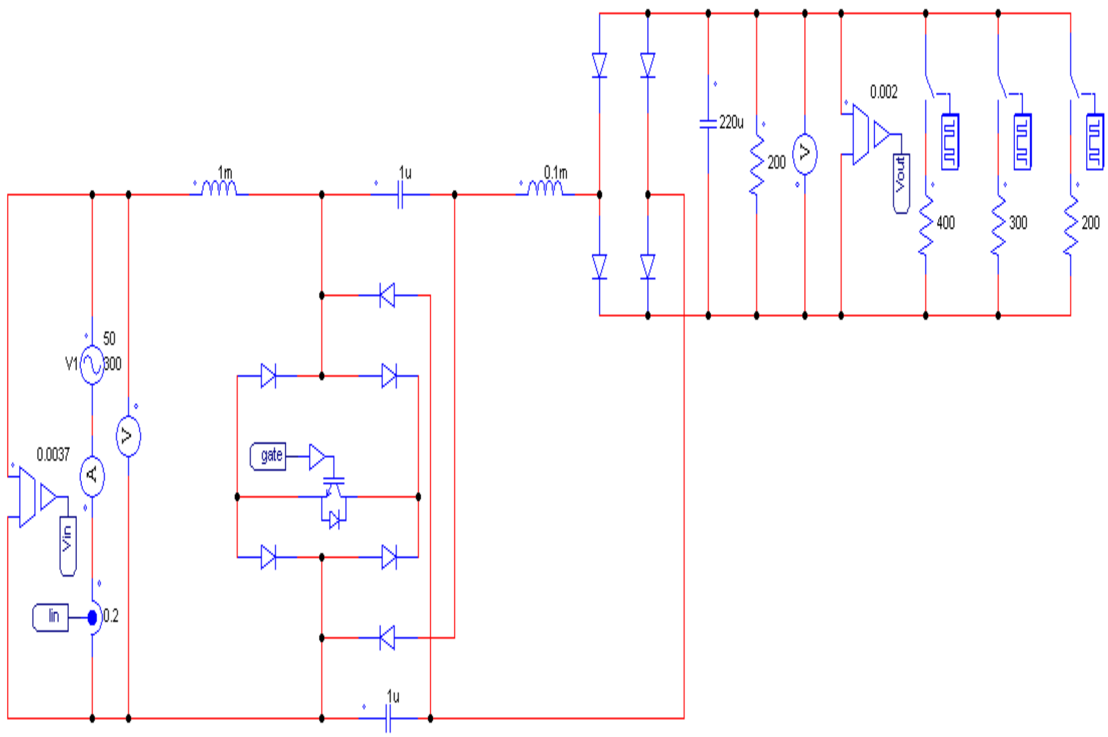


(c)

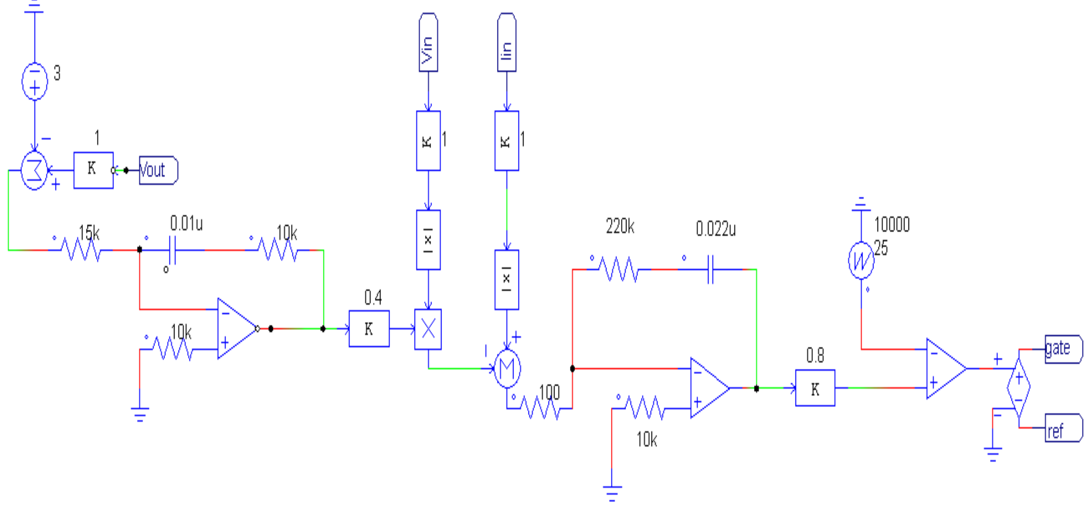
Figure 4.17: Input switched single phase $\hat{C}$uk AC-DC Converter – Output Diode Bridge configuration operating as boost converter (a) Efficiency, (b) THD and (c) power factor

Load Regulation:

Figure 4.18 shows Proposed Input Switched Single Phase $\widehat{C}$uk Topology Based Rectifier - Bridge Configuration with PFC controller and dynamic load variation capability. Initially load resistance was 100Ω. After 500msec the value of load resistance is reduced to 80Ω. From 1000msec to 1833msec the value of load resistance is increased to 100Ω again. After 1833msc the load resistance is increased to 120Ω. It is observed from the response in Fig. 4.19 (a) that though load is varied, output voltage adjusts to its original setting. Dynamic response of the circuit to regulate the output voltage load variation and change of input current are shown in Figure 4.19 (a) and (b) respectively.

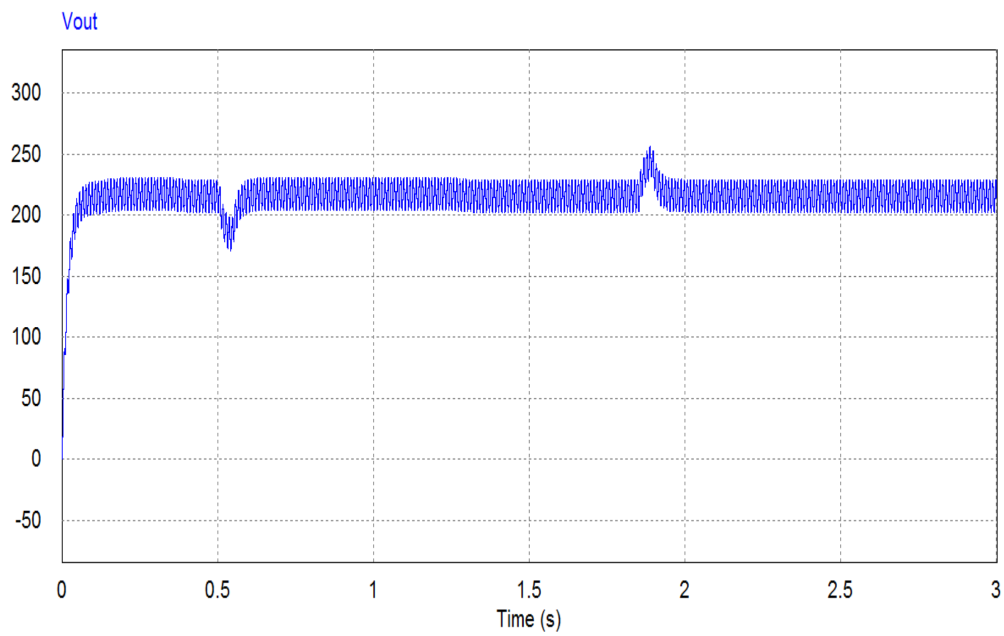


(a)

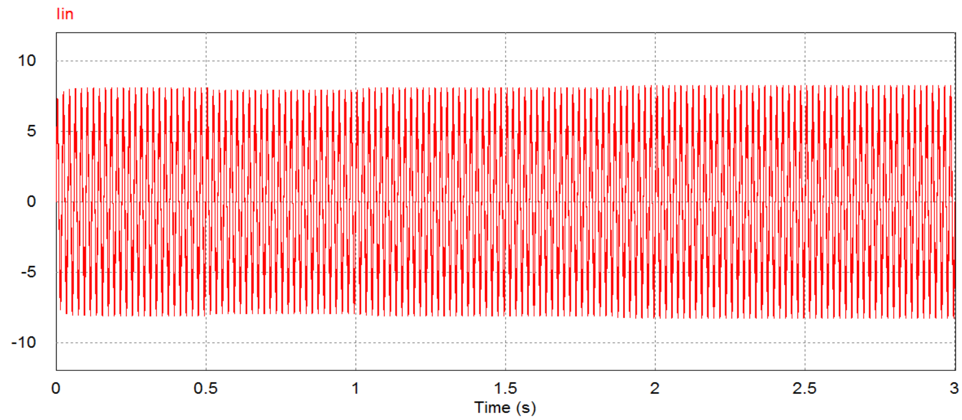


(b)

Figure 4.18: Proposed Input Switched Single Phase $\widehat{C}$uk Topology Based Rectifier – Output Diode Bridge Configuration with (a) Dynamic Load Variation (b) and PFC controller



(a)



(b)

Figure 4.19: (a) Dynamic response of output voltage with load variation
(b) Dynamic response of input current with load variation
(Load variation ± 20% of 100Ω at 0.5, 1 and 1.833 seconds)

4.5.3 Proposed Input Switched Single Phase $\hat{C}$uk Topology Based Rectifier With PFC Controller- Output Half Diode Bridge Configuration

Proposed input switched $\hat{C}$uk topology based single phase power factor corrected (PFC) rectifier of output bridgeless configuration is shown in Figure 4.20. Feedbacks are taken from input voltage (which may also be taken from rectifier output), output voltage and input current (which may also be taken from the inductor after the rectifier).

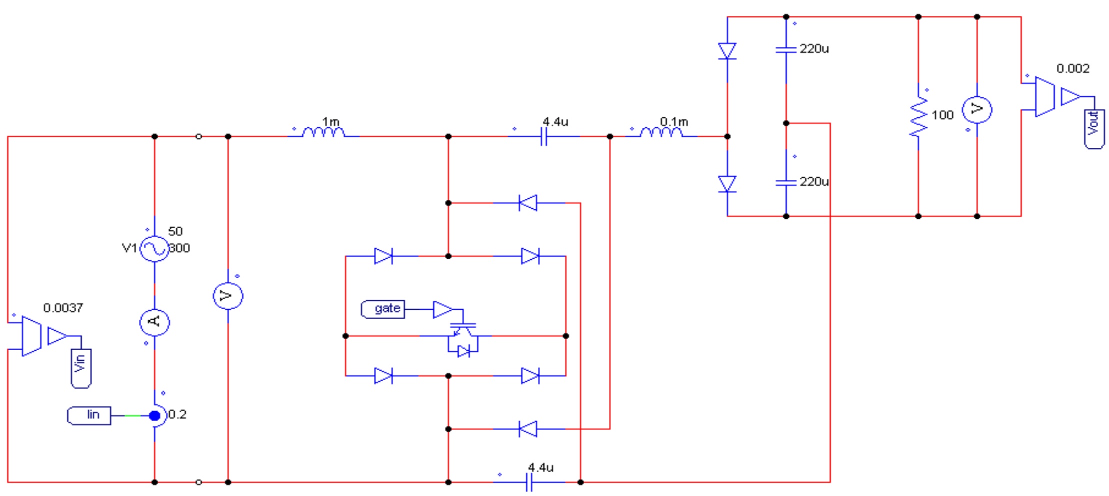


Figure 4.20: Proposed Input Switched Single Phase $\hat{C}$uk Topology Based AC-DC Converter- Output Half Diode Bridge Configuration

Buck Operation:

Proposed Input Switched Single Phase $\hat{C}$uk Topology based AC-DC converter – Bridgeless Configuration has both buck and boost gain characteristics. The control pulse of the switch of the converter for buck operation is produced by the control circuit as shown in Figure 4.21. The typical results of which are shown from Figure 4.22. Figure 4.22 (a) and (b) show the input/output voltages, input current and the input current spectrum. Input power factor is reasonably high and the input current total harmonic distortion is considerably low (less than 10 percent).

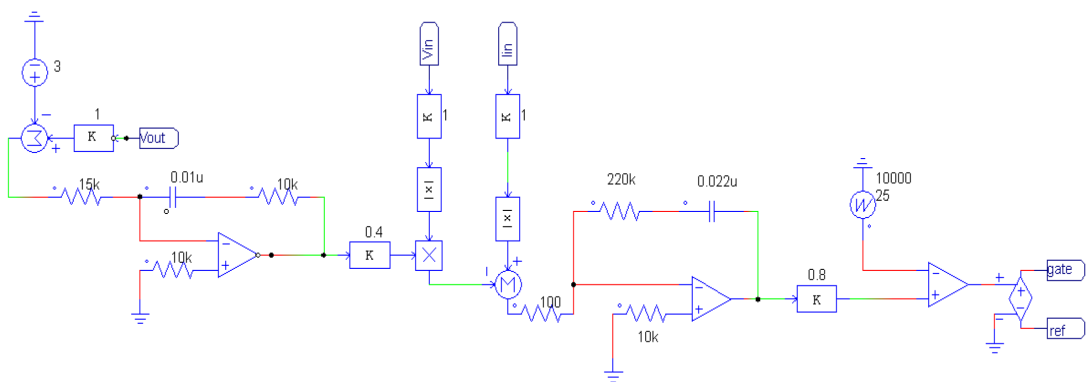
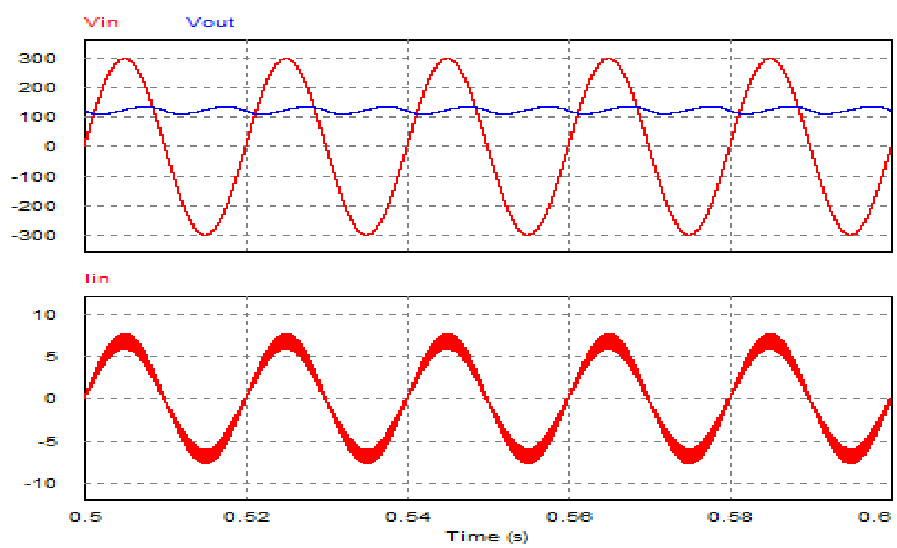
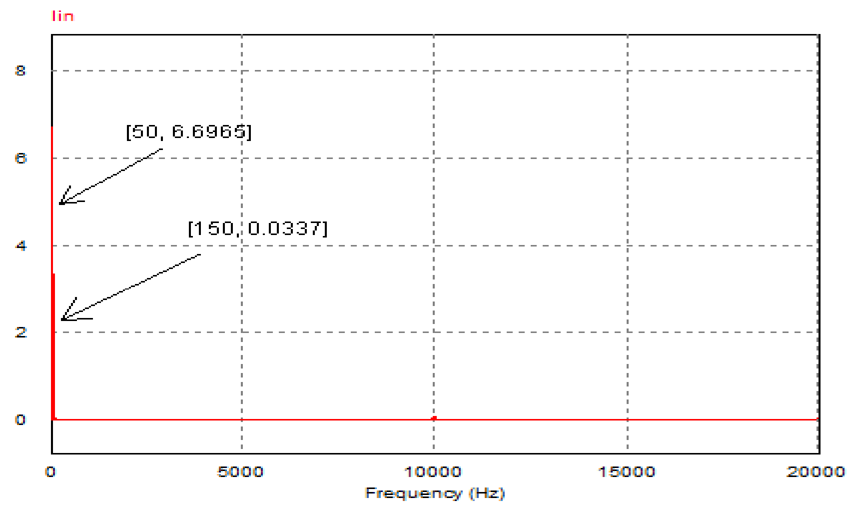


Figure 4.21: Feedback Circuit for Proposed Input Switched Single Phase $\hat{C}$uk Topology Based AC-DC Converter- Output Half Diode Bridge Configuration (Buck Operation)



(a)



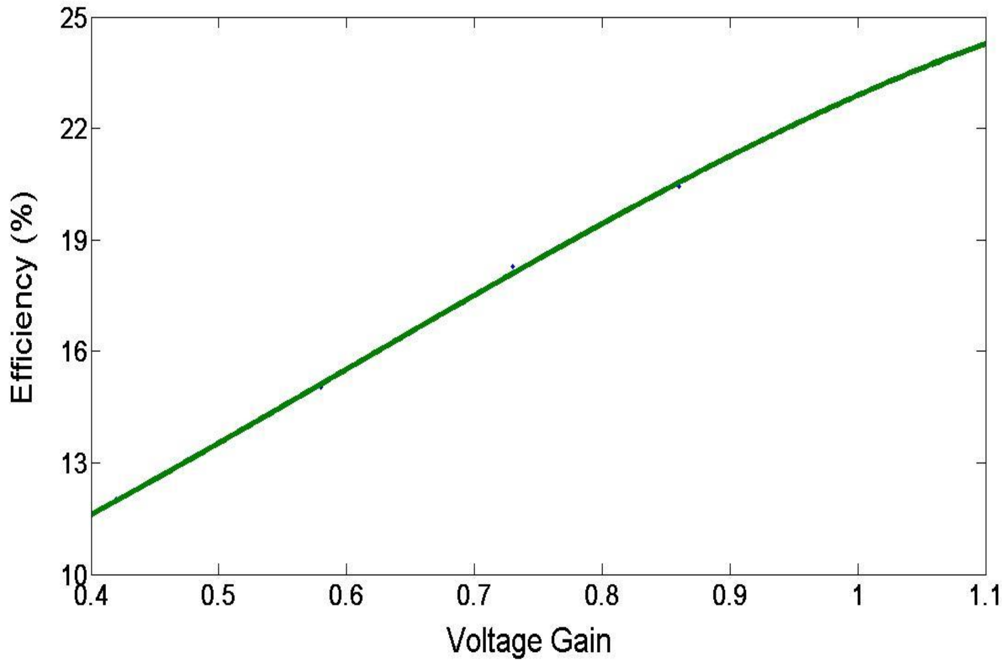
(b)
Figure 4.22: (a) Input-output voltage and input current
(b) Spectrum of input current wave shape
(Control voltage set for regulated output voltage of 125V DC)

In this subsection, the power and controller circuit with feedbacks are designed for buck operation of the converter. Table 4.4 shows that for voltage gain between 0.42 and 1.01, the power factor of the circuit remains above 0.9963 and input current THD is below 10 percent. However, the efficiency is low compared to conventional single phase output switched $\hat{C}$uk rectifier. Typical input/output voltages, input current waveform and the spectrum of input current of the circuit is shown in Figure 4.23. Simulated results indicate the ability of the circuit of voltage regulation maintaining the good power factor and input current THD of the rectifier but low efficiency.

Performance of the proposed circuit shown above is listed in the Table 4.4.

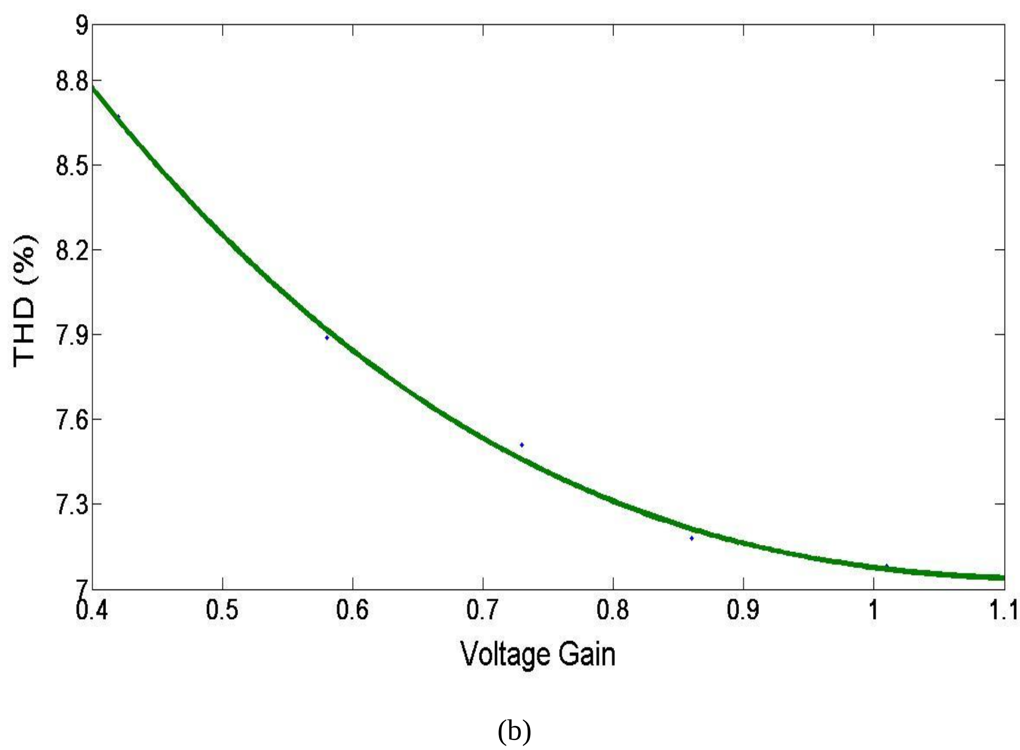
Table 4.4: Performance of input switched single phase $\widehat{C}$uk converter – Output Half Diode Bridge configuration operating as buck converter

Vin	Vout	Gain	Efficiency (%)	THD (%)	PF
212	90.56	0.42	12.02	8.67	0.9963
212	122.89	0.58	15.04	7.89	0.9969
212	155.8	0.73	18.27	7.51	0.9973
212	183.6	0.86	20.44	7.18	0.9975
212	213.18	1.01	23.07	7.08	0.9976



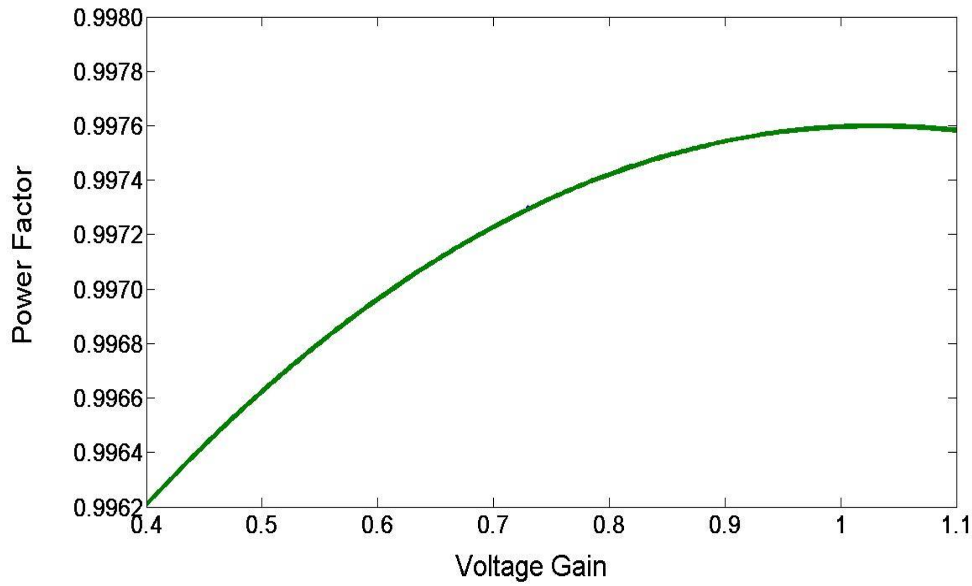
Efficiency (%)
25
22
19
16
13
10
0.4
0.5
0.6
0.7
0.8
0.9
1
1.1
Voltage Gain

(a)



THD (%)
9
8.8
8.5
8.2
7.9
7.6
7.3
7
0.4
0.5
0.6
0.7
0.8
0.9
1
1.1
Voltage Gain

(b)



(c)

Figure 4.23: Input switched single phase $\hat{C}$uk AC-DC Converter – Output Half Diode Bridge configuration operating as buck converter (a) Efficiency, (b) THD and (c) power factor

Boost Operation:

The control pulse of the switch of the converter for boost operation is produced by the control circuit as shown in Figure 4.24. The typical results of which are shown from Figure 4.25. Figure 4.25 (a) and (b) show the input/output voltages, input current and the input current spectrum. Input power factor is reasonably high and the input current total harmonic distortion is considerably low (less than 10 percent).

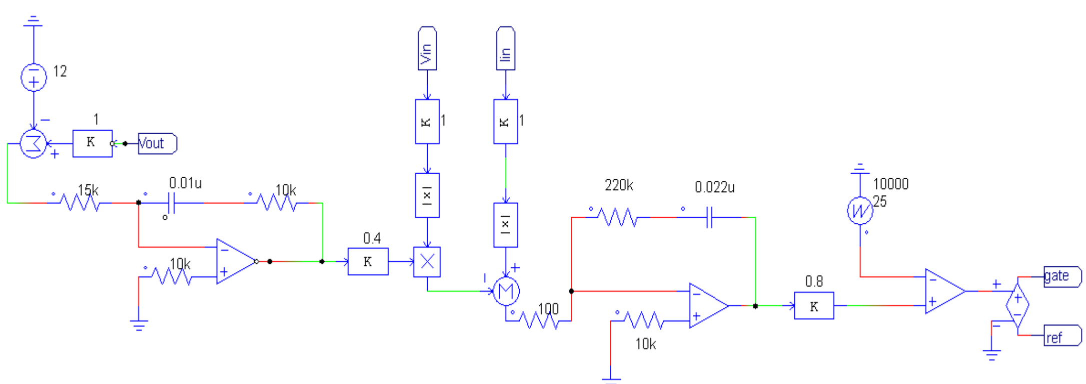
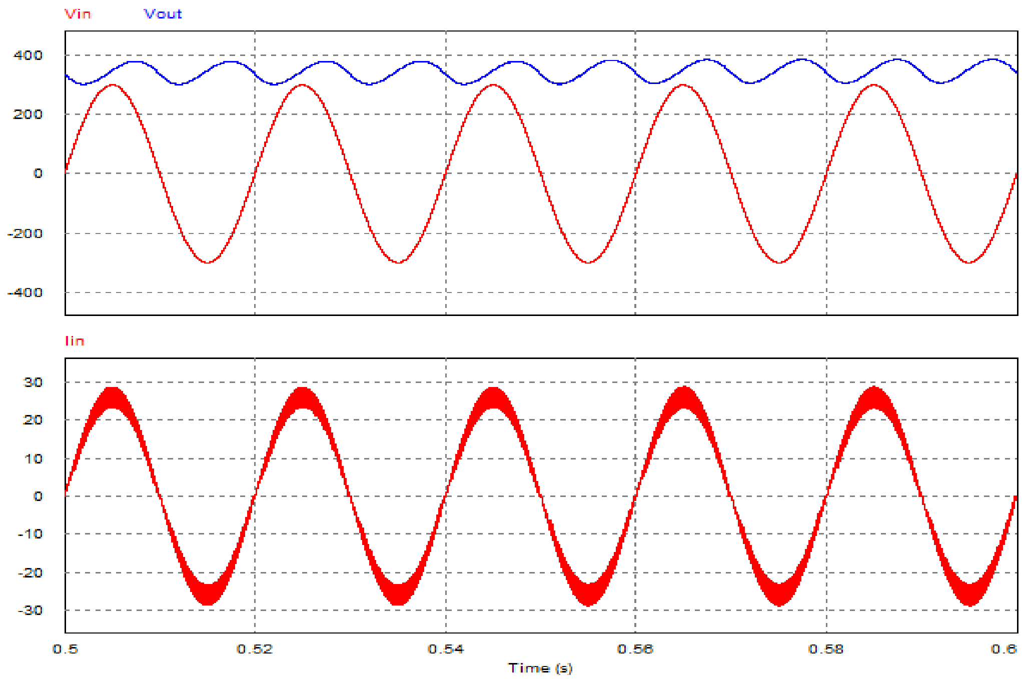
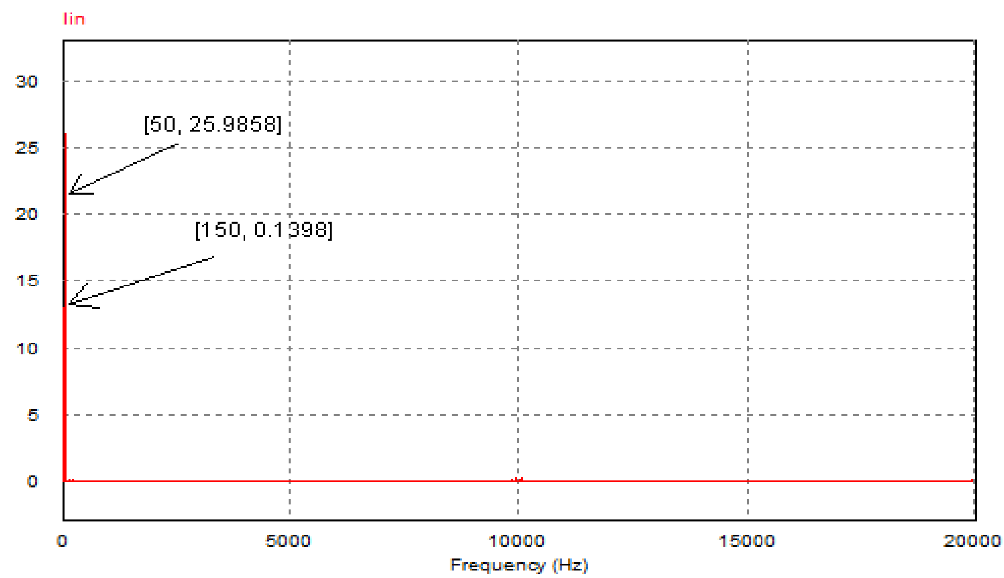


Figure 4.24: Feedback Circuit for Proposed Input Switched Single Phase $\hat{C}$uk Topology Based Rectifier- Output Half Diode Bridge Configuration (Boost Operation)



(a)



(b)

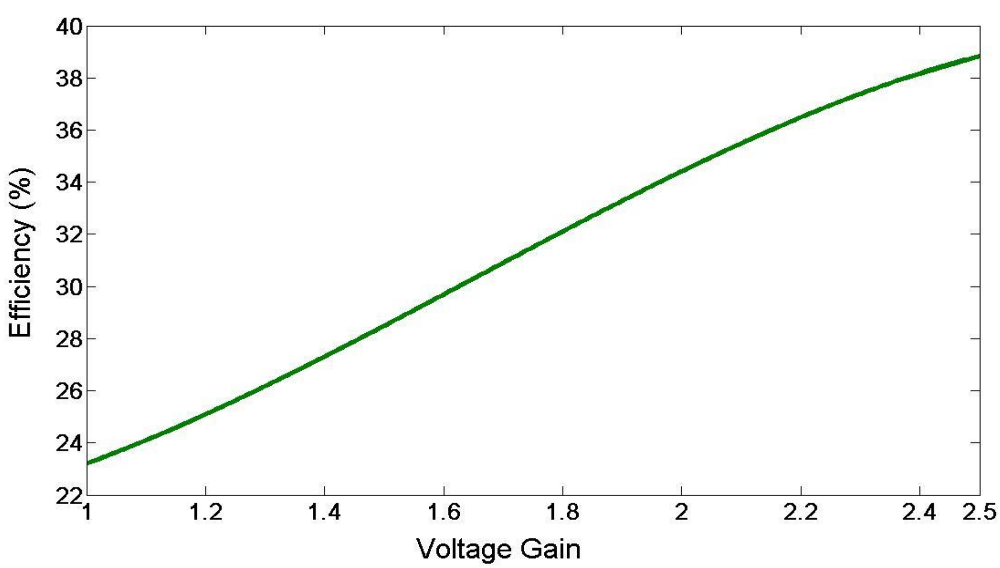
Figure 4.25: (a) Input-output voltage and input current
(b) Spectrum of input current wave shape
(Control voltage set for regulated output voltage of 350V DC)

In this subsection, the power and controller circuit with feedbacks are designed for boost operation of the converter. Table 4.5 shows that for voltage gain between 1.01 and 2.35, the power factor of the circuit remains above 0.9976 and input current THD is below 10 percent. However, the efficiency is low compared to conventional output switched $\hat{C}$uk AC-DC converter. Typical input/output voltages, input current waveform and the spectrum of input current of the circuit is shown in Figure 4.26. Simulated results indicate the ability of the circuit of voltage regulation maintaining the good power factor and input current THD of the rectifier but low efficiency.

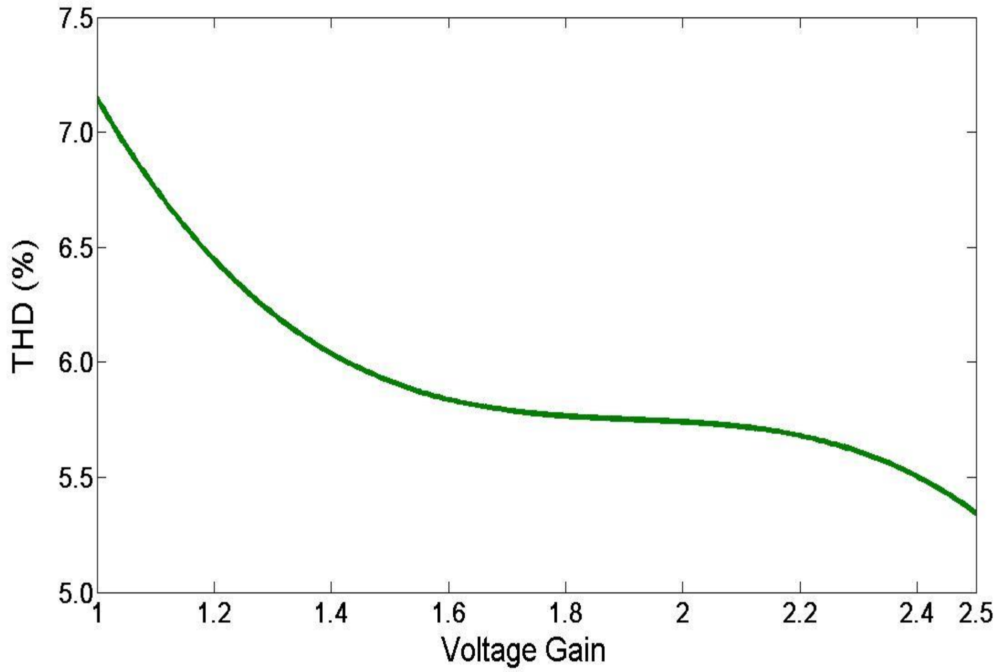
Performance of the proposed circuit shown above is listed in the Table 4.5.

Table 4.5: Performance of input switched single phase $\hat{C}$uk converter – Output Half Diode Bridge configuration operating as boost converter

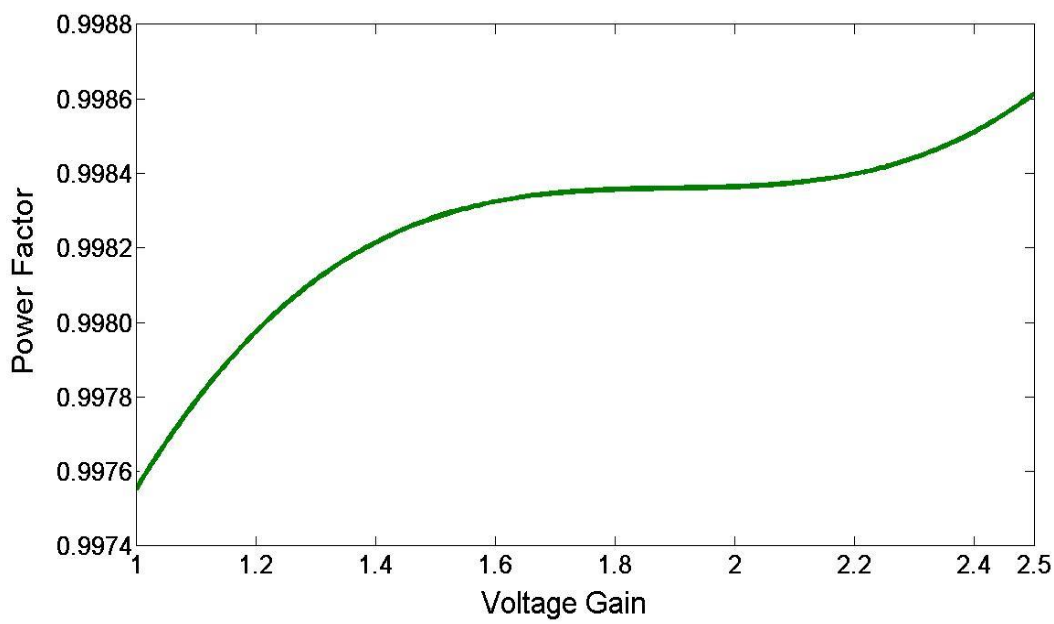
Vin	Vout	Gain	Efficiency (%)	THD (%)	PF
212	213.18	1.01	23.07	7.08	0.9976
212	282.9	1.33	27.23	6.21	0.9981
212	338.9	1.6	29.45	5.92	0.9983
212	394.6	1.86	31.95	5.51	0.9985
212	473.06	2.23	38.49	6.01	0.9982
212	499.5	2.35	36.75	5.36	0.9986



(a)



(b)

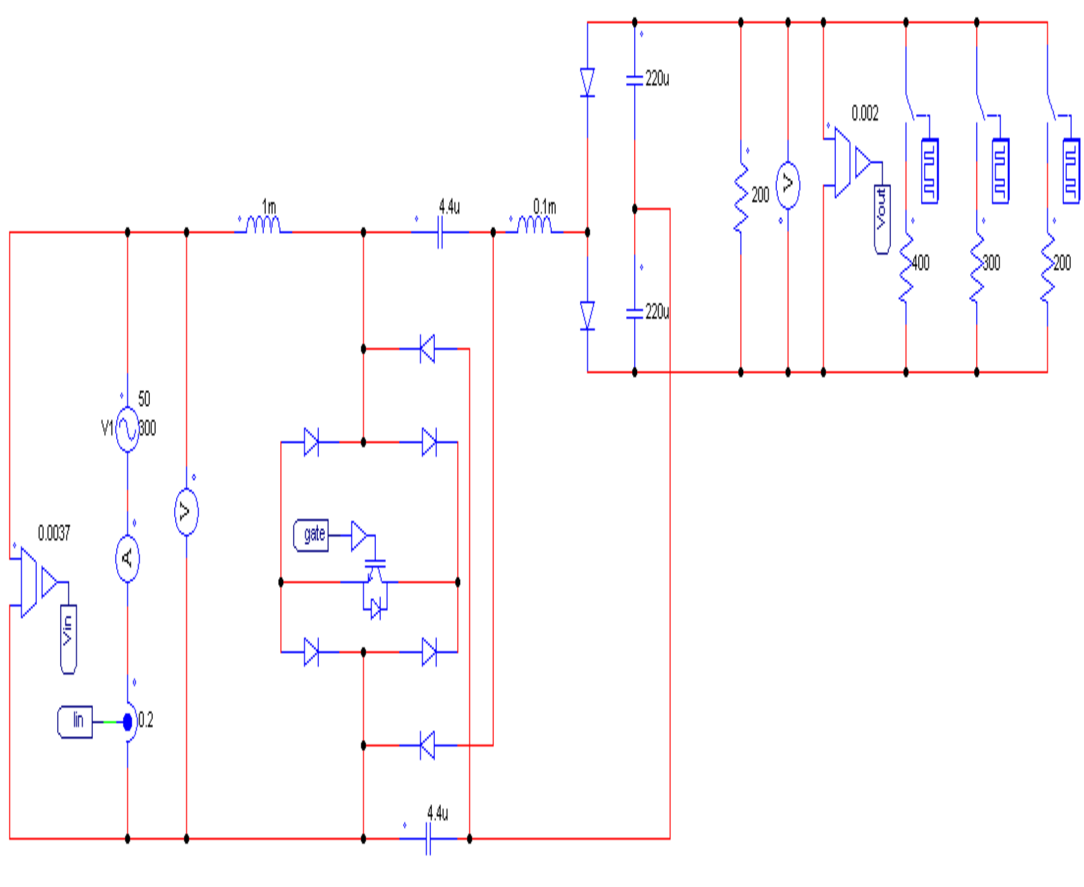


(c)

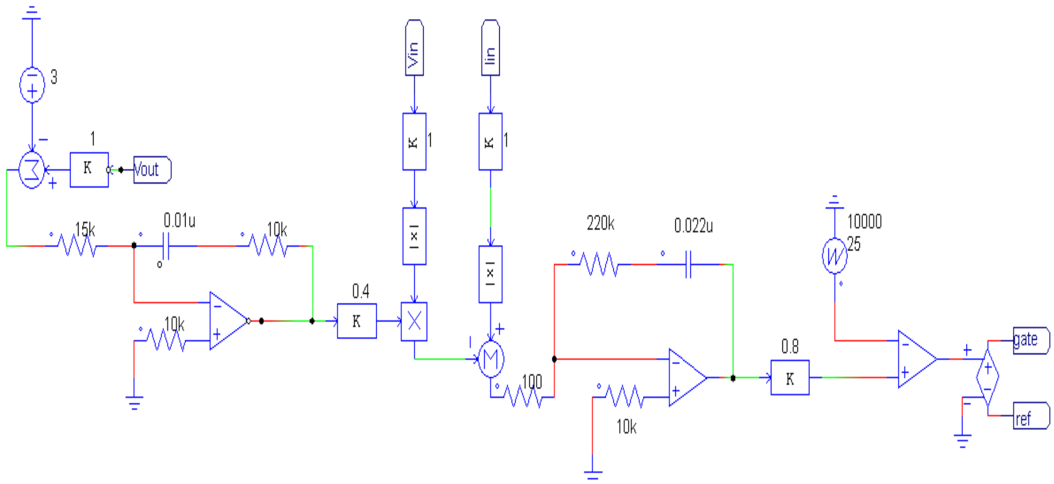
Figure 4.26: Input switched single phase $\hat{C}$uk AC-DC Converter – Output Half Diode Bridge configuration operating as boost converter (a) Efficiency, (b) THD and (c) power factor

Load Regulation:

Figure 4.27 shows Proposed Input Switched Single Phase Ĉuk Topology Based Rectifier - Bridgeless Configuration with PFC controller and dynamic load variation capability. Initially load resistance was 100Ω. After 500msec the value of load resistance is reduced to 80Ω. From 1000msec to 1833msec the value of load resistance is increased to 100Ω again. After 1833msc the load resistance is increased to 120Ω. It is observed from the response in Fig. 4.28 (a) that though load is varied, output voltage adjusts to its original setting. Dynamic response of the circuit to regulate the output voltage load variation and change of input current are shown in Figure 4.28 (a) and (b) respectively.

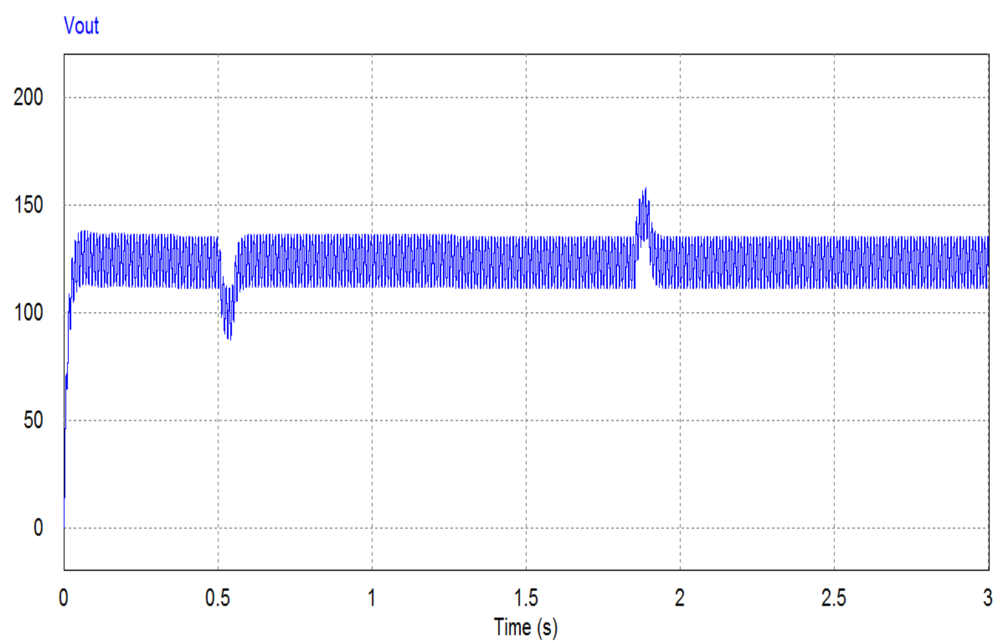


(a)

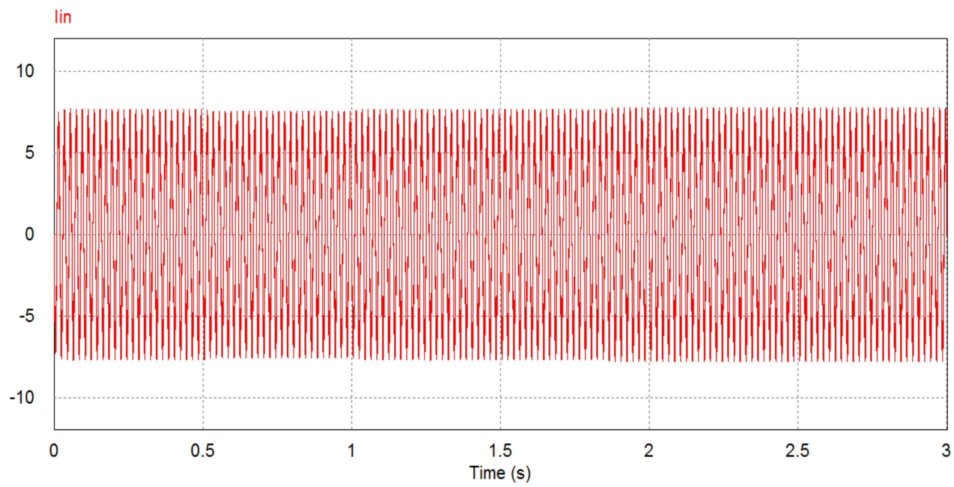


(b)

Figure 4.27: Proposed Input Switched Single Phase $\widehat{C}$uk Topology Based Rectifier – Output Half Diode Bridge Configuration with (a) Dynamic Load Variation (b) and PFC controller



(a)



(b)

Figure 4.28: (a) Dynamic response of output voltage with load variation
(b) Dynamic response of input current with load variation
(Load variation ± 20% of 100Ω at 0.5, 1 and 1.833 seconds)

4.5.4 Proposed Modified Single Phase $\hat{C}$uk Topology Based Rectifier With PFC Controller- Configuration-1

Proposed Modified Single Phase $\hat{C}$uk Topology Based Rectifier With PFC Controller-Configuration-1 is shown in Figure 4.29. Feedbacks are taken from input voltage (which may also be taken from rectifier output), output voltage and input current (which may also be taken from the inductor after the rectifier).

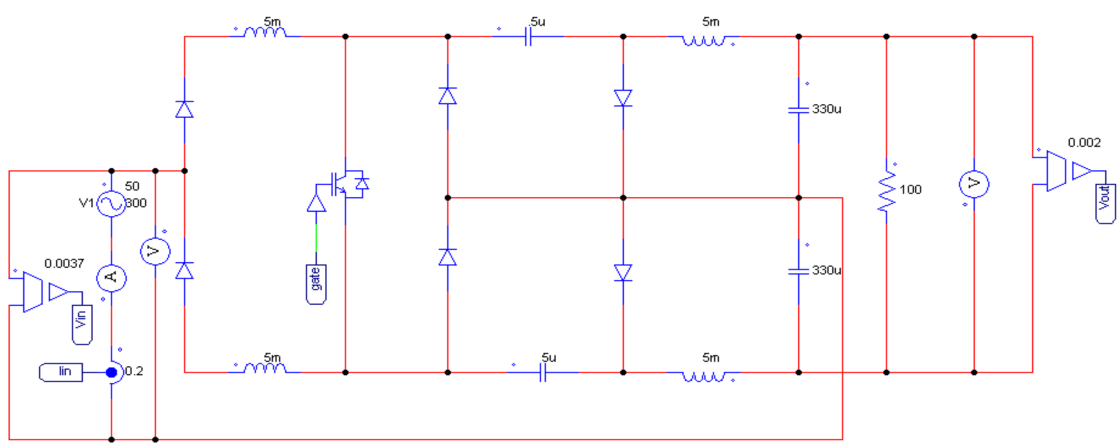


Figure 4.29: Proposed Modified Single Phase $\hat{C}$uk Topology Based Rectifier Configuration-1

Buck Operation

Proposed Modified Single Phase $\hat{C}$uk Topology Based Rectifier Configuration-1 has both buck and boost gain characteristics. The control pulse of the switch of the converter for buck operation is produced by the control circuit as shown in Figure 4.30. The typical results of which are shown from Figure 4.31. Figure 4.31 (a) and (b) show the input/output voltages, input current and the input current spectrum. Input power factor is reasonably high and the input current total harmonic distortion is considerably low (less than 10 percent).

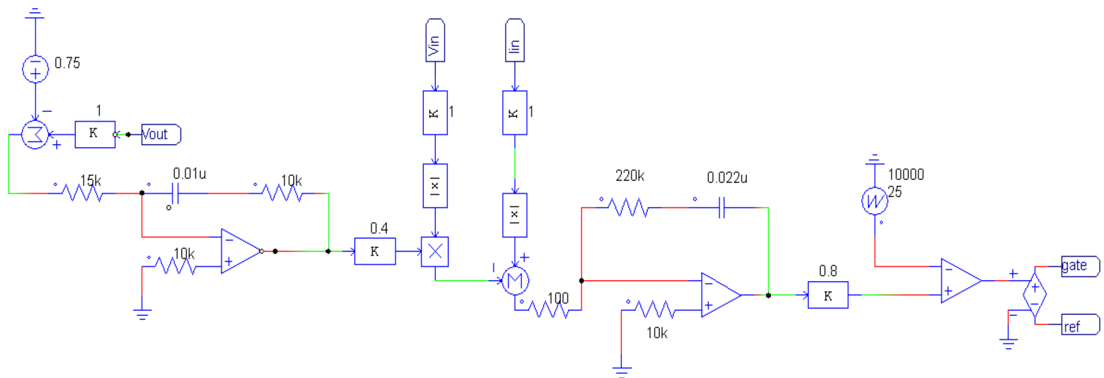
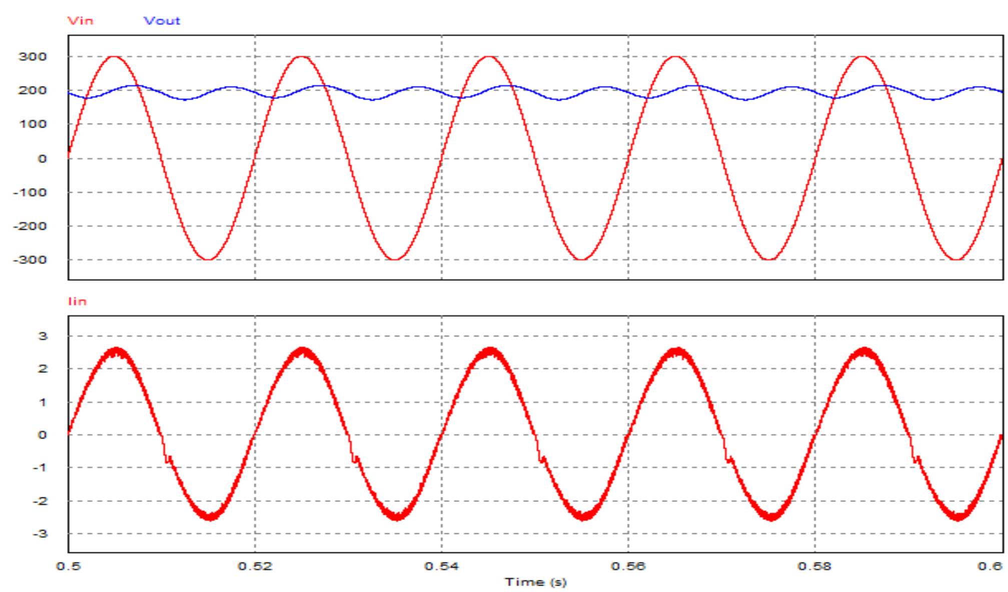
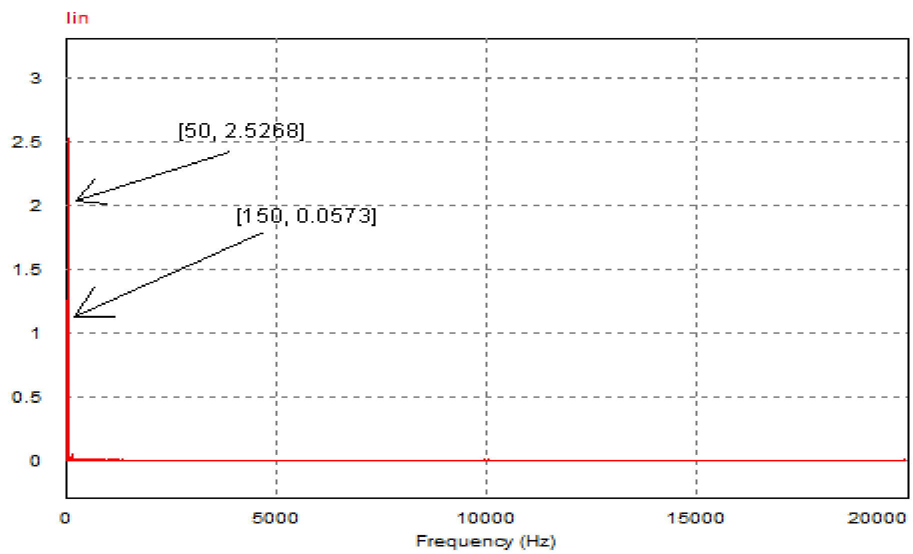


Figure 4.30: Feedback Circuit for Proposed Modified Single Phase $\hat{C}$uk Topology Based Rectifier Configuration-1 (Buck Operation)



(a)



(b)

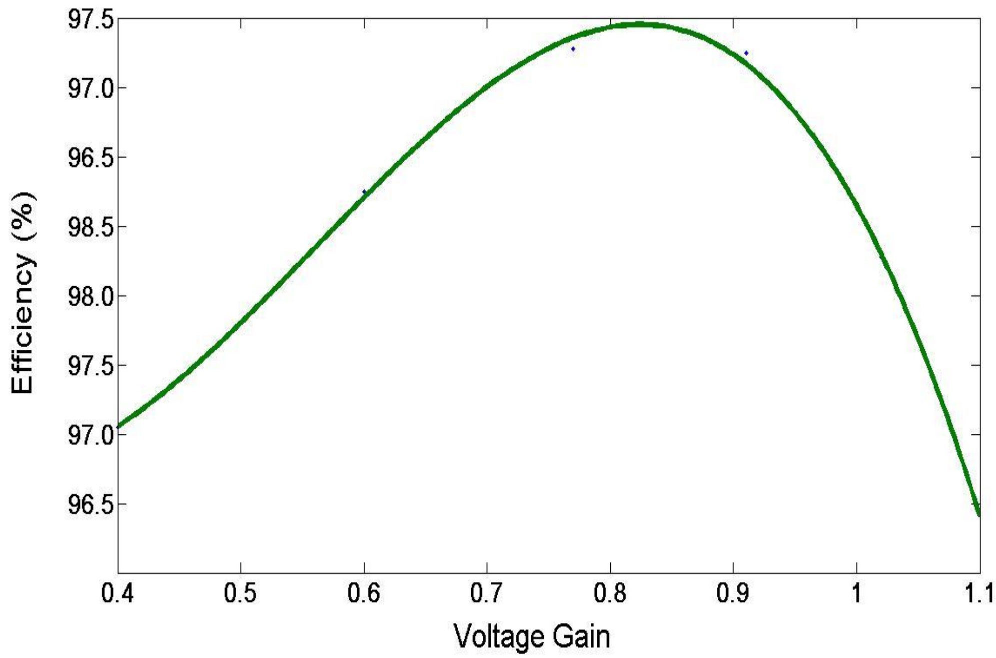
Figure 4.31: (a) Input-output voltage and input current
(b) Spectrum of input current wave shape
(Control voltage set for regulated output voltage of 200V DC)

In this subsection, the power and controller circuit with feedbacks are designed for buck operation of the converter. Table 4.6 shows that for voltage gain from 0.4 to 1.02, the power factor of the circuit remains above 0.9907 and input current THD is below 10 percent and the efficiency is above 97 percent. Typical input/output voltages, input current waveform and the spectrum of input current of the circuit is shown in Figure 4.32. Simulated results indicate the ability of the circuit of voltage regulation maintaining the good power factor and input current THD of the rectifier.

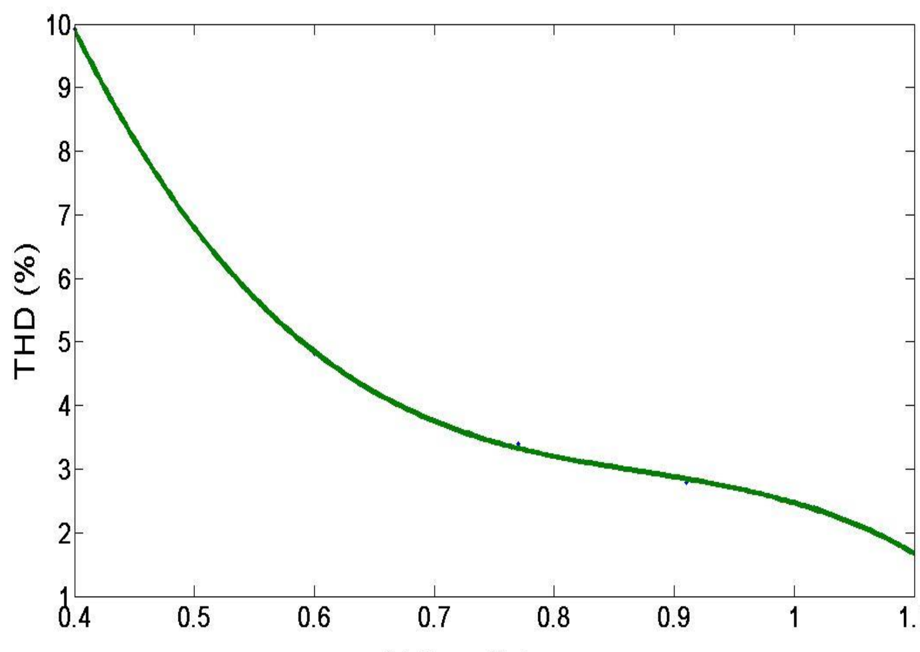
Performance of the proposed circuit shown above is listed in the Table 4.6.

Table 4.6: Performance of Proposed Modified Single Phase $\widehat{C}$uk Topology Based Rectifier Configuration-1 operating as buck converter

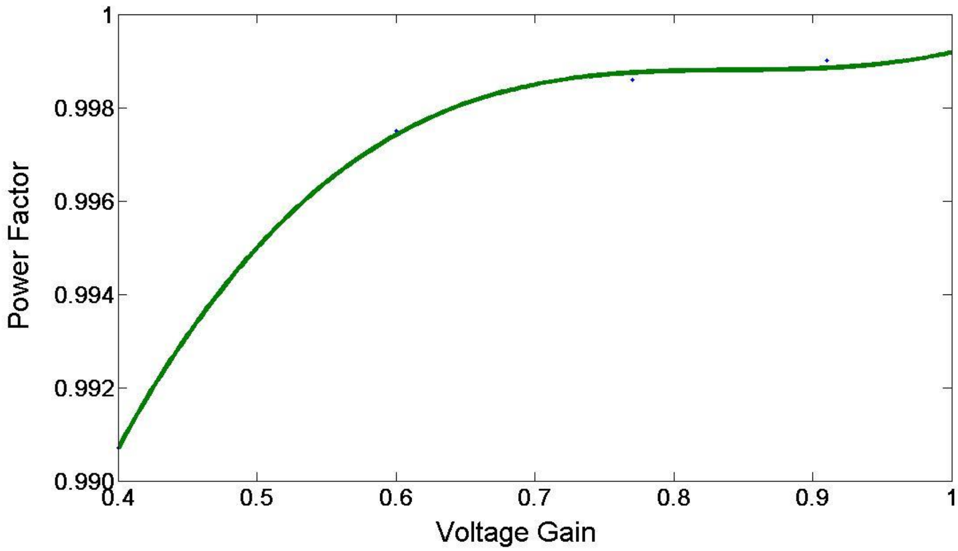
Vin	Vout	Gain	Efficiency (%)	THD (%)	PF
212	84.57	0.4	97.22	9.92	0.9907
212	128.86	0.6	97.90	4.82	0.9975
212	164.6	0.77	98.31	3.4	0.9986
212	192.6	0.91	98.30	2.79	0.9990
212	216.3	1.02	97.71	2.38	0.9993


97.5
97.0
96.5
98.5
98.0
97.5
97.0
96.5
Efficiency (%)
0.4
0.5
0.6
0.7
0.8
0.9
1
1.1
Voltage Gain

(a)


10
9
8
7
6
5
4
3
2
1
THD (%)
0.4
0.5
0.6
0.7
0.8
0.9
1
1.1
Voltage Gain

(b)



(c)

Figure 4.32: Modified single phase $\hat{C}$uk AC-DC Converter configuration-1 operating as buck operation (a) Efficiency, (b) THD and (c) power factor

Boost Operation:

The control pulse of the switch of the converter for boost operation is produced by the control circuit as shown in Figure 4.33. The typical results of which are shown from Figure 4.34. Figure 4.34 (a) and (b) show the input/output voltages, input current and the input current spectrum. Input power factor is reasonably high and the input current total harmonic distortion is considerably low (less than 10 percent).

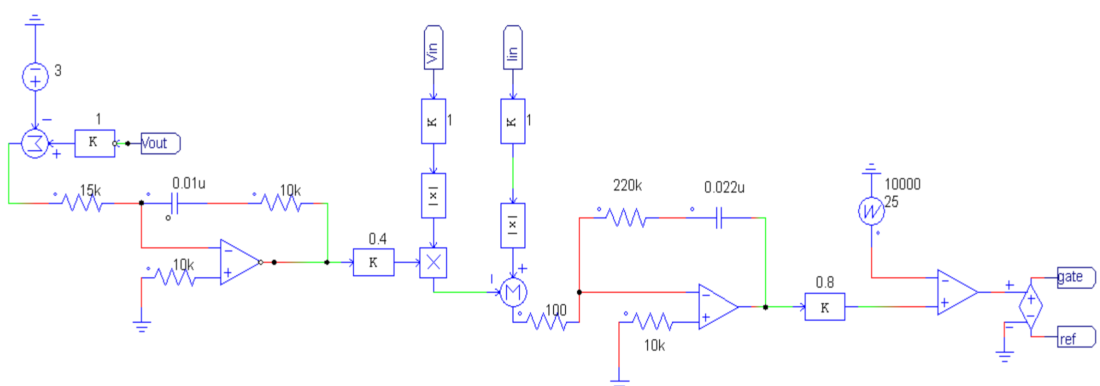
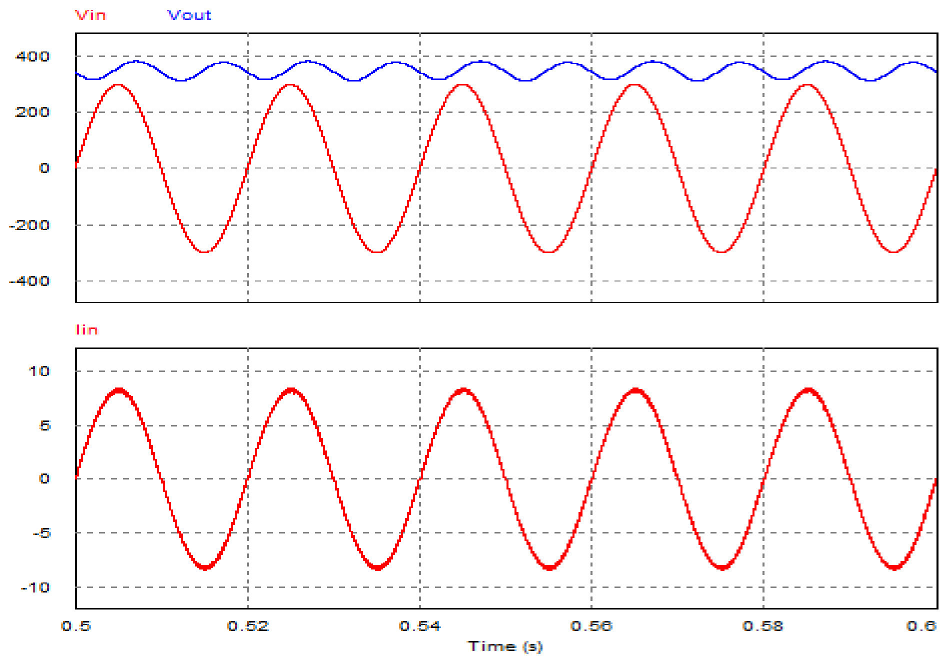
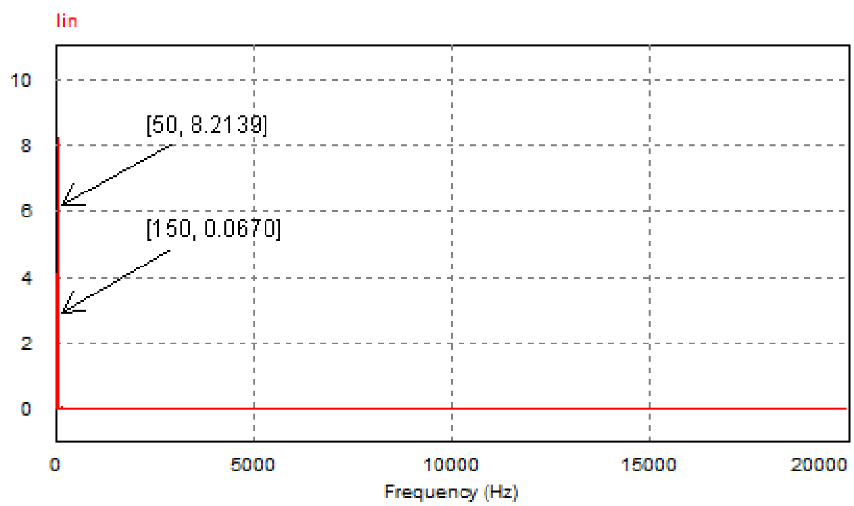


Figure 4.33: Feedback Circuit for Proposed Modified Single Phase $\hat{C}$uk Topology Based Rectifier Configuration-1 (Boost Operation)



(a)



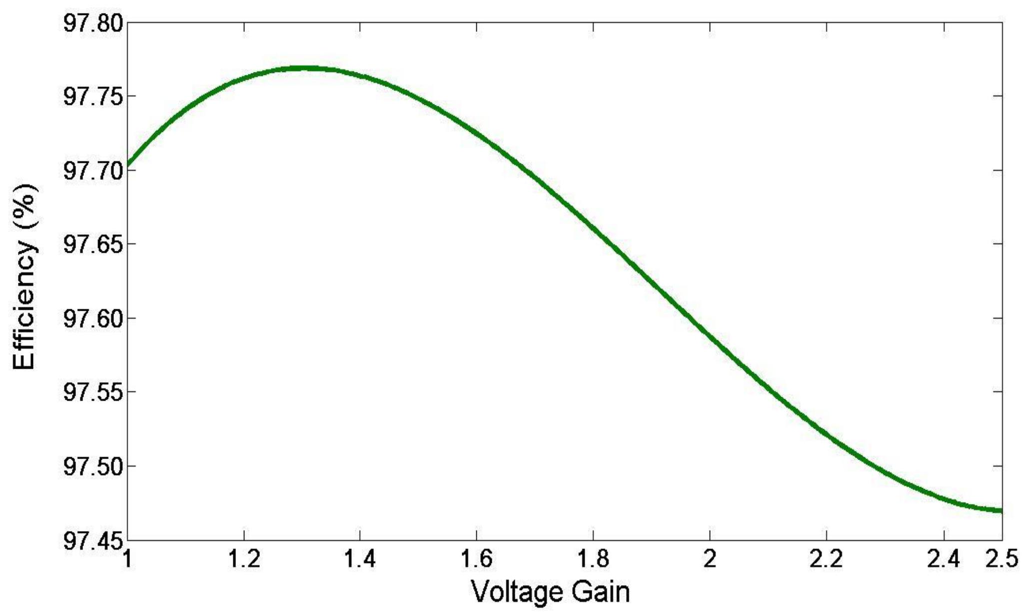
(b)

Figure 4.34: (a) Input-output voltage and input current
(b) Spectrum of input current wave shape
(Control voltage set for regulated output voltage of 350V DC)

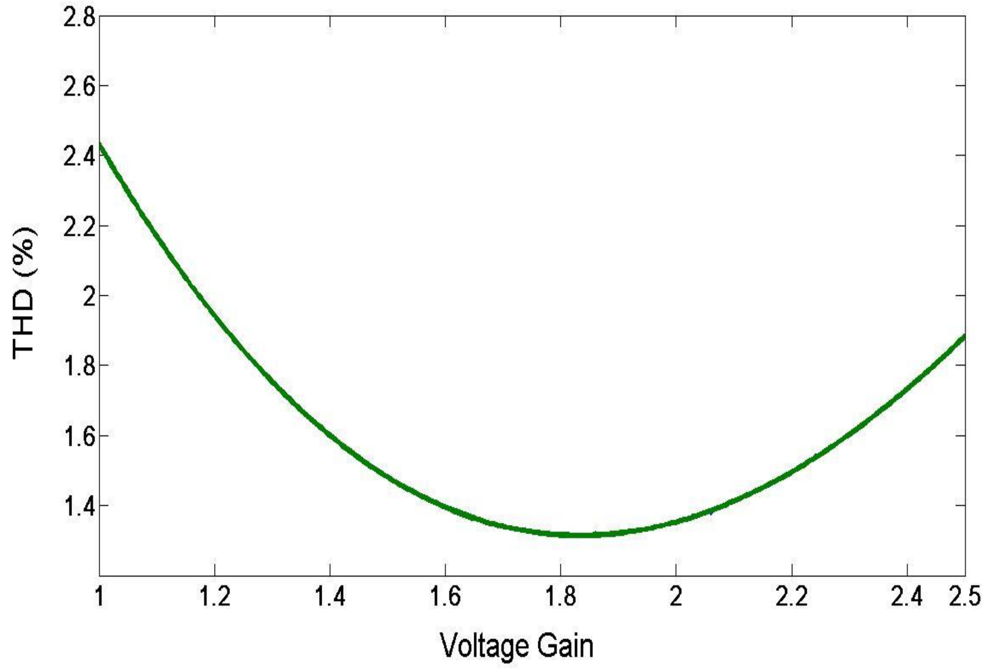
In this subsection, the power and controller circuit with feedbacks are designed for boost operation of the converter. Table 4.7 shows that for voltage gain between 1.02 to 2.24, the power factor of the circuit remains above 0.9993 and input current THD is below 10 percent and the efficiency is above 95 percent. Typical input/output voltages, input current waveform and the spectrum of input current of the circuit is shown in Figure 4.35. Simulated results indicate the ability of the circuit of voltage regulation maintaining the good power factor and input current THD of the rectifier.
Performance of the proposed circuit shown above is listed in the Table 4.7.

Table 4.7: Performance of Modified single phase $\widehat{C}$uk converter -1 configuration operating as boost converter

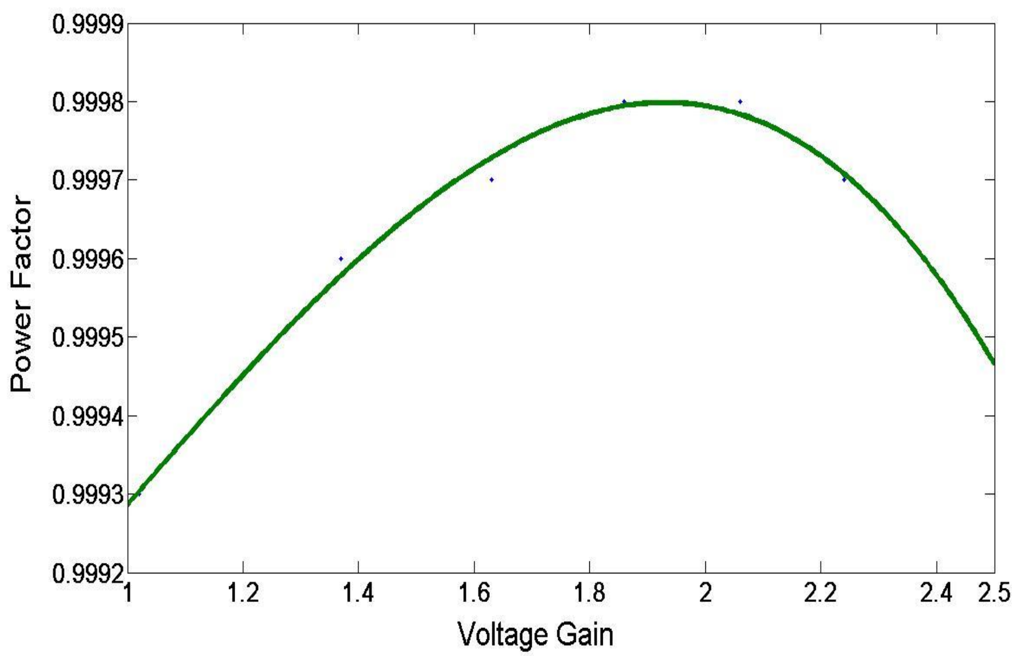
Vin	Vout	Gain	Efficiency (%)	THD (%)	PF
212	216.3	1.02	97.71	2.38	0.9993
212	289.9	1.37	97.78	1.64	0.9996
212	346.6	1.63	97.69	1.38	0.9997
212	394.5	1.86	97.66	1.32	0.9998
212	436.6	2.06	97.56	1.38	0.9998
212	474.7	2.24	97.51	1.54	0.9997



(a)



(b)

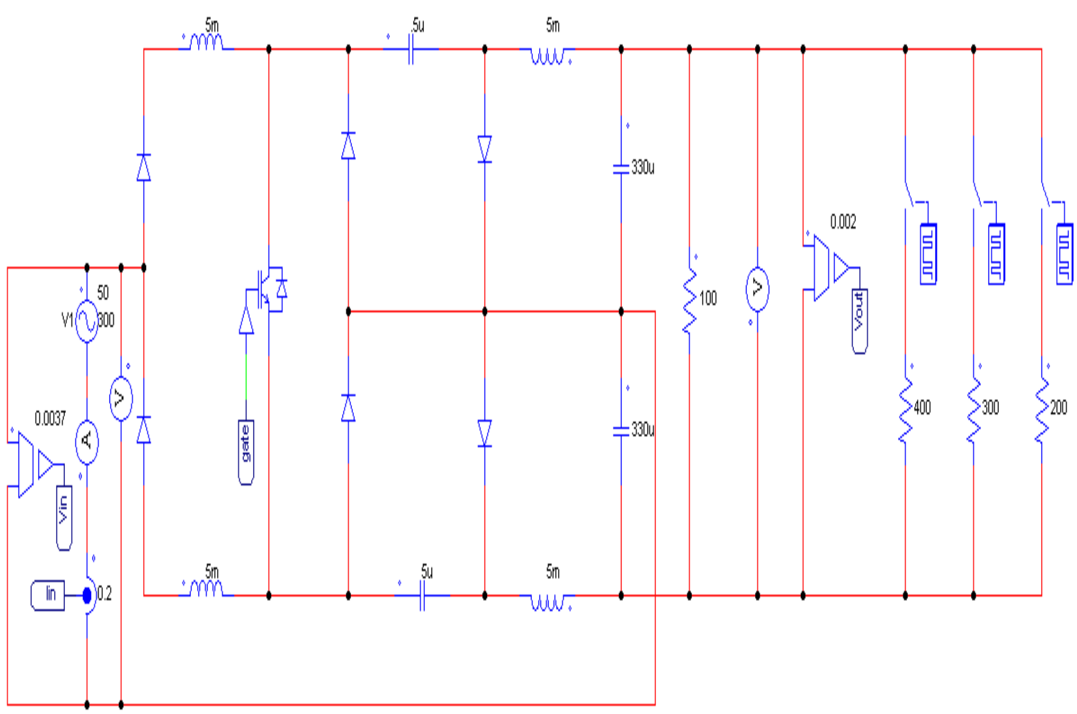


(c)

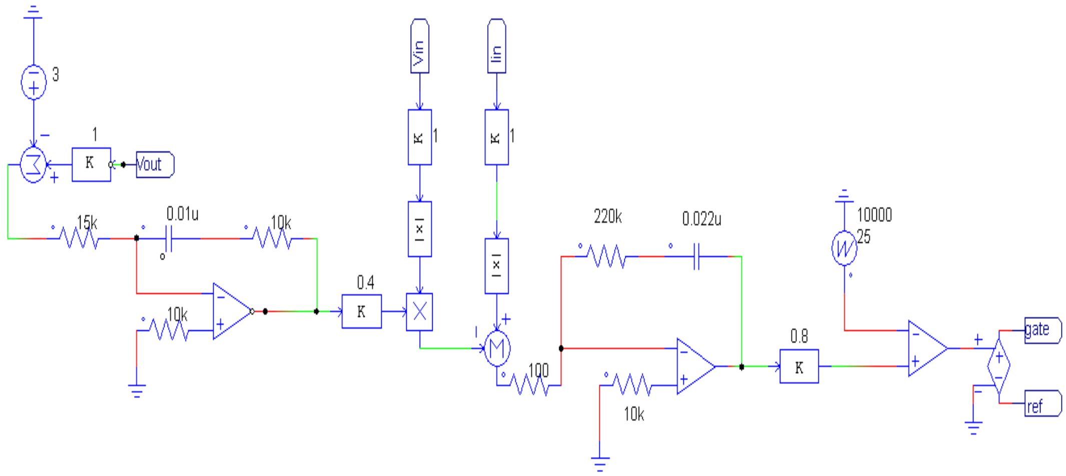
Figure 4.35: Modified Single Phase $\hat{C}$uk AC-DC Converter configuration-1 operating as boost converter (a) Efficiency, (b) THD and (c) power factor

Load Regulation:

Figure 4.36 shows Proposed Modified single phase $\hat{C}$uk AC-DC Converter configuration-1 with PFC controller and dynamic load variation capability. Initially load resistance was 100Ω. After 500msec the value of load resistance is reduced to 80Ω. From 1000msec to 1833msec the value of load resistance is increased to 100Ω again. After 1833msc the load resistance is increased to 120Ω. It is observed from the response in Fig. 4.37 (a) that though load is varied, output voltage adjusts to its original setting. Dynamic response of the circuit to regulate the output voltage load variation and change of input current are shown in Figure 4.37 (a) and (b) respectively.

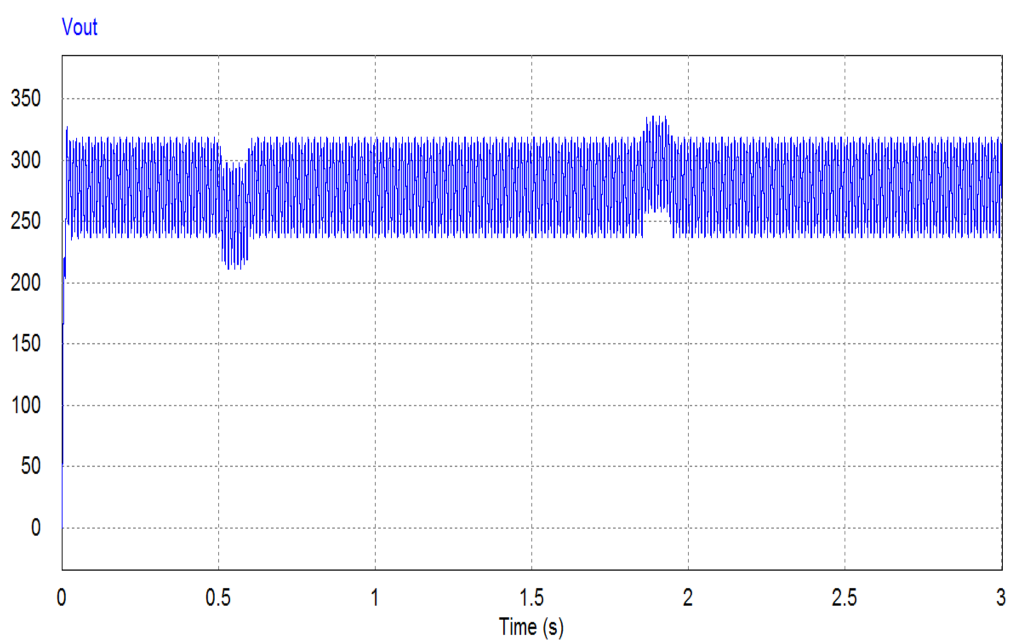


(a)

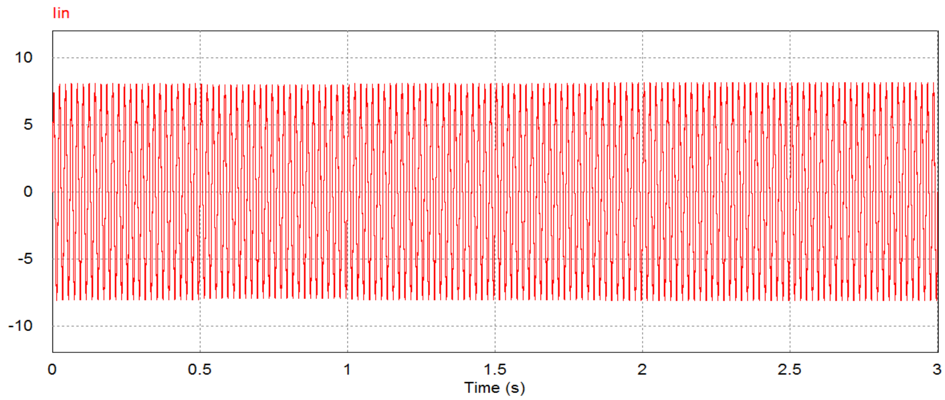


(b)

Figure 4.36: Proposed Modified Single Phase $\widehat{C}$uk Topology Based Rectifier Configuration- 1 with (a) Dynamic Load Variation (b) and PFC controller



(a)



(b)

Figure 4.37: (a) Dynamic response of output voltage with load variation
(b) Dynamic response of input current with load variation
(Load variation ± 20% of 100Ω at 0.5, 1 and 1.833 seconds)

4.5.5 Proposed Modified Single Phase Ĉuk Topology Based Rectifier With PFC Controller- Configuration-2

Proposed Modified Single Phase Ĉuk Topology Based AC/DC Rectifier With PFC Controller- Configuration-2 is shown in Figure 4.38. Feedbacks are taken from input voltage (which may also be taken from rectifier output), output voltage and input current (which may also be taken from the inductor after the rectifier).

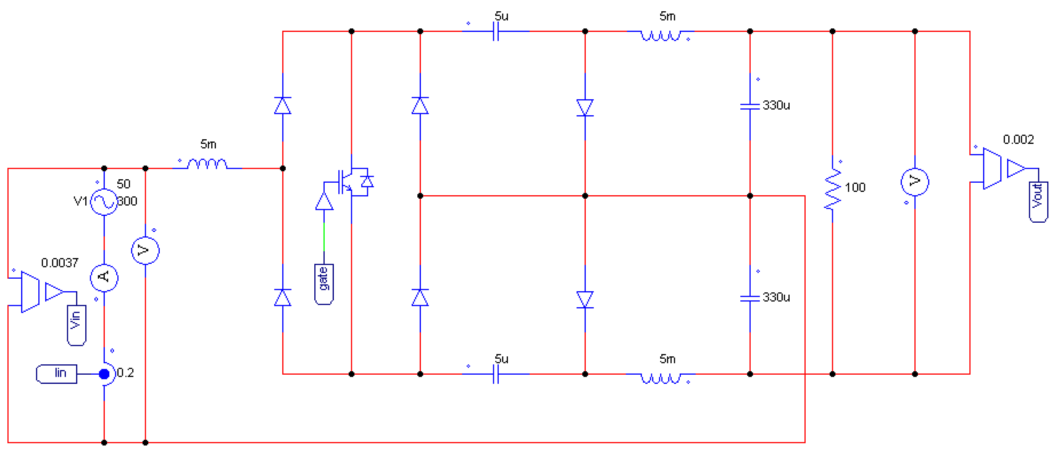


Figure 4.38: Proposed Modified Single Phase Ĉuk Topology Based Rectifier Configuration-2

Buck Operation

Proposed Modified Single Phase $\hat{C}$uk Topology Based Rectifier Configuration-2 has both buck and boost gain characteristics. The control pulse of the switch of the converter for buck operation is produced by the control circuit as shown in Figure 4.39. The typical results of which are shown from Figure 4.40. Figure 4.40 (a) and (b) show the input/output voltages, input current and the input current spectrum. Input power factor is reasonably high and the input current total harmonic distortion is considerably low (less than 10 percent).

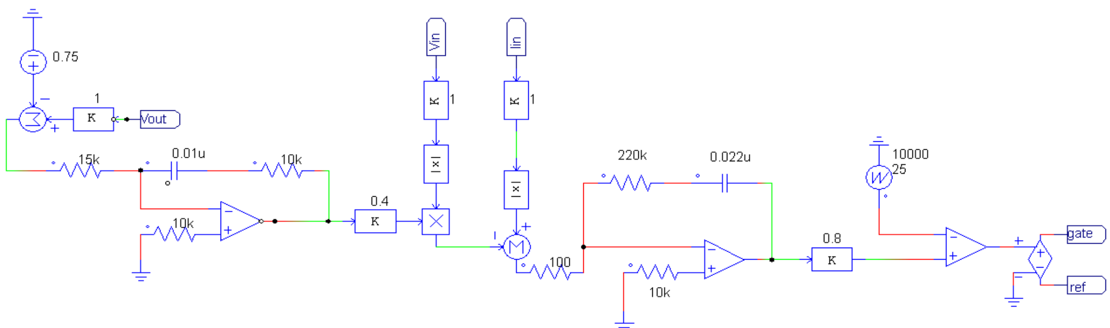
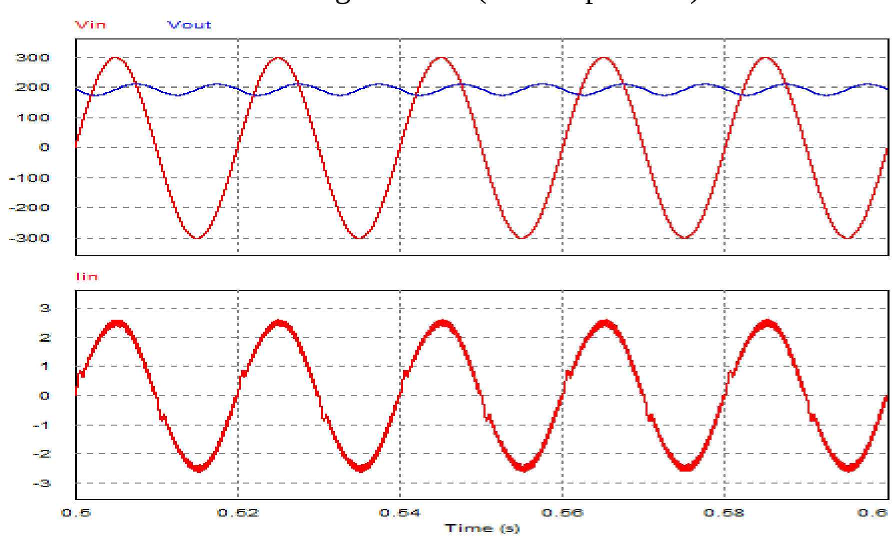
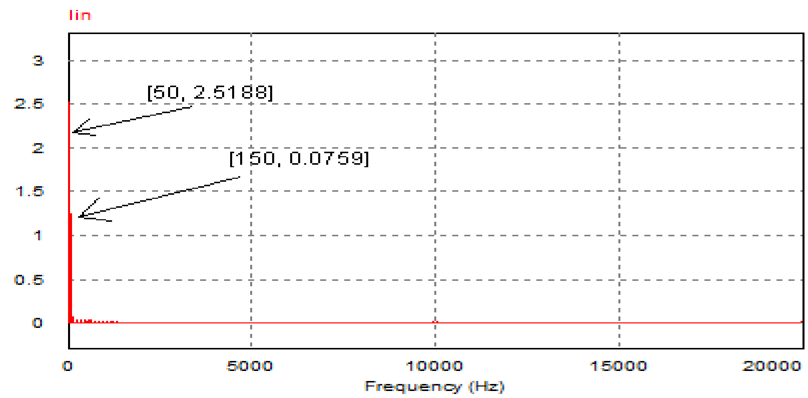


Figure 4.39: Feedback Circuit for Proposed Modified Single Phase $\hat{C}$uk Topology Based Rectifier Configuration-2 (Buck Operation)



(a)



(b)

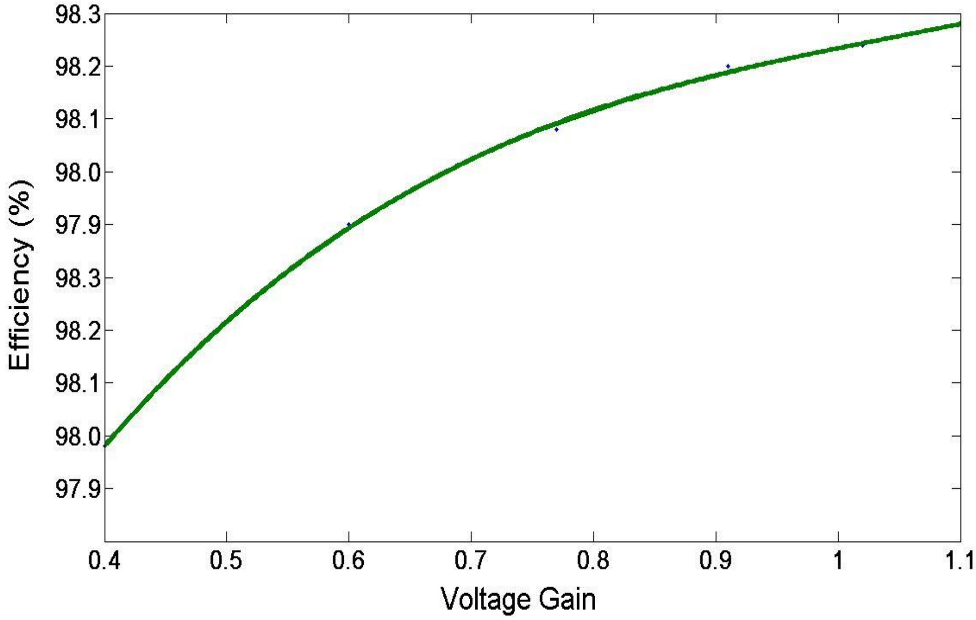
Figure 4.40: (a) Input-output voltage and input current
(b) Spectrum of input current wave shape
(Control voltage set for regulated output voltage of 200V DC)

In this subsection, the power and controller circuit with feedbacks are designed for buck operation of the converter. Table 4.8 shows that for voltage gain from 0.4 to 1.02, the power factor of the circuit remains above 0.8931 and input current THD is low in percentage for voltage gain and the efficiency is above 95 percent. Typical input/output voltages, input current waveform and the spectrum of input current of the circuit is shown in Figure 4.41. Simulated results indicate the ability of the circuit of voltage regulation maintaining the good power factor and input current THD of the rectifier.

Performance of the proposed circuit shown above is listed in the Table 4.8.

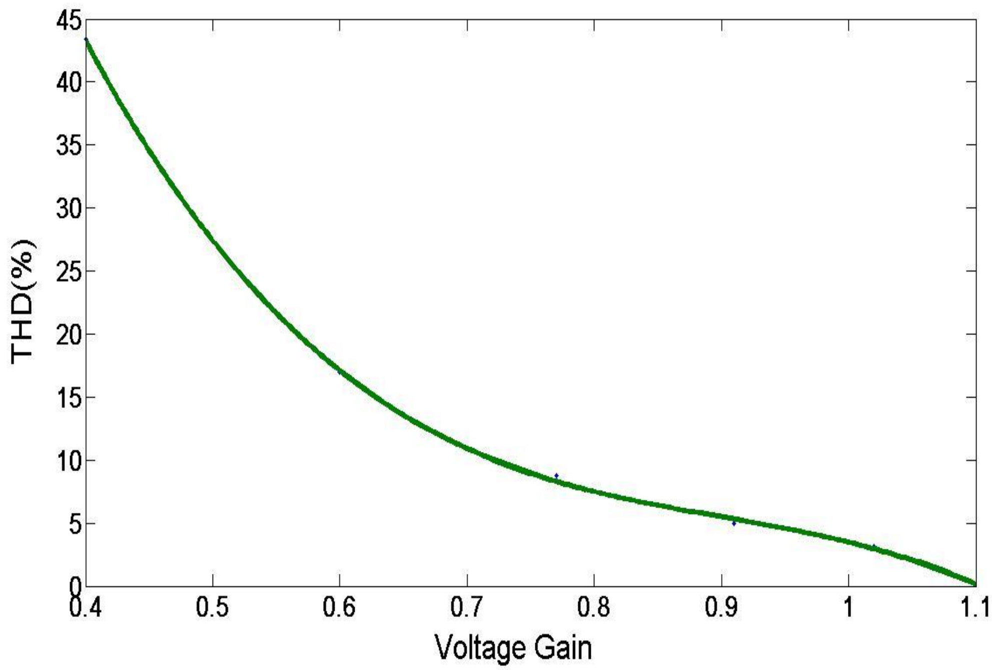
Table 4.8: Performance of Modified single phase $\widehat{C}$uk converter -2 configuration operating as buck converter

Vin	Vout	Gain	Efficiency (%)	THD(%)	PF
212	86.21	0.4	97.89	43.37	0.8931
212	128.05	0.6	98.10	16.93	0.9831
212	164.06	0.77	98.19	8.74	0.9952
212	192.18	0.91	98.25	4.98	0.9982
212	216.1	1.02	98.27	3.12	0.9991



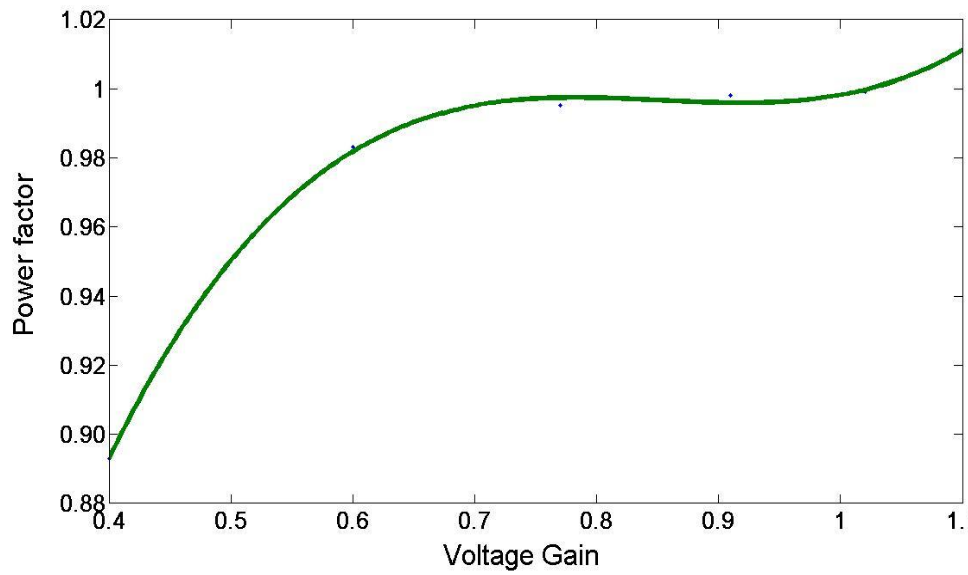
98.3
98.2
98.1
98.0
97.9
98.3
98.2
98.1
98.0
97.9
Efficiency (%)
0.4
0.5
0.6
0.7
0.8
0.9
1
1.1
Voltage Gain

(a)



45
40
35
30
25
20
15
10
5
0
THD(%)
0.4
0.5
0.6
0.7
0.8
0.9
1
1.1
Voltage Gain

(b)



(c)

Figure 4.41: Modified Single Phase $\hat{C}$uk AC-DC Converter configuration-2 operating as buck converter (a) Efficiency, (b) THD and (c) power factor

Boost Operation:

The control pulse of the switch of the converter for boost operation is produced by the control circuit as shown in Figure 4.42. The typical results of which are shown from Figure 4.43. Figure 4.43 (a) and (b) show the input/output voltages, input current and the input current spectrum. Input power factor is reasonably high and the input current total harmonic distortion is considerably low (less than 10 percent).

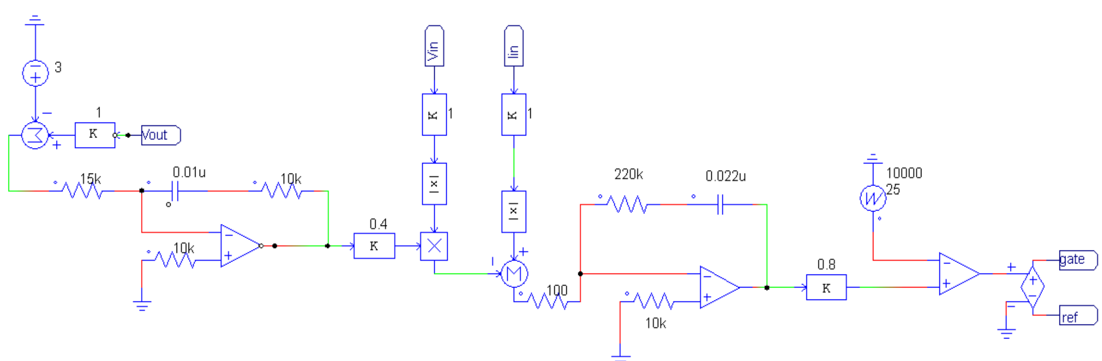
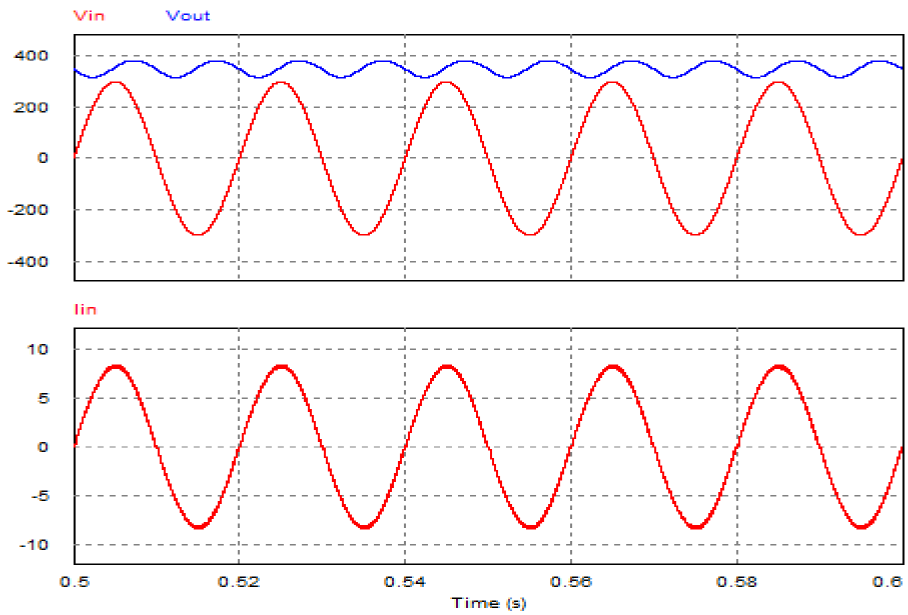
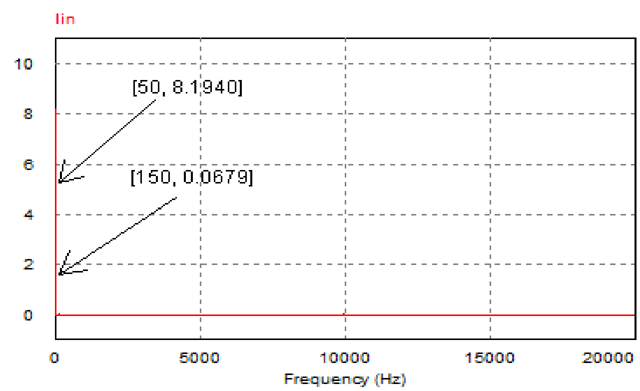


Figure 4.42: Feedback Circuit for Proposed Modified Single Phase $\hat{C}$uk Topology Based Rectifier Configuration-2 (Boost Operation)



(a)



(b)

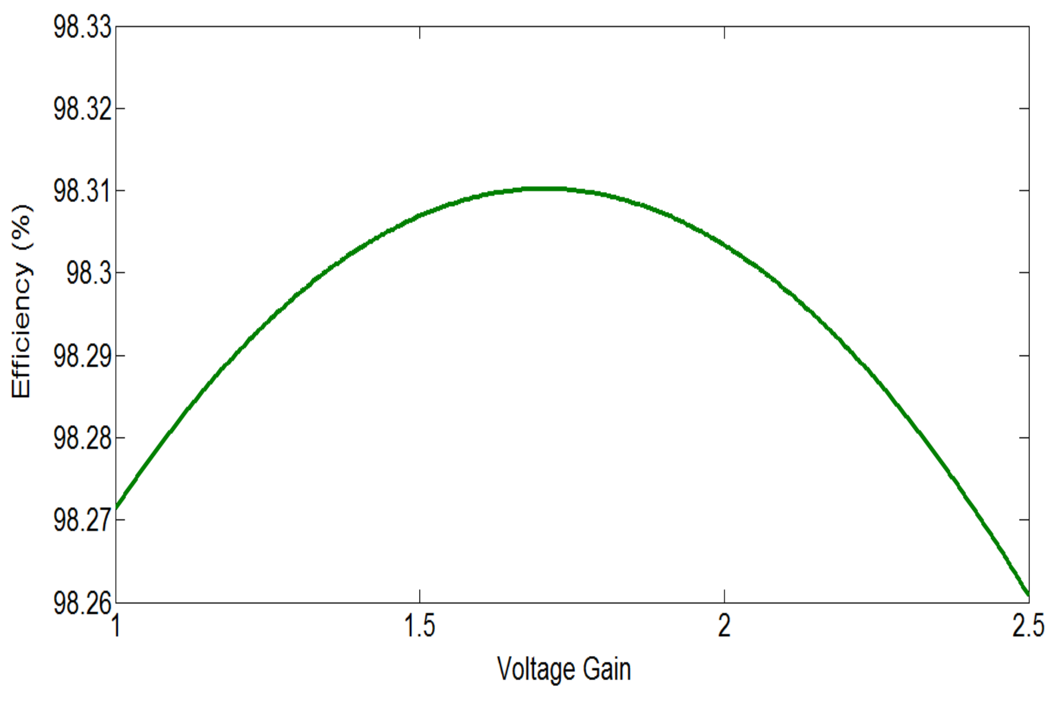
Figure 4.43: (a) Input-output voltage and input current
(b) Spectrum of input current wave shape
(Control voltage set for regulated output voltage of 350V DC)

In this subsection, the power and controller circuit with feedbacks are designed for boost operation of the converter. Table 4.9 shows that for voltage gain between 1.02 to 2.25, the power factor of the circuit remains above 0.9991 and input current THD is below 10 percent and the efficiency is above 98 percent. Typical input/output voltages, input current waveform and the spectrum of input current of the circuit is shown in Figure 4.44. Simulated results indicate the ability of the circuit of voltage regulation maintaining the good power factor and input current THD of the rectifier.

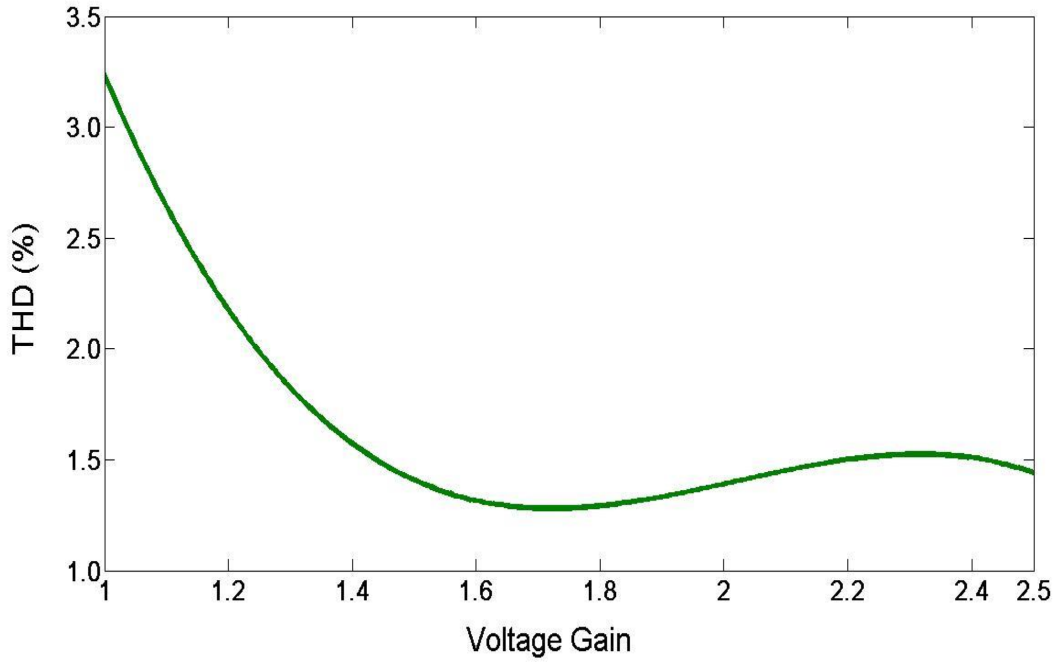
Performance of the proposed circuit shown above is listed in the Table 4.9.

Table 4.9: Performance of Modified Single Phase $\widehat{C}$uk converter configuration-2 operating as boost converter

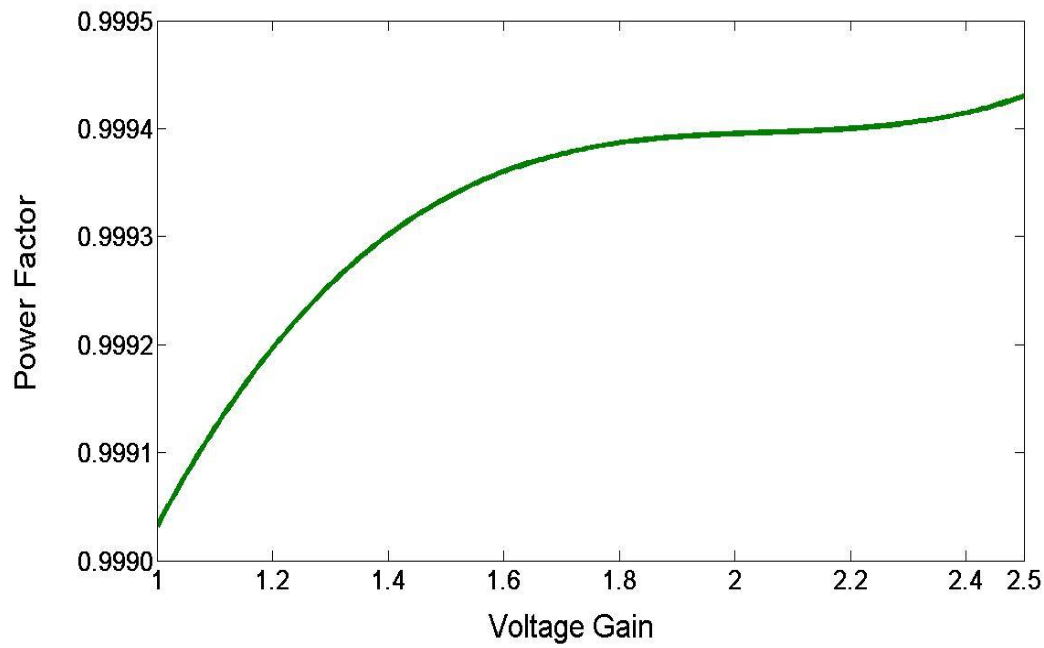
Vin	Vout	Gain	Efficiency (%)	THD (%)	PF
212	216.1	1.02	98.27	3.12	0.9991
212	290.5	1.37	98.31	1.60	0.9996
212	347.6	1.64	98.31	1.35	0.9997
212	395.8	1.86	98.30	1.32	0.9998
212	438.3	2.07	98.30	1.39	0.9998
212	476.7	2.25	98.29	1.54	0.9998



(a)



(b)

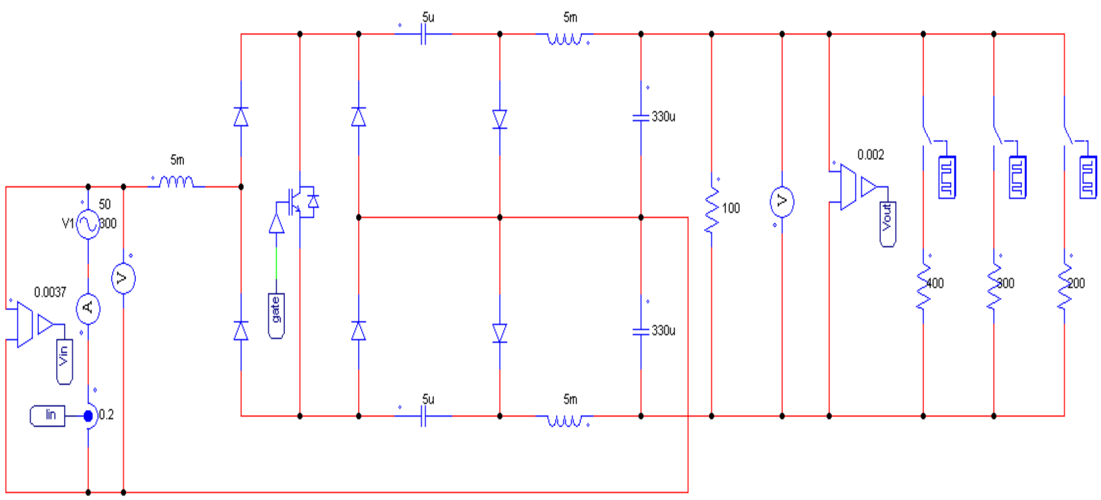


(c)

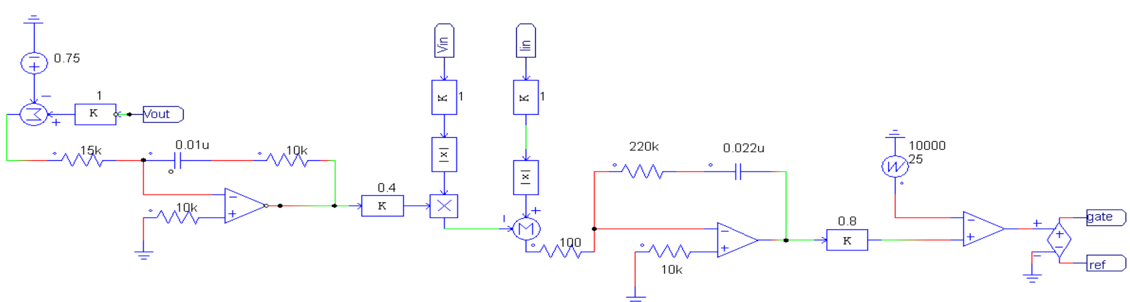
Figure 4.44: Modified Single Phase $\hat{C}$uk AC-DC Converter configuration-2 operating as boost converter (a) Efficiency, (b) THD and (c) power factor

Load Regulation:

Figure 4.45 shows Proposed Modified single phase Ĉuk AC-DC Converter configuration-2 with PFC controller and dynamic load variation capability. Initially load resistance was 100Ω. After 500msec the value of load resistance is reduced to 80Ω. From 1000msec to 1833msec the value of load resistance is increased to 100Ω again. After 1833msc the load resistance is increased to 120Ω. It is observed from the response in Fig. 4.46 (a) that though load is varied, output voltage adjusts to its original setting. Dynamic response of the circuit to regulate the output voltage load variation and change of input current are shown in Figure 4.46 (a) and (b) respectively.

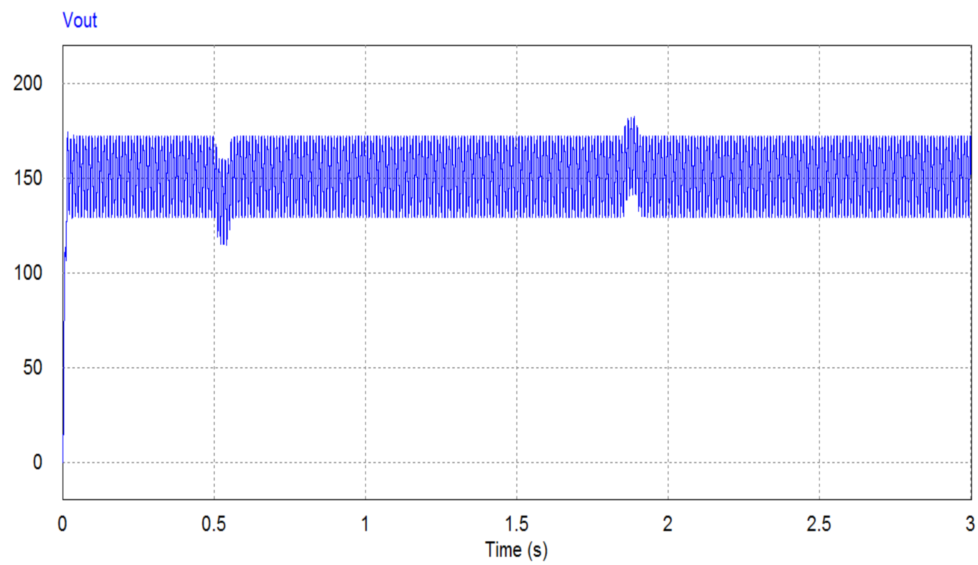


(a)

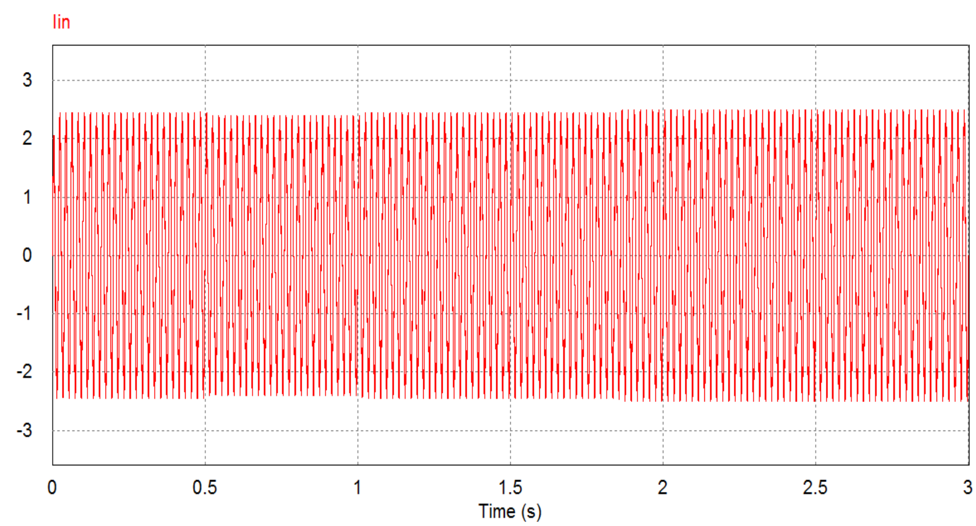


(b)

Figure 4.45: Proposed Modified Single Phase Ĉuk Topology Based Rectifier Configuration- 2 with (a) Dynamic Load Variation (b) and PFC controller



(a)



(b)

Figure 4.46: (a) Dynamic response of output voltage with load variation
(b) Dynamic response of input current with load variation
(Load variation ± 20% of 100Ω at 0.5, 1 and 1.833 seconds)

Chapter 5

Comparison between Conventional and Proposed Single Phase Ĉuk AC-DC Converter Topologies

Performance comparison of conventional and proposed four topologies of single phase AC-DC converter in terms of efficiency, input current THD, input power factor with voltage gain variation are discussed in this chapter. Table 5.1 to 5.6 and Figure 5.1 to 5.6 show the performance of proposed configurations of single phase Ĉuk topology based rectifiers with conventional output switched Ĉuk rectifier and conventional output switched boost rectifier. Tables 5.1 - 5.3 and Figures 5.1 - 5.3 represent the comparison when the conventional and proposed topologies are operating as buck converter. Tables 5.4 – 5.6 and Figures 5.4 – 5.6 represent the comparison when the conventional and proposed topologies are operating as boost converter.

The single phase topologies of rectifiers' comparison are given numerical number for easier representation which indicates the following configurations when operating as buck and boost converter:

Topology-1: Conventional output switched boost rectifier

Topology-2: Conventional output switched Ĉuk rectifier

Topology-3: Input switched Ĉuk rectifier output bridge configuration

Topology-4: Input switched Ĉuk rectifier output half bridge configuration

Topology-5: Modified Ĉuk Converter-1 Switched Within Bridge

Topology-6: Modified Ĉuk Converter-2 Switched Within Bridge

Table 5.1: Comparison of Efficiency between Conventional and Proposed Topologies of Single Phase AC-DC Converter Operating as Buck Converter

Voltage Gain	Efficiency (%)				
	Topology-2	Topology-3	Topology-4	Topology-5	Topology-6
0.4	96.39	26.14	12.02	97.22	97.89
0.6	96.68	30.57	15.04	97.90	98.10
0.8	96.60	37.44	18.27	98.31	98.19
0.9	96.75	40.04	20.44	98.30	98.25
1.0	96.80	41.2	23.07	97.71	98.27

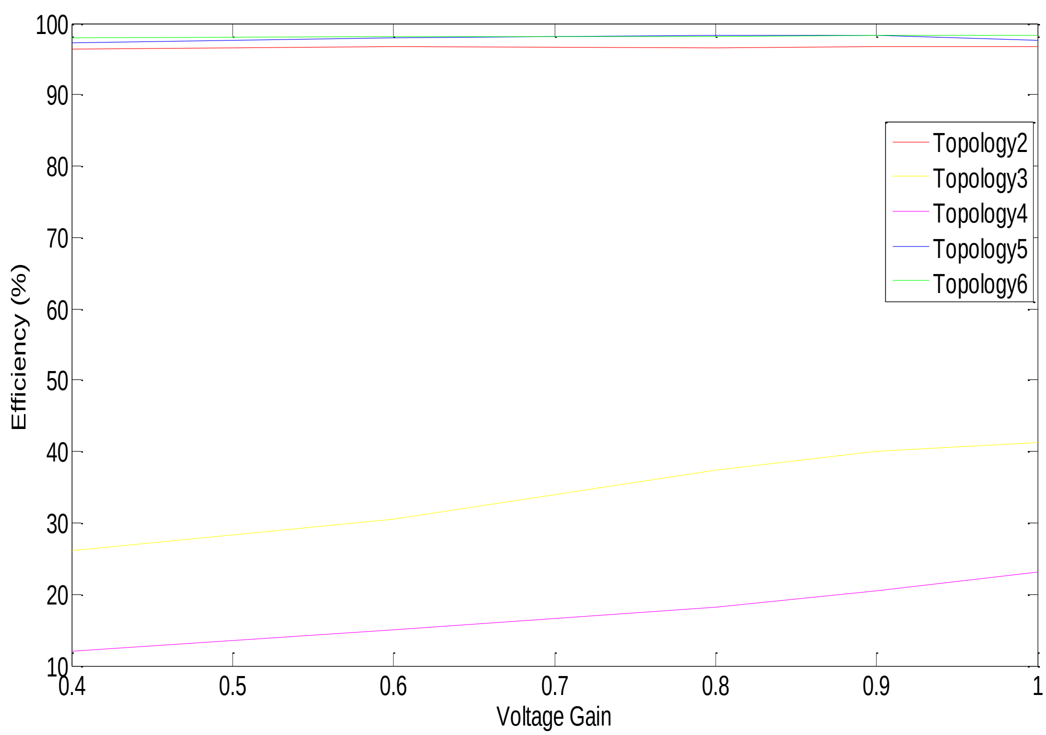


Figure 5.1: Comparison of Efficiency between conventional and proposed topologies of single phase AC-DC converter operating as buck converter

Table 5.2: Comparison of Input Current THD between Conventional and Proposed Topologies of Single Phase AC-DC Converter Operating as Buck Converter

Voltage Gain	THD (%)				
	Topology-2	Topology-3	Topology-4	Topology-5	Topology-6
0.4	42.45	12.13	8.67	9.92	43.37
0.6	15.71	10.80	7.89	4.82	16.93
0.8	7.48	10.09	7.51	3.4	8.74
0.9	4.02	9.84	7.18	2.79	4.98
1.0	2.99	9.35	7.08	2.38	3.12

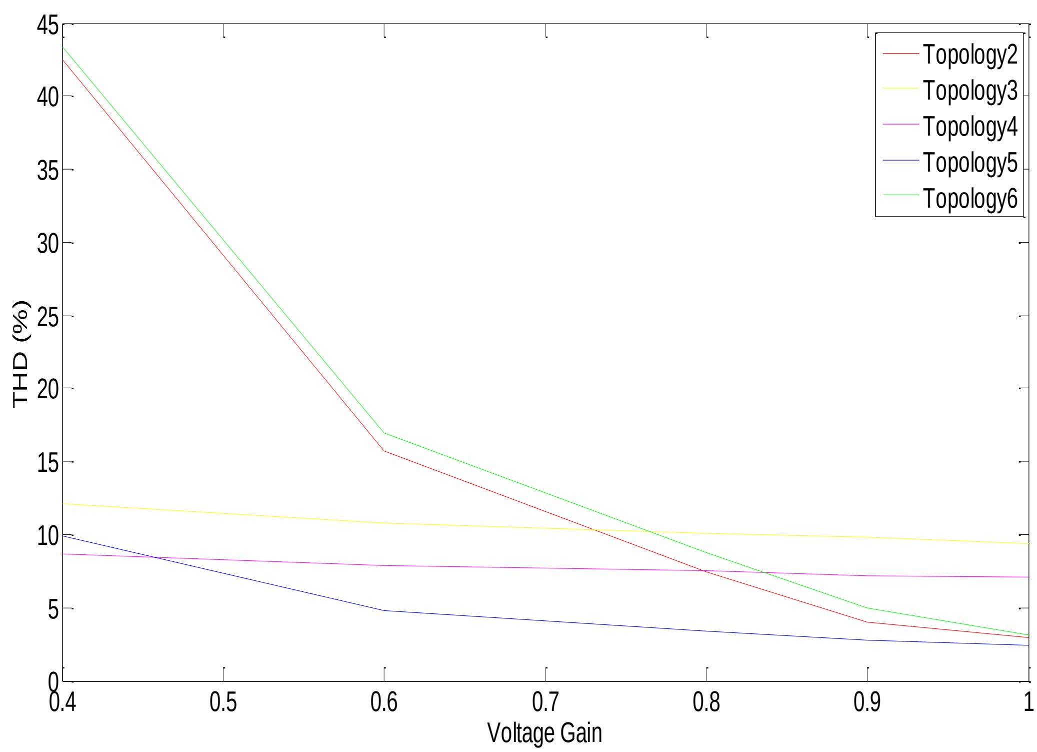


Figure 5.2: Comparison of input current THD between conventional and proposed topologies of single phase AC-DC converter operating as buck converter

Table 5.3: Comparison of Input Power Factor between Conventional and Proposed Topologies of Single Phase AC-DC Converter Operating as Buck Converter

Voltage Gain	Power Factor				
	Topology-2	Topology-3	Topology-4	Topology-5	Topology-6
0.4	0.8911	0.9925	0.9963	0.9907	0.8931
0.6	0.9843	0.9943	0.9969	0.9975	0.9831
0.8	0.9961	0.9950	0.9973	0.9986	0.9952
0.9	0.9986	0.9953	0.9975	0.9990	0.9982
1.0	0.9992	0.9958	0.9976	0.9993	0.9991

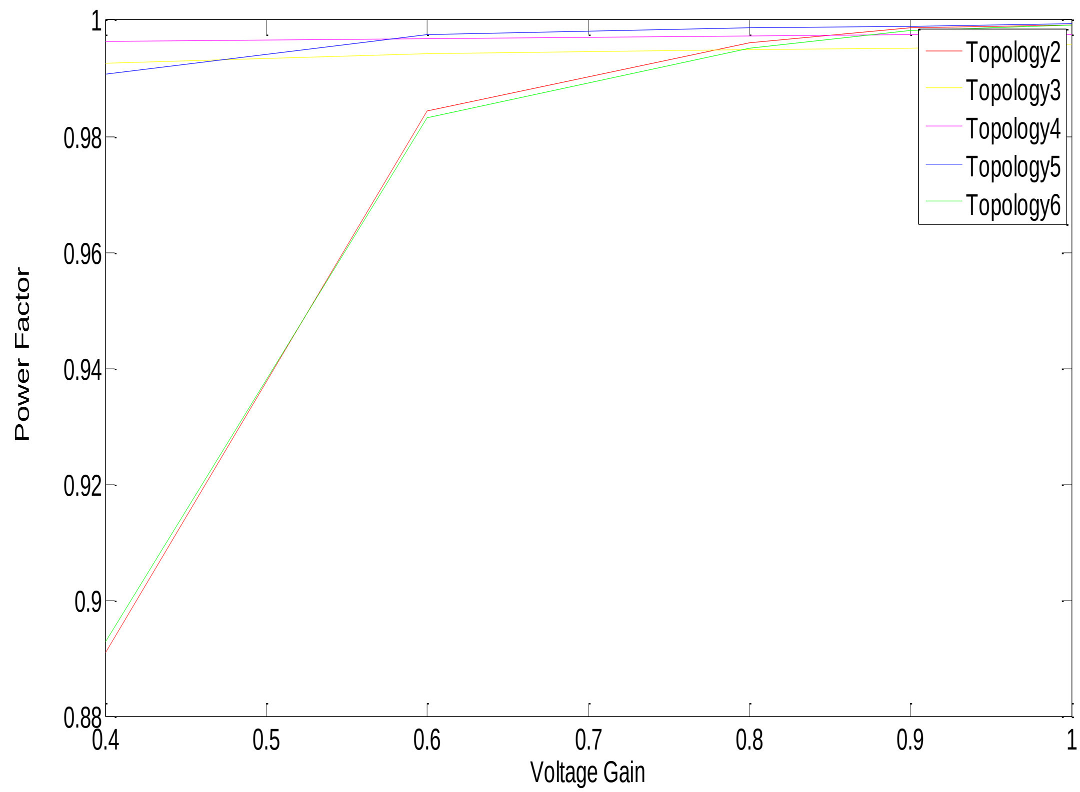


Figure 5.3: Comparison of Input Power factor between conventional and proposed topologies of single phase AC-DC converter operating as buck converter

After studying data of the Tables and the Figures it is evident that conventional single phase Ĉuk rectifier and proposed modified Ĉuk converter-1 and converter -2 switched within bridge perform better than other proposed topologies in terms of efficiency. Though all the proposed topologies give lower input current THD and give higher input P.F. than the conventional single phase Ĉuk rectifier, Modified Ĉuk converter-1 switched within bridge shows the best performance when the converters are operating as buck converter.

Table 5.4: Comparison of Efficiency between Conventional and Proposed Topologies of Single Phase AC-DC Converter Operating as Boost Converter

Voltage Gain	Efficiency (%)					
	Topology 1	Topology 2	Topology 3	Topology 4	Topology 5	Topolog y 6
1.4	97.35	96.85	45.78	27.23	97.78	98.31
1.6	97.33	96.92	48.3	29.45	97.69	98.31
1.8	97.31	96.94	49.9	31.95	97.66	98.30
2.1	97.10	96.96	53.4	38.49	97.56	98.30
2.3	97.45	96.85	54.64	36.75	97.51	98.29

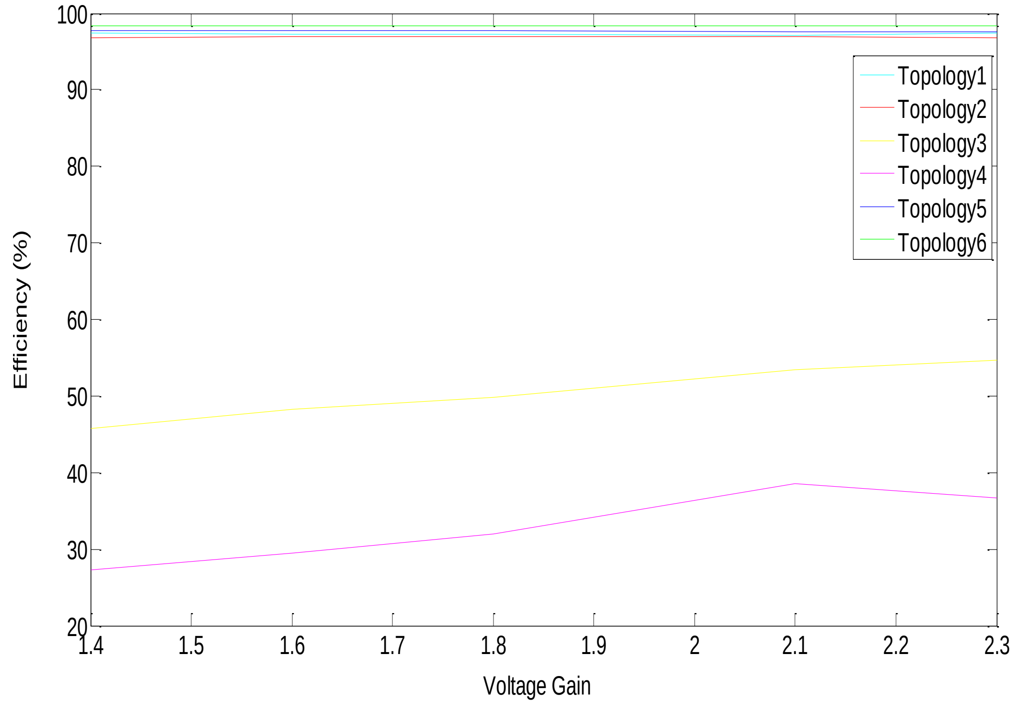


Figure 5.4: Comparison of Efficiency between conventional and proposed topologies of single phase AC-DC converter operating as boost converter

Table 5.5: Comparison of Input Current THD between Conventional and Proposed Topologies of Single Phase AC-DC Converter Operating as Boost Converter

Voltage Gain	**THD (%)**					
	Topology 1	**Topology 2**	**Topology 3**	**Topology 4**	**Topology 5**	**Topology 6**
1.4	10.2	2.0	8.68	6.21	1.64	1.60
1.6	1.66	1.89	9.04	5.92	1.38	1.35
1.8	1.85	2.05	8.10	5.51	1.32	1.32
2.1	2.44	2.34	7.69	6.01	1.38	1.39
2.3	2.81	2.82	8.26	5.36	1.54	1.54

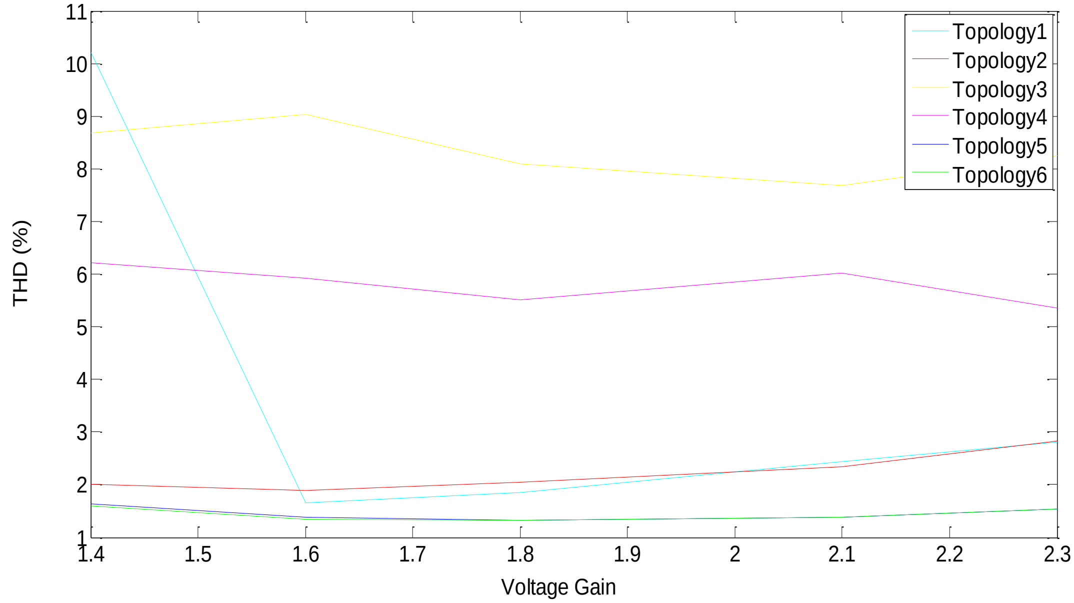


Figure 5.5: Comparison of input current THD between conventional and proposed topologies of single phase AC-DC converter operating as boost converter

Table 5.6: Comparison of Input Power Factor between Conventional and Proposed Topologies of Single Phase AC-DC Converter Operating as Boost Converter

Voltage Gain	**Power Factor**					
	Topology 1	**Topology 2**	**Topology 3**	**Topology 4**	**Topology 5**	**Topology 6**
1.4	0.8220	0.9995	0.9964	0.9981	0.9996	0.9996
1.6	0.8845	0.9997	0.9963	0.9983	0.9997	0.9997
1.8	0.9312	0.9997	0.9968	0.9985	0.9998	0.9998
2.1	0.9700	0.9996	0.9971	0.9982	0.9998	0.9998
2.3	0.9791	0.9995	0.9970	0.9986	0.9997	0.9998

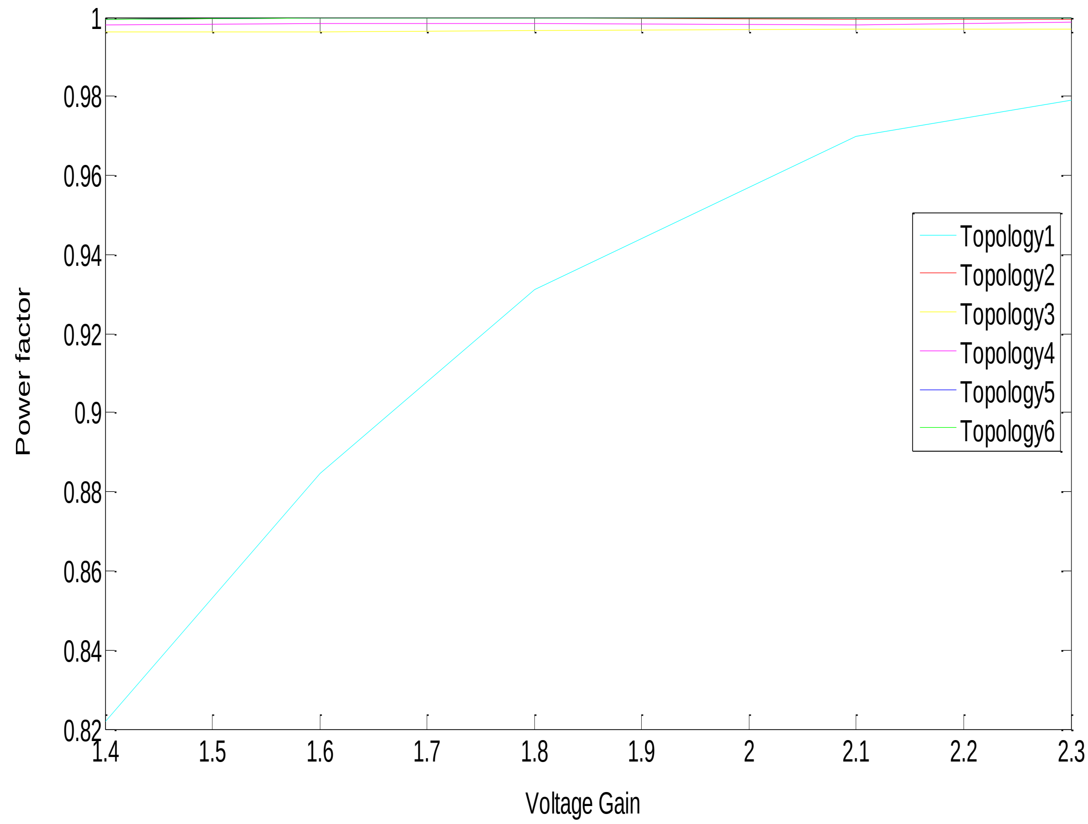


Figure 5.6: Comparison of Input Power factor between conventional and proposed topologies of single phase AC-DC converter operating as boost converter

All conventional and proposed topologies except input switched Ĉuk rectifier output bridge configuration and output half bridge configuration give higher efficiency (over 95%). Every proposed topology of rectifiers and also the conventional output switched single phase boost, Ĉuk rectifier give input power factor above 0.9 and keep input current THD below 10%. The comparison are made when the converters are operating as boost converter.

Proposed modified Ĉuk converter-1 and converter -2 switched within bridge give best performance in terms of efficiency, input current THD and input power factor than any other proposed configurations and conventional output switched boost and Ĉuk rectifiers when operating as buck and boost converter.

Chapter 6

Experimental Results without Feedback Control

The proposed single phase Ĉuk rectifier circuit configurations without feedback of Figures 3.16 and 3.21 are implemented practically for observing the performance of the circuits. The experimental results shown in this chapter are input, output voltages, input current, input current THD and power factor of the circuit for variation of duty cycle. The waveforms of input, output voltages, input currents and input currents' spectrum are taken from digital oscilloscope and power factor and THD are observed using power quality analyzer. The real power, reactive power and apparent power consumption of the circuit at a particular duty cycle can also be seen form power quality analyzer. The circuit configurations practically implemented are single phase Modified Ĉuk AC-DC converter switched within bridge configuration-1 and single phase Modified Ĉuk AC-DC converter switched within bridge configuration-2. The circuits have been practically implemented with following circuit parameters,

L_1 = 5mH, L_2 = 5mH

C =220μF (Coupling capacitor)

C_0 = 330μF (Output capacitor)

ECR = 100Ω (Equivalent Ĉuk Resistor/output resistor)

V_{in} = 15V_{RMS} (Approximately), 50 Hz

f_{switch} = 4KHz

6.1 Single phase Modified Ĉuk AC-DC Converter Switched Within Bridge Configuration-1

The experimental results of the single phase Modified Ĉuk AC-DC converter switched within bridge configuration-1 based power factor corrected (PFC) rectifier without feedback have been recorded in Table 6.1 and graphically represented in Figures 6.1 to 6.18 for duty cycle (D) of 0.2, 0.5 and 0.7. It is evident that the converter has buck-boost voltage gain, and power factor above 0.7 for D of 0.2, 0.5. THD of input current is however, higher than 25 percent. For better input power factor and input current THD values proper feedback circuit as has been studied in the simulation studies are necessary.

Table 6.1: Performance of Modified-1 single phase Ĉuk rectifier

Duty Cycle	Input Voltage	Output Voltage	THD %	PF	Input Power	Efficiency %
0.2	14.84	- 10.80	27.8	0.91	0.8	72.90
0.5	15.00	- 24.00	50.3	0.74	3.4	84.70
0.7	14.91	- 35.00	37.2	0.64	9.3	65.86

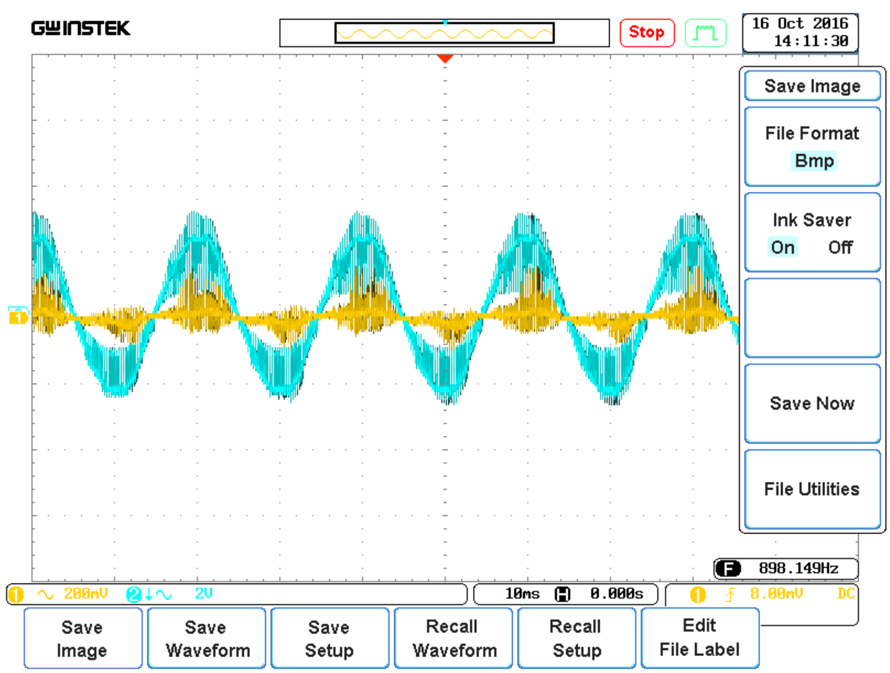


Figure 6.1: Input Voltage (Blue) and Input Current (Yellow) Waveforms of Modified-1 Single Phase Ĉuk Rectifier for D = 0.2 From Oscilloscope

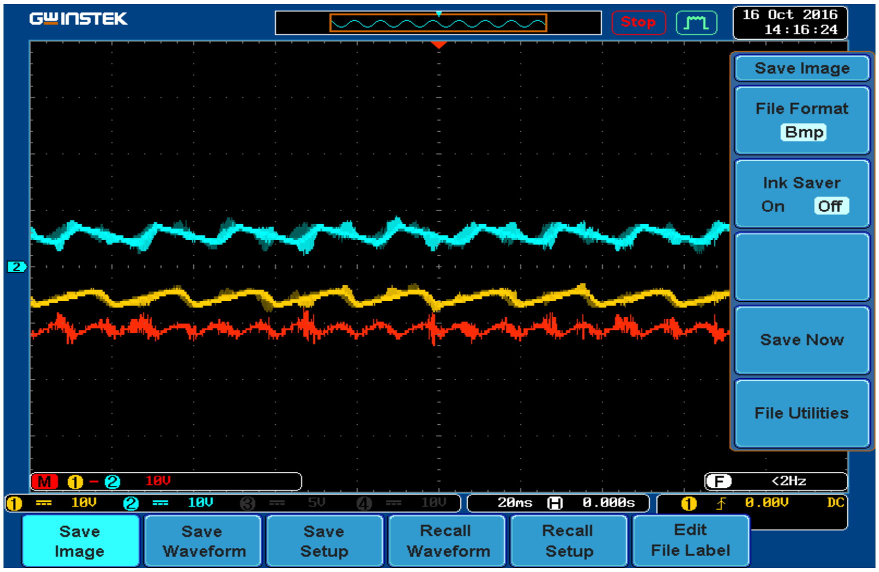


Figure 6.2: Output and Intermediate Capacitor Voltages (Red) for Modified-1 Single Phase Ĉuk Rectifier for D = 0.2 From Oscilloscope

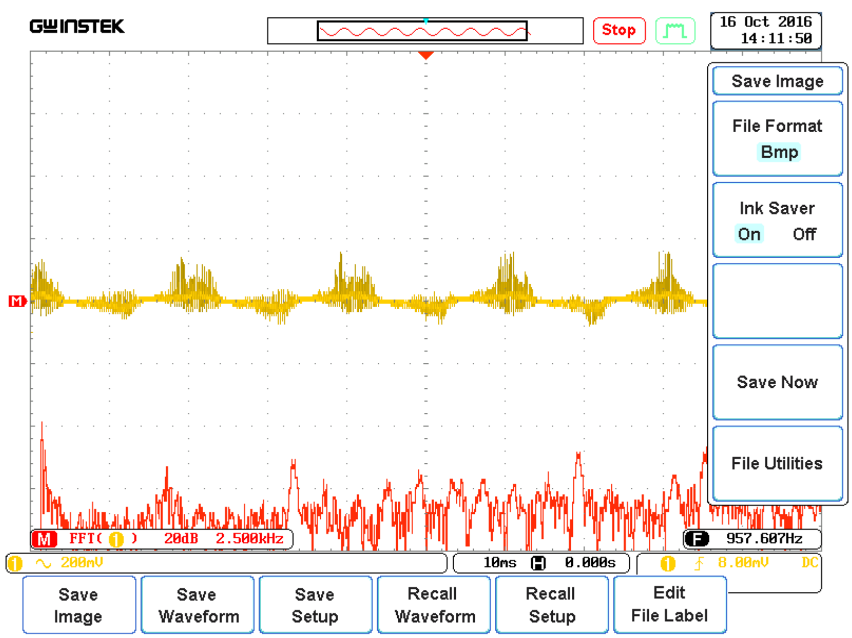


Figure 6.3: Input Current (Yellow) and its Fourier Transform (Red) for Modified-1 Single Phase Ĉuk Rectifier for D = 0.2 From Oscilloscope

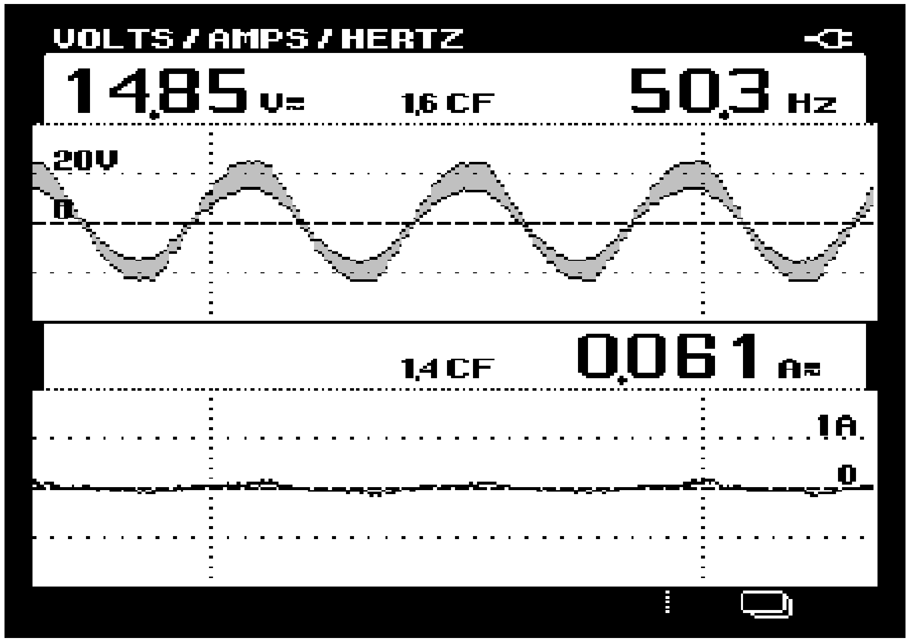


Figure 6.4: Input Voltage and Input Current waveforms for Modified-1 Single Phase Ĉuk Rectifier for D = 0.2 From Power Quality Analyzer

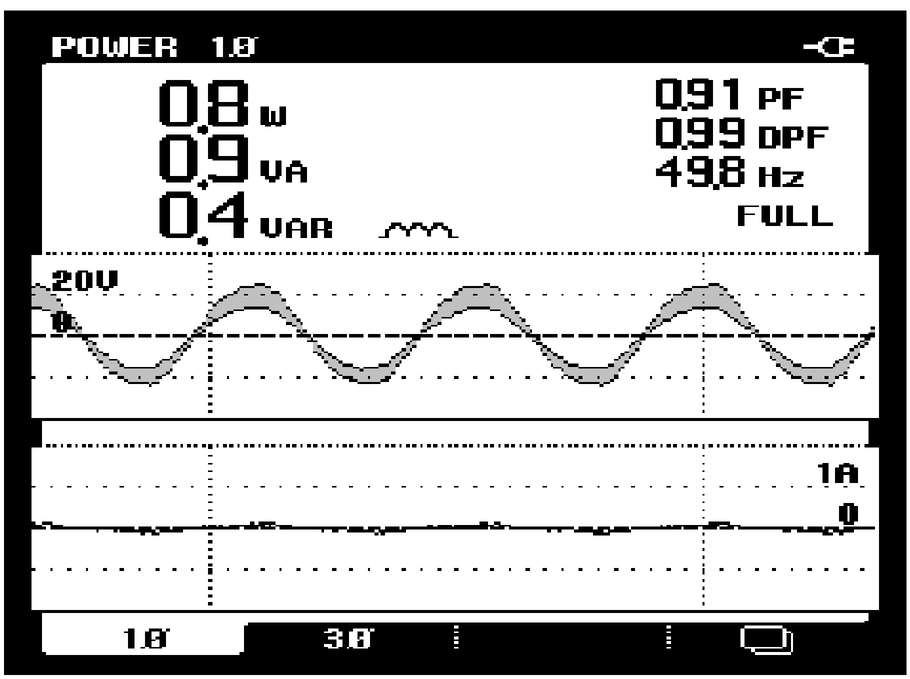


Figure 6.5: Power factor, Real power, Reactive Power, Apparent Power of Modified-1 Single Phase Ĉuk Rectifier for D = 0.2 From Power Quality Analyzer

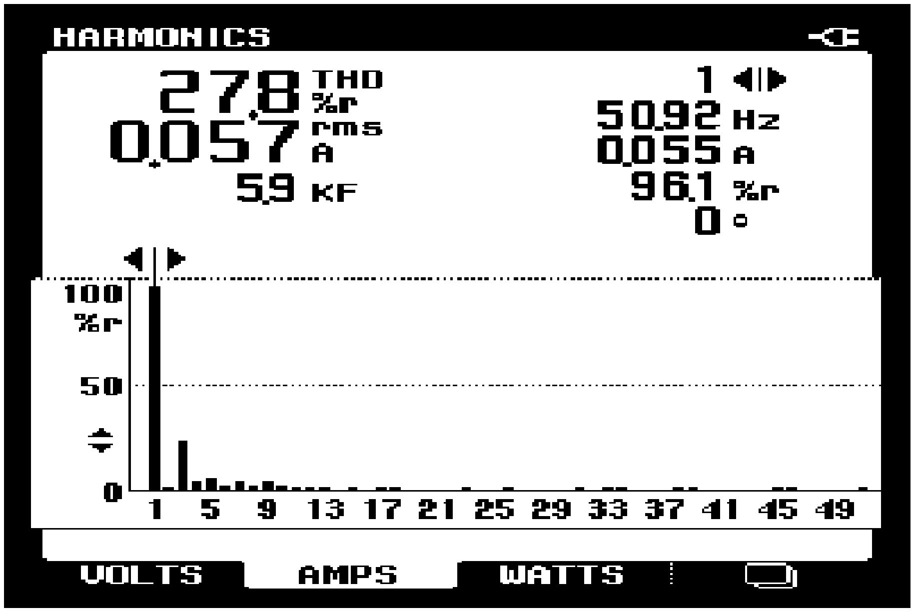


Figure 6.6: Spectrum of Input Current of Modified-1 Single Phase Ĉuk Rectifier for D = 0.2 From Power Quality Analyzer

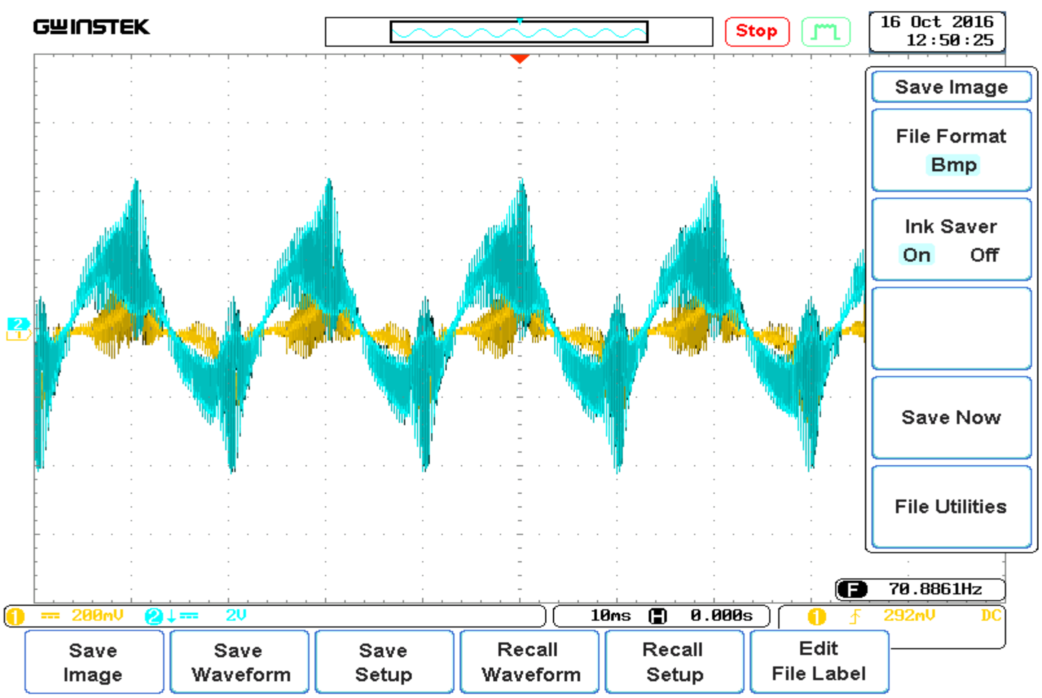


Figure 6.7: Input Voltage (Blue) and Input Current (Yellow) Waveforms for Modified-1 Single Phase Ĉuk Rectifier for D = 0.5 From Oscilloscope

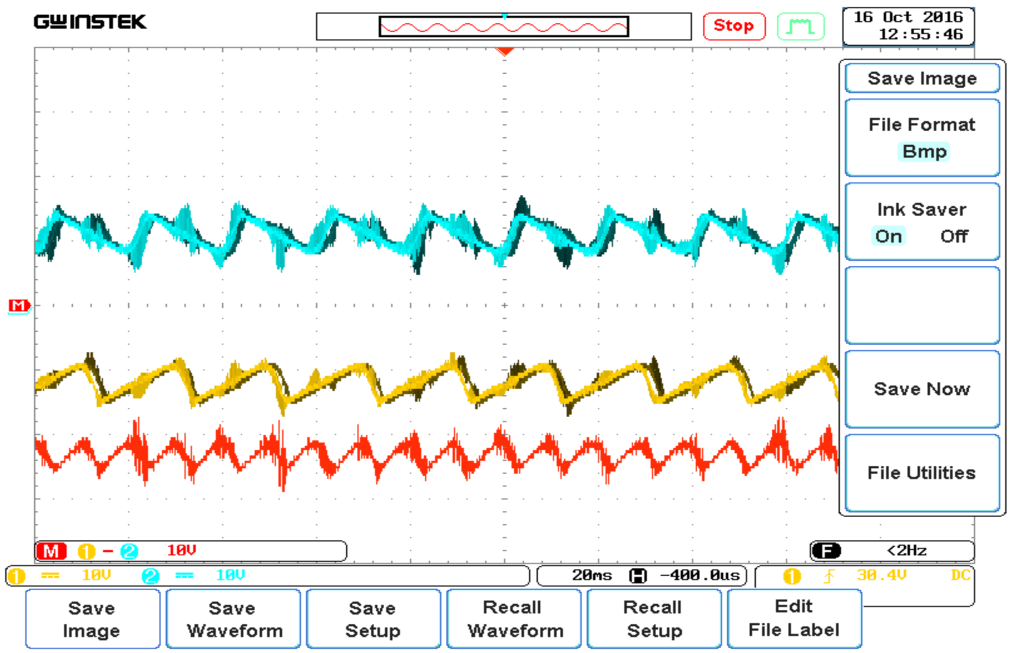


Figure 6.8: Output and Intermediate Capacitor Voltages (Red) for Modified-1 Single Phase Ĉuk Rectifier of D = 0.5 From Oscilloscope

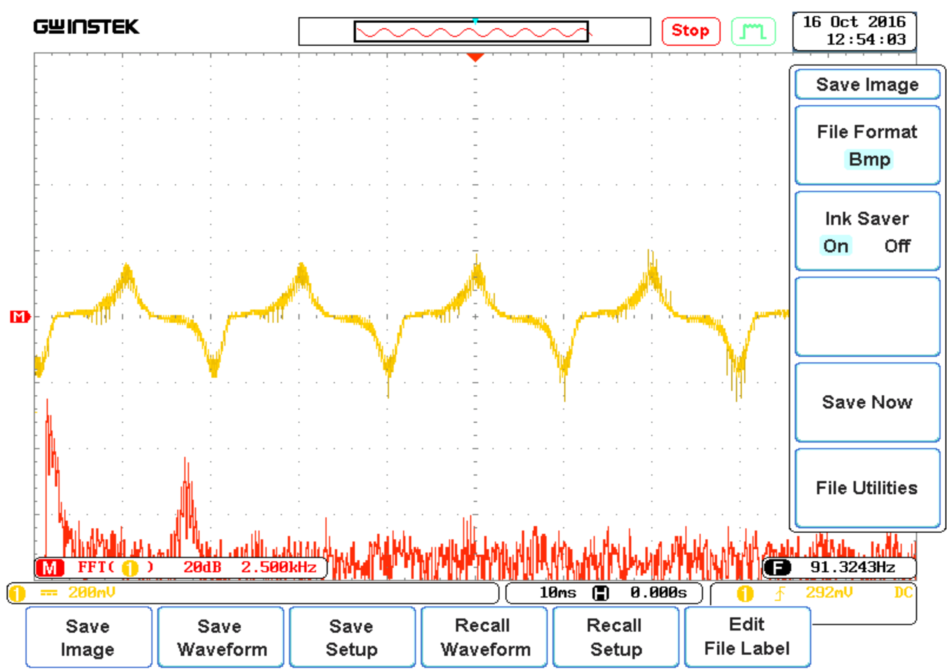


Figure 6.9: Input Current (Yellow) and its Fourier Transform (Red) for Modified-1 Single Phase Ĉuk Rectifier for D = 0.5 From Oscilloscope

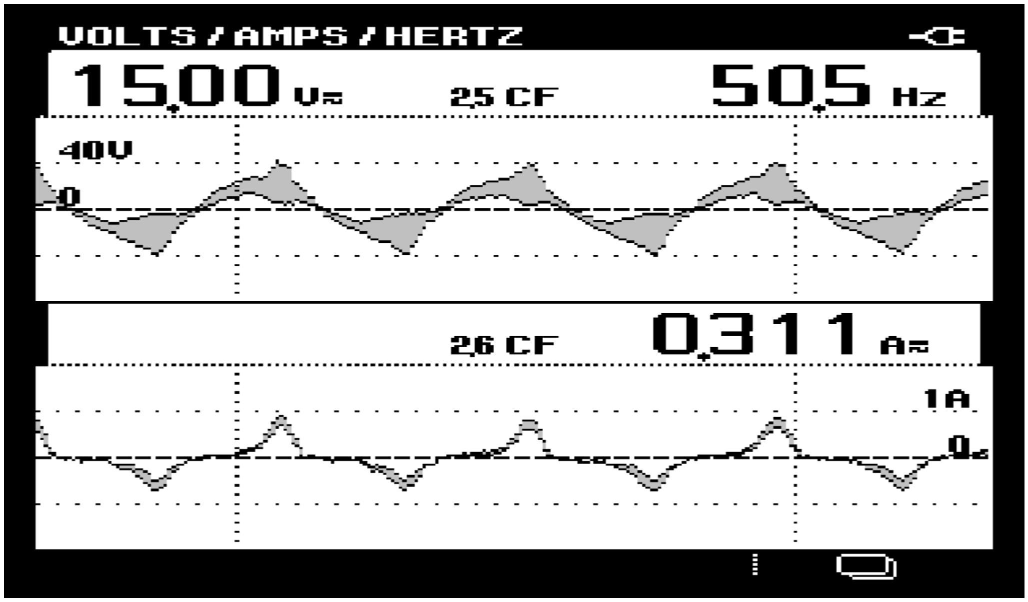


Figure 6.10: Input Voltage and Input Current waveforms for Modified-1 Single Phase Ĉuk Rectifier for D = 0.5 From Power Quality Analyzer

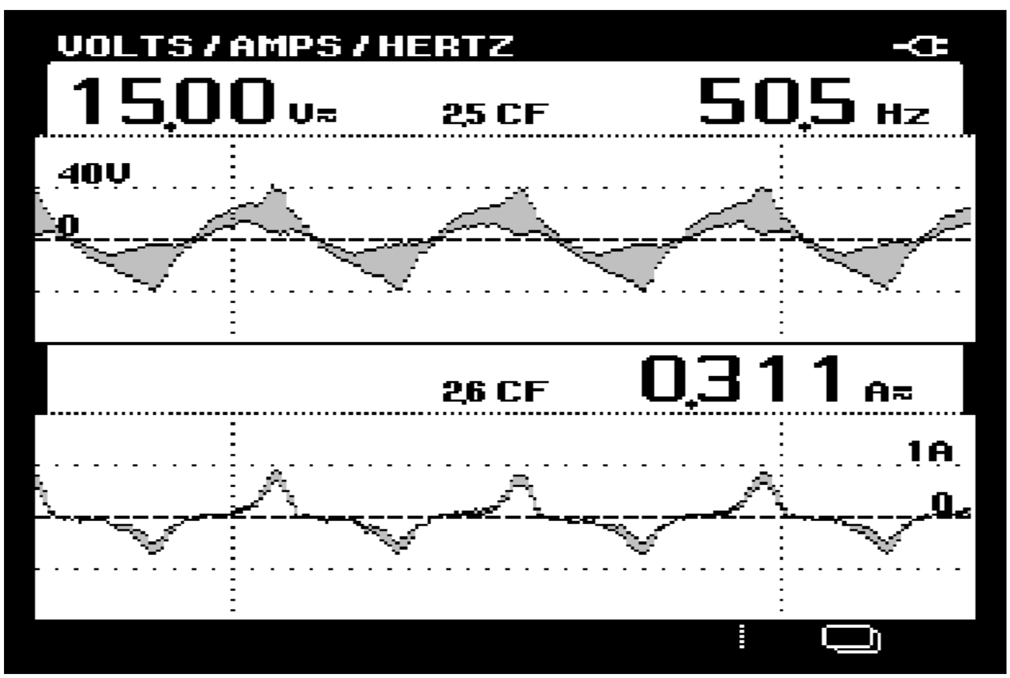


Figure 6.11: Power factor, Real power, Reactive Power, Apparent Power of Modified-1 Single Phase Ĉuk Rectifier for D = 0.5 From Power Quality Analyzer

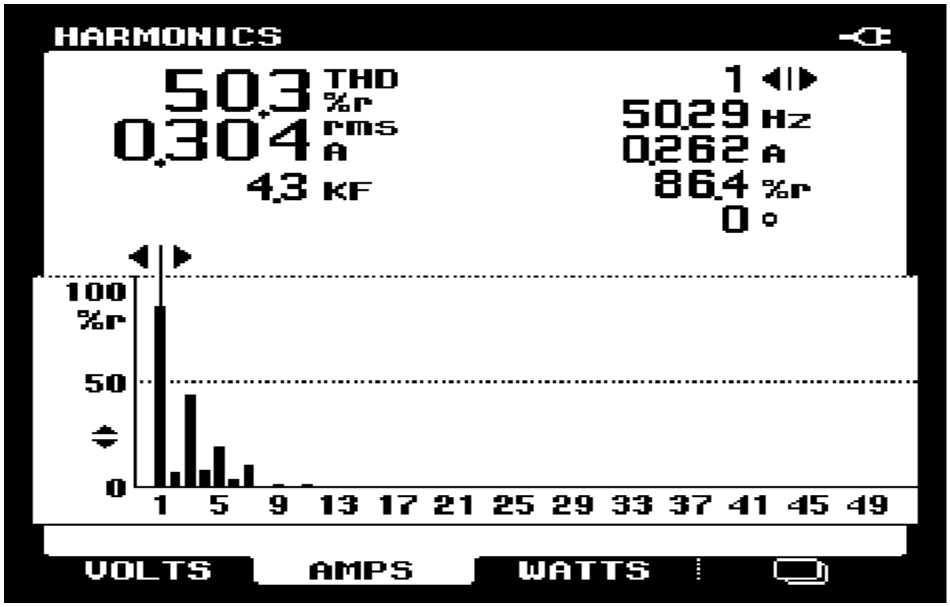


Figure 6.12: Spectrum of Input Current of Modified-1 Single Phase Ĉuk Rectifier for D = 0.5 From Power Quality Analyzer

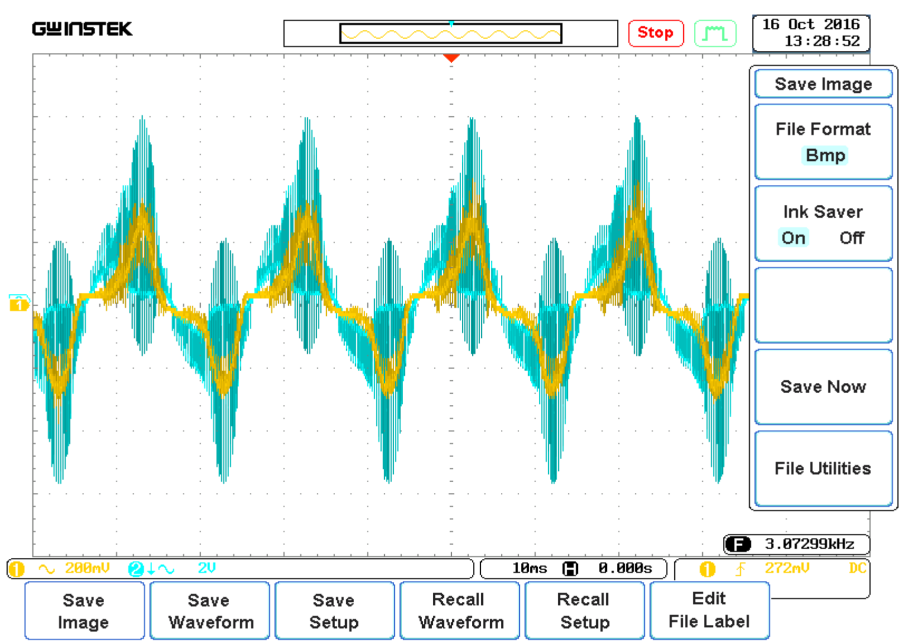


Figure 6.13: Input Voltage (Blue) and Input Current (Yellow) Waveforms for Modified-1 Single Phase Ĉuk Rectifier for D = 0.7 From Oscilloscope

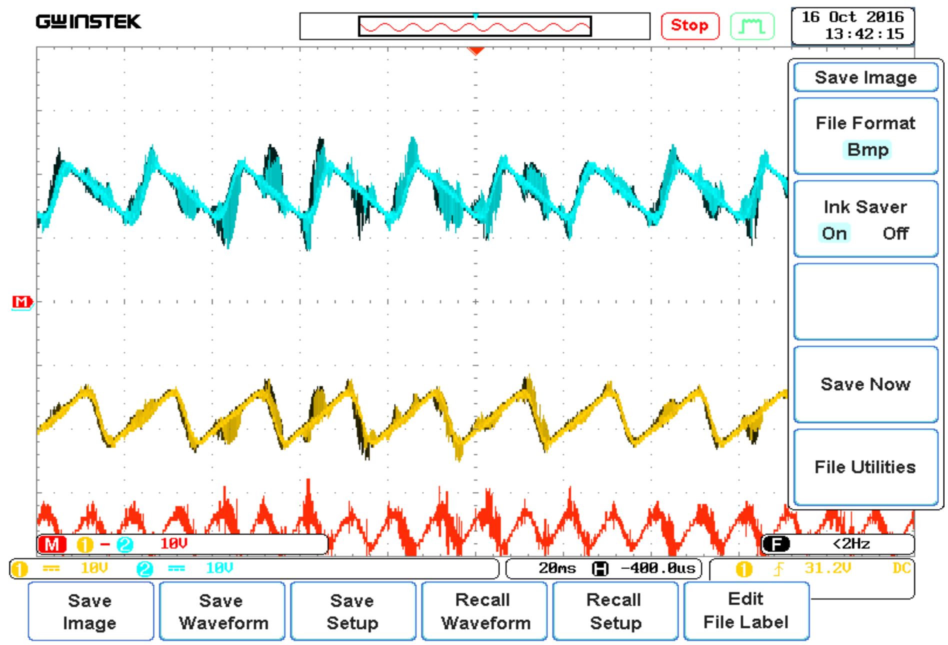


Figure 6.14: Output Voltage (Red) for Modified-1 Single Phase Ĉuk Rectifier for D = 0.7 From Oscilloscope

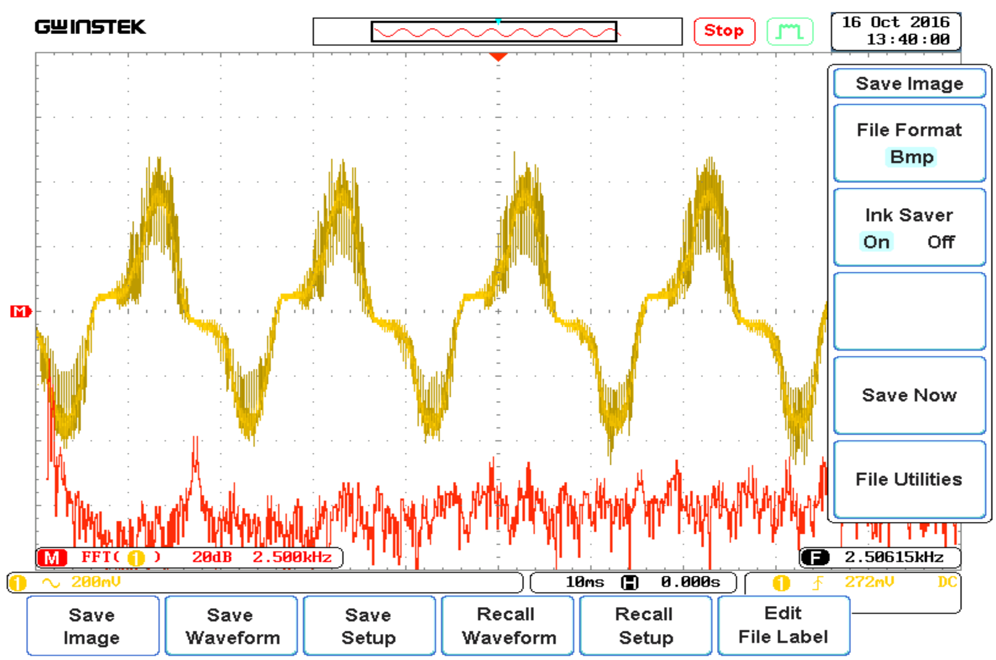


Figure 6.15: Input Current (Yellow) and its Fourier Transform (Red) for Modified-1 Single Phase Ĉuk Rectifier for D = 0.7 From Oscilloscope

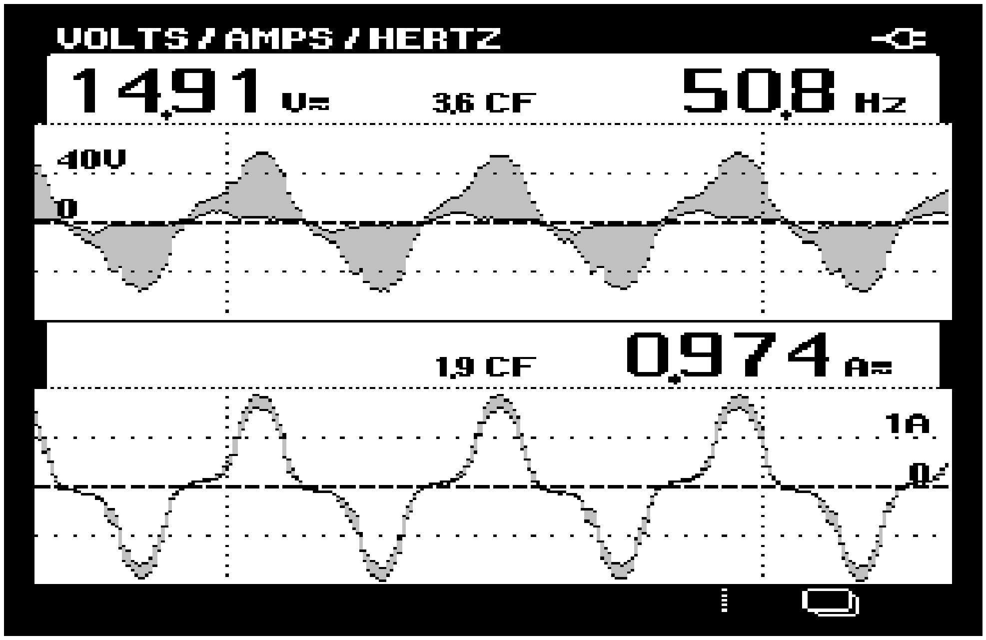


Figure 6.16: Input Voltage and Input Current waveforms for Modified-1 Single Phase Ĉuk Rectifier for D = 0.7 From Power Quality Analyzer

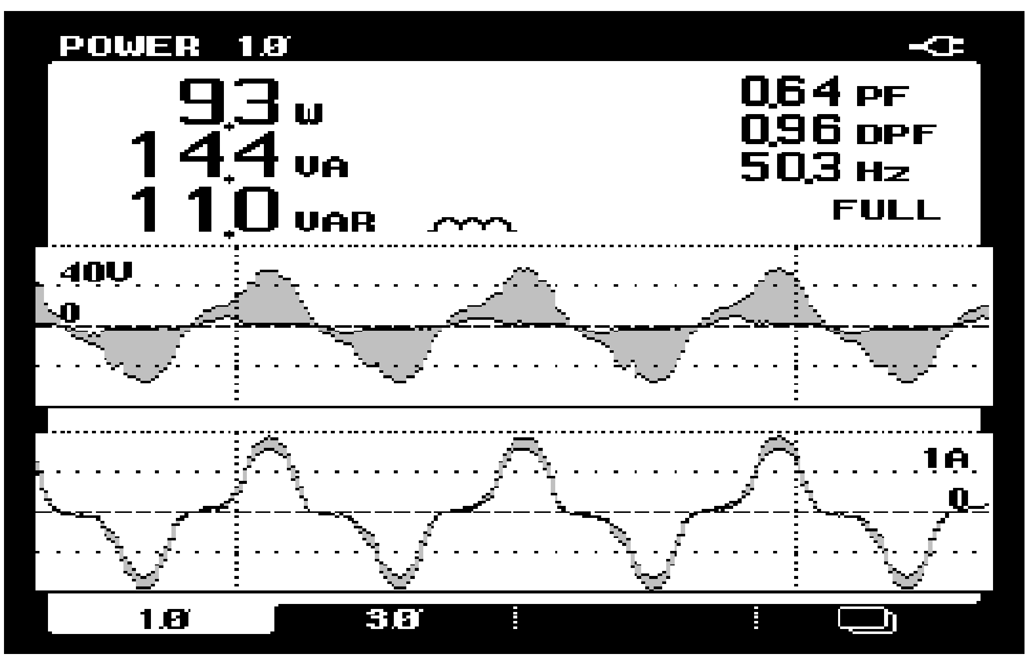


Figure 6.17: Power factor, Real power, Reactive Power, Apparent Power of Modified-1 Single Phase Ĉuk Rectifier for D = 0.7 From Power Quality Analyzer

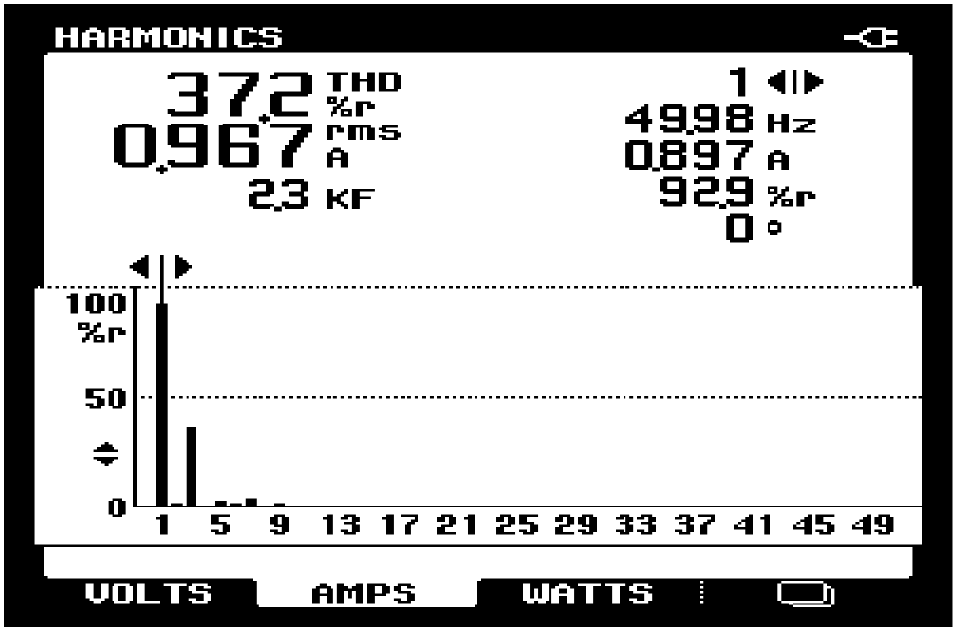


Figure 6.18: Spectrum of Input Current of Modified-1 Single Phase Ĉuk Rectifier for D = 0.7 From Power Quality Analyzer

6.2 Single Phase Modified Ĉuk AC-DC Converter Switched Within Bridge Configuration-2

The experimental results of the proposed single phase Modified - 2 AC-DC converter on Ĉuk topology based power factor corrected (PFC) rectifier without feedback have been recorded in Table 6.2 and graphically represented in Figures 6.19 to 6.36 for duty cycle (D) of 0.3, 0.5 and 0.7. It is evident that the converter has buck-boost voltage gain, and power factor above 0.8 for D of 0.3, 0.5. THD of input current is greater than 30 percent. For improved power factor further and input current THD, proper feedbacks are necessary.

Table 6.2: Performance single phase Modified Cuk AC-DC converter switched within bridge configuration-2

Duty Cycle	Input Voltage	Output Voltage	THD %	PF	Input Power	Efficiency %
0.3	14.93	- 12.0	35	0.87	0.8	90.0
0.5	15.16	- 25.0	50.9	0.74	3.9	80.12
0.7	14.89	- 40.0	33.8	0.64	10.8	74.07

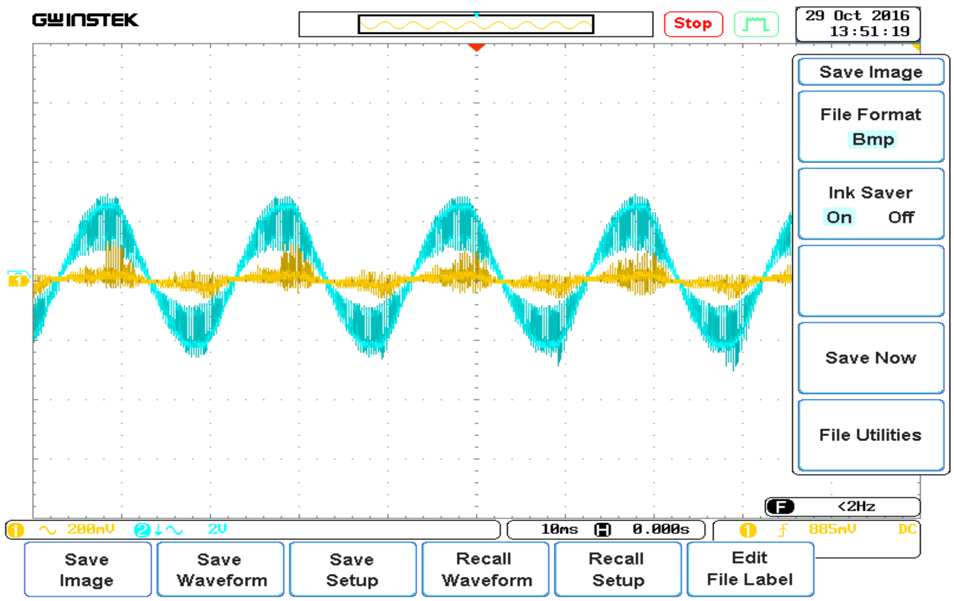


Figure 6.19: Input Voltage (Blue) and Input Current (Yellow) Waveforms for Modified-2 Single Phase Ĉuk Rectifier for D = 0.3 From Oscilloscope

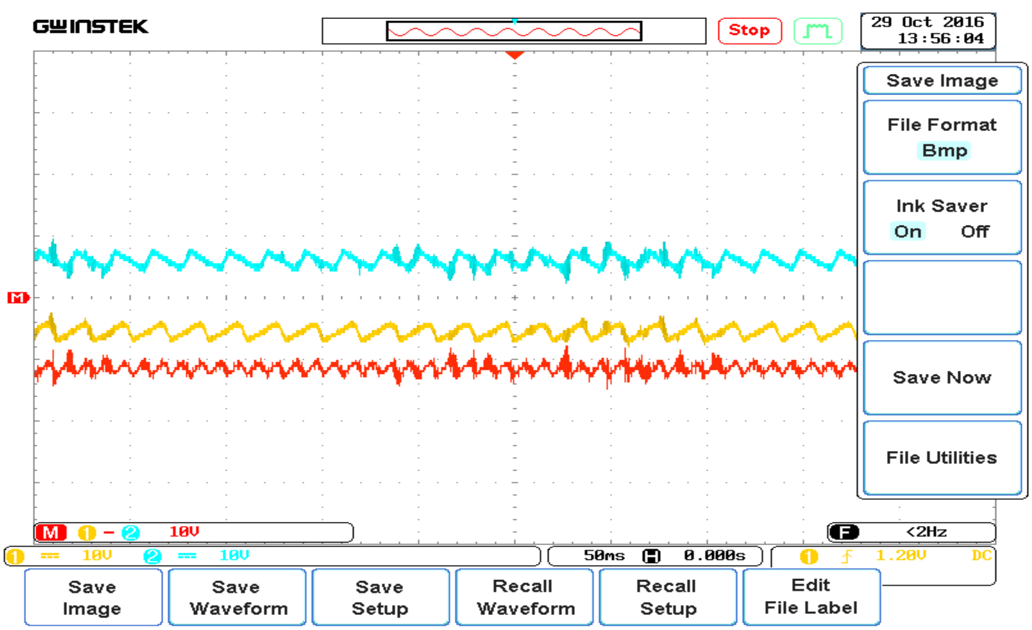


Figure 6.20: Output and Intermediate Capacitor Voltages (Red) for Modified-2 Single Phase Ĉuk Rectifier for D = 0.3 From Oscilloscope

Figure 6.21: Input Current (Yellow) and its Fourier Transform (Red) for Modified-2 Single Phase Ĉuk Rectifier for D = 0.3 From Oscilloscope

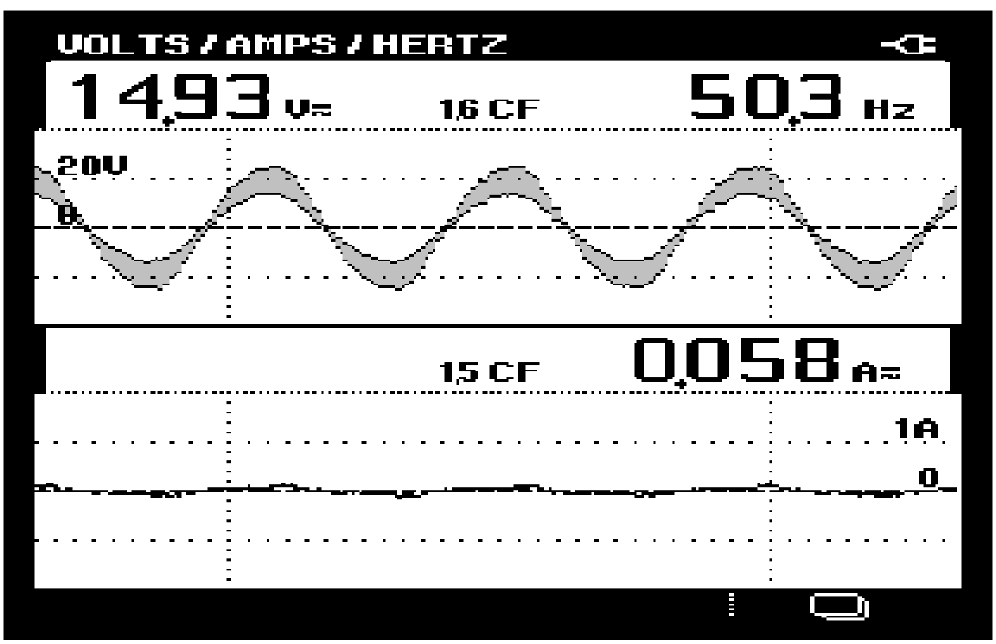


Figure 6.22: Input Voltage and Input Current waveforms for Modified-2 Single Phase Ĉuk Rectifier for D = 0.3 From Power Quality Analyzer

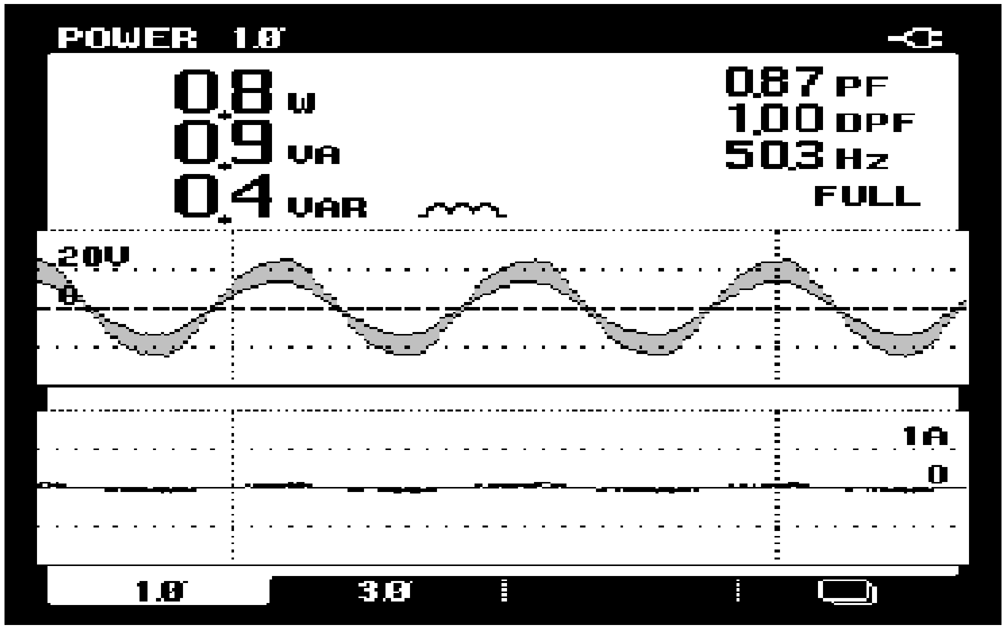


Figure 6.23: Power factor, Real power, Reactive Power, Apparent Power of Modified-2 Single Phase Ĉuk Rectifier for D = 0.3 From Power Quality Analyzer

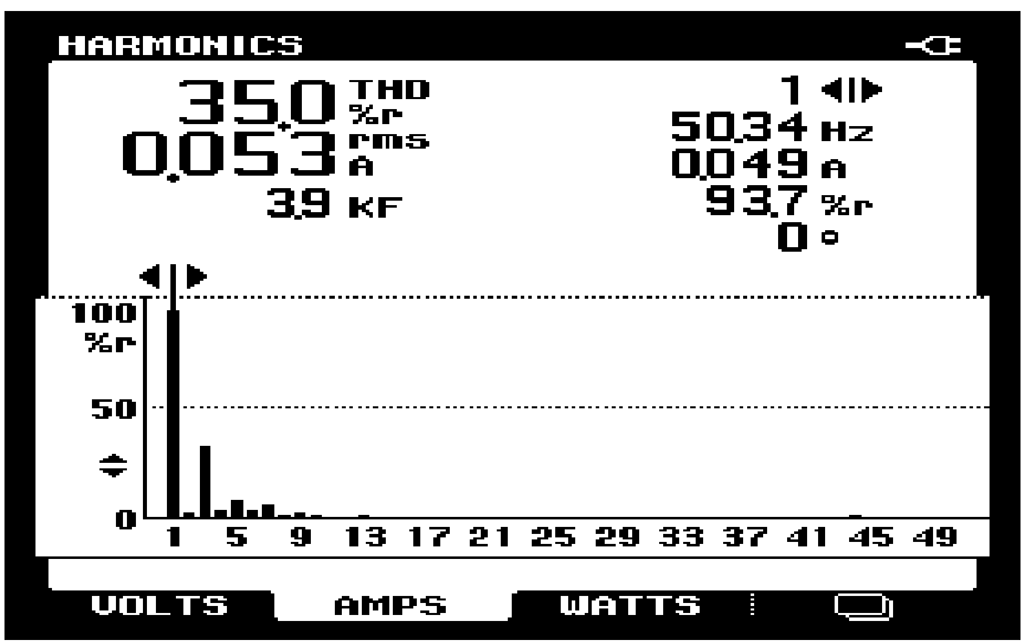


Figure 6.24: Spectrum of Input Current of Modified-2 Single Phase Ĉuk Rectifier for D = 0.3 From Power Quality Analyzer

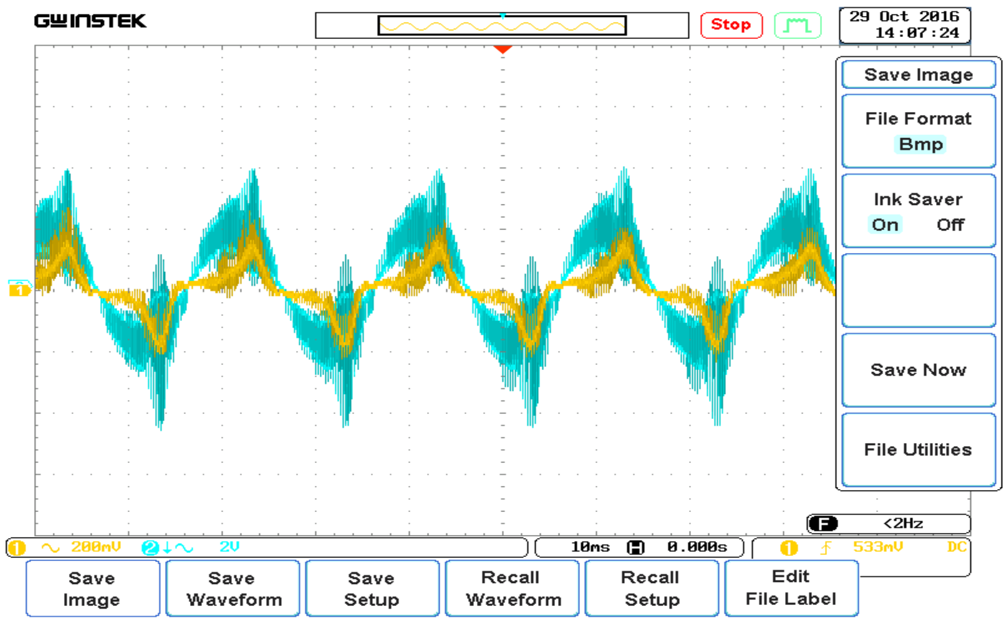


Figure 6.25: Input Voltage (Blue) and Input Current (Yellow) Waveforms for Modified-2 Single Phase Ĉuk Rectifier for D = 0.5 From Oscilloscope

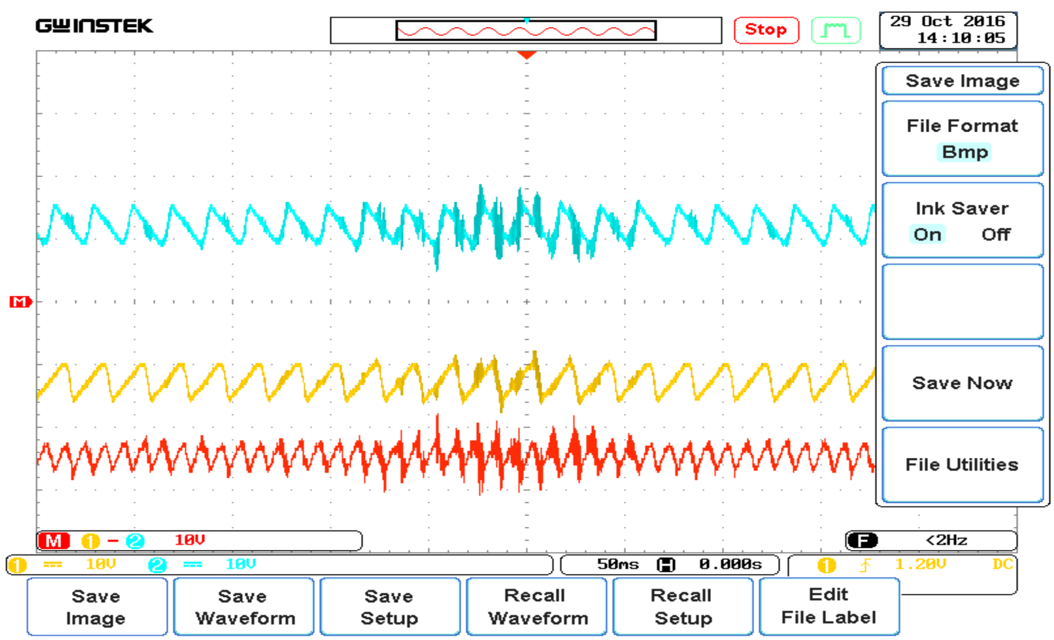


Figure 6.26: Output and Intermediate Capacitor Voltages for Modified-2 Single Phase Ĉuk Rectifier for D = 0.5 From Oscilloscope

Figure 6.27: Input Current (Yellow) and its Fourier Transform (Red) for Modified-2 Single Phase Ĉuk Rectifier for D = 0.5 From Oscilloscope

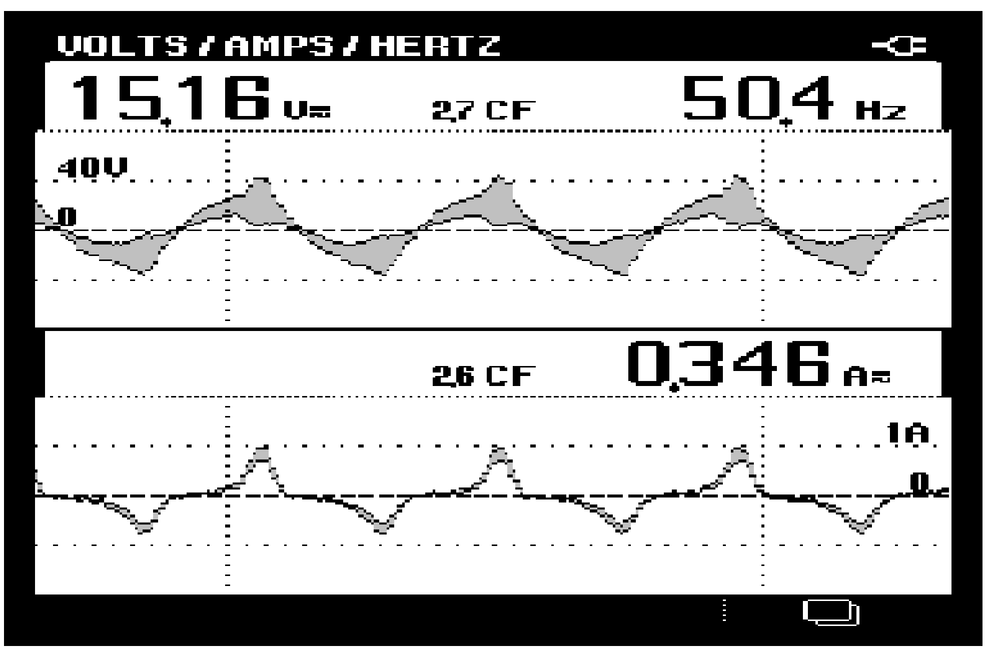


Figure 6.28: Input Voltage and Input Current waveforms for Modified-2 Single Phase Ĉuk Rectifier for D = 0.5 From Power Quality Analyzer

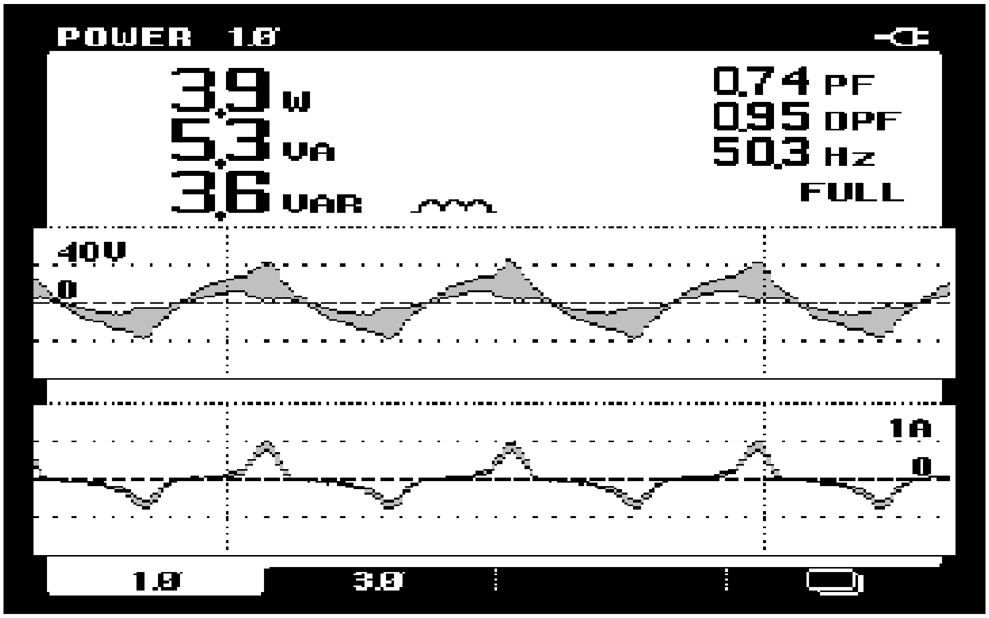


Figure 6.29: Power factor, Real power, Reactive Power, Apparent Power of Modified-3 Single Phase Ĉuk Rectifier for D = 0.5 From Power Quality Analyzer

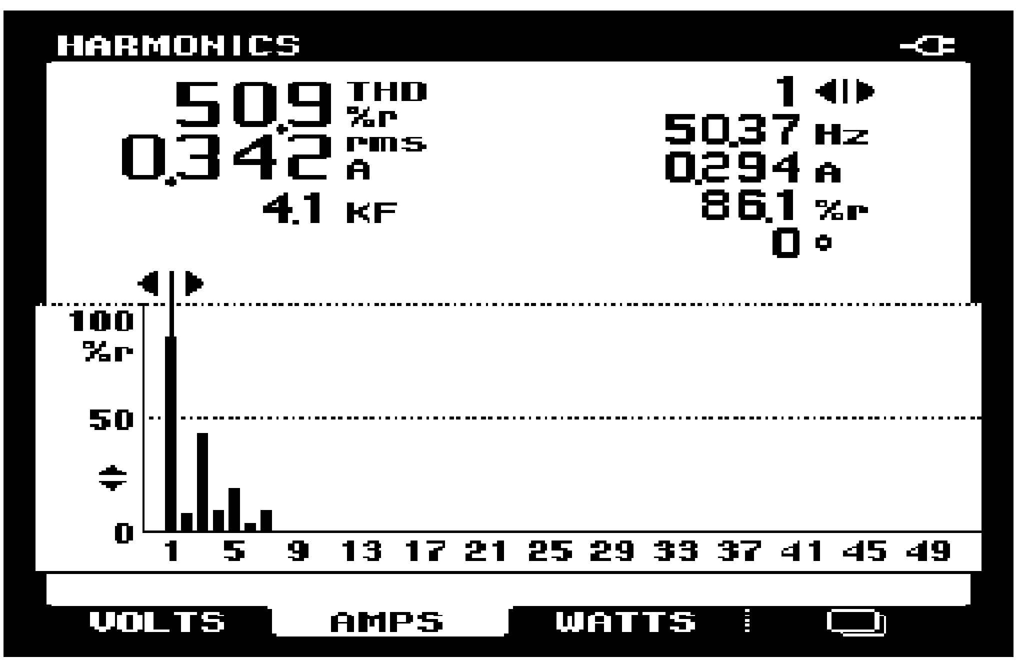


Figure 6.30: Spectrum of Input Current of Modified-2 Single Phase Ĉuk Rectifier for D = 0.5 From Power Quality Analyzer

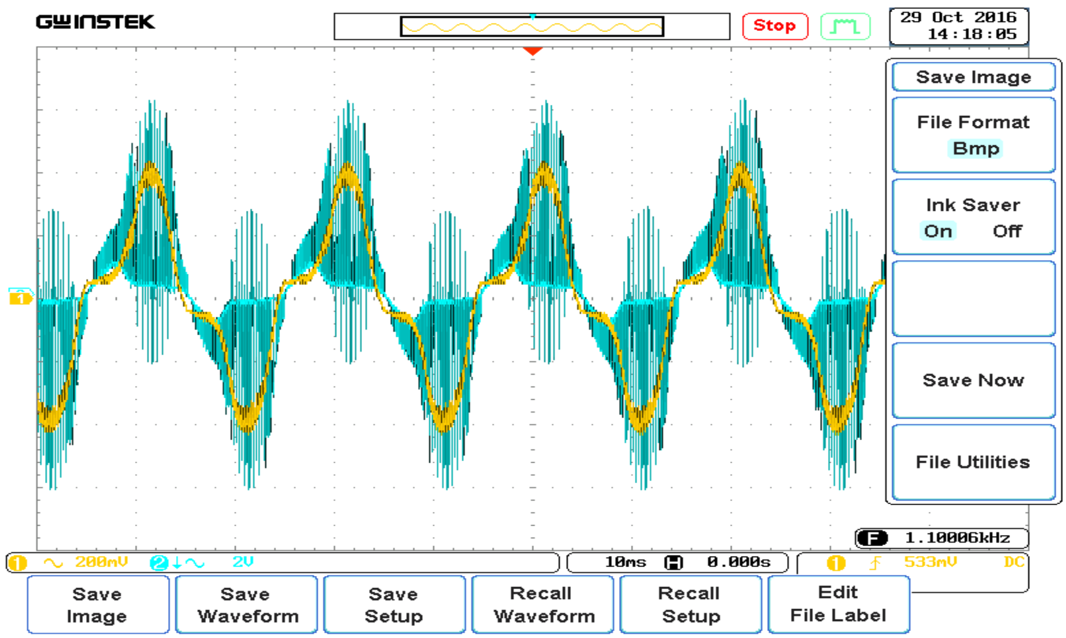


Figure 6.31: Input Voltage (Blue) and Input Current (Yellow) Waveforms for Modified-2 Single Phase Ĉuk Rectifier for D = 0.7 From Oscilloscope

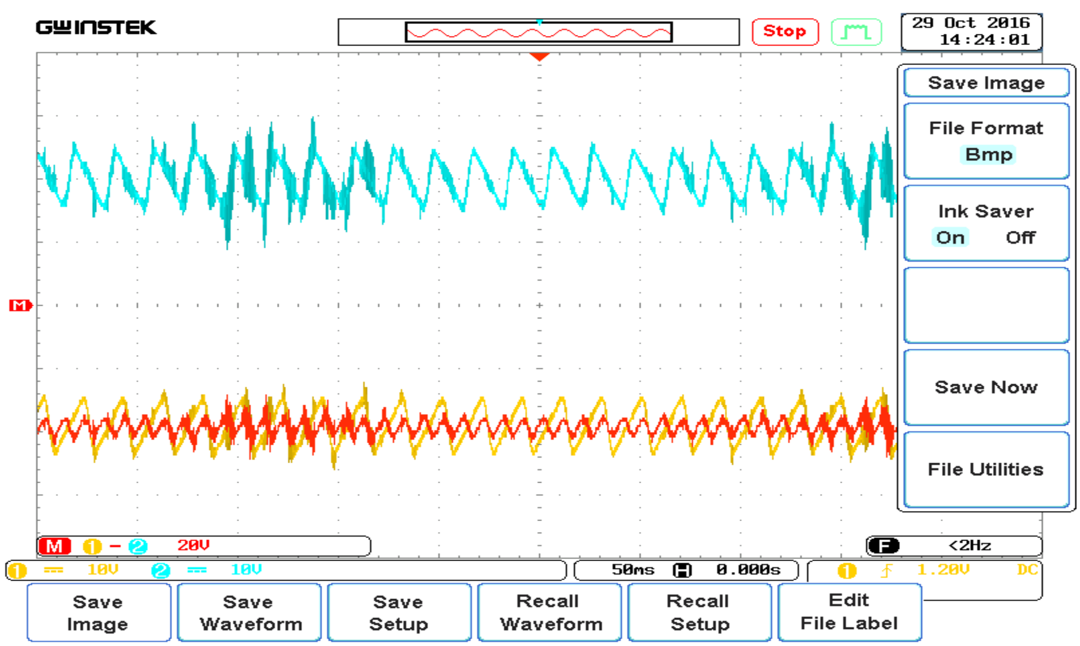


Figure 6.32: Output and Intermediate Capacitor Voltages for Modified-2 Single Phase Ĉuk Rectifier for D = 0.7 From Oscilloscope

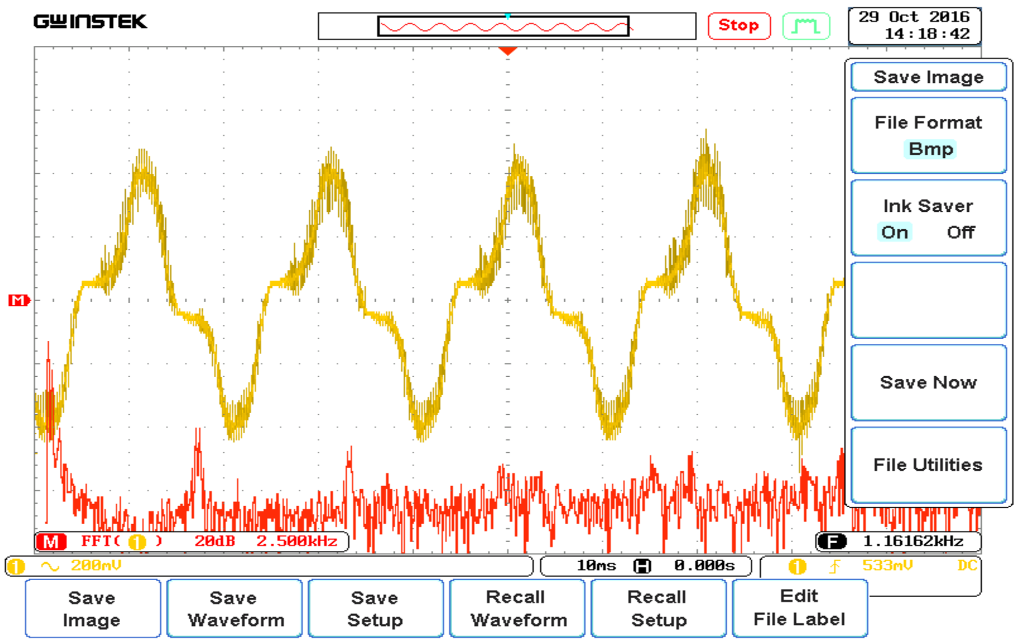


Figure 6.33: Input Current (Yellow) and its Fourier Transform (Red) for Modified-2 Single Phase Ĉuk Rectifier for D = 0.7 From Oscilloscope

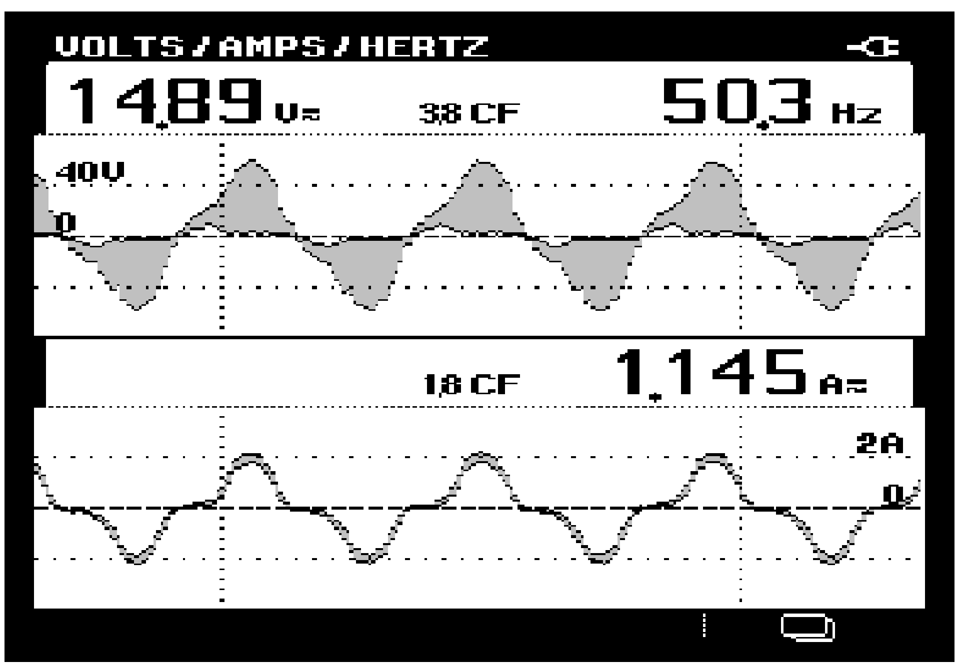


Figure 6.34: Input Voltage and Input Current waveforms for Modified-2 Single Phase Ĉuk Rectifier for D = 0.7 From Power Quality Analyzer

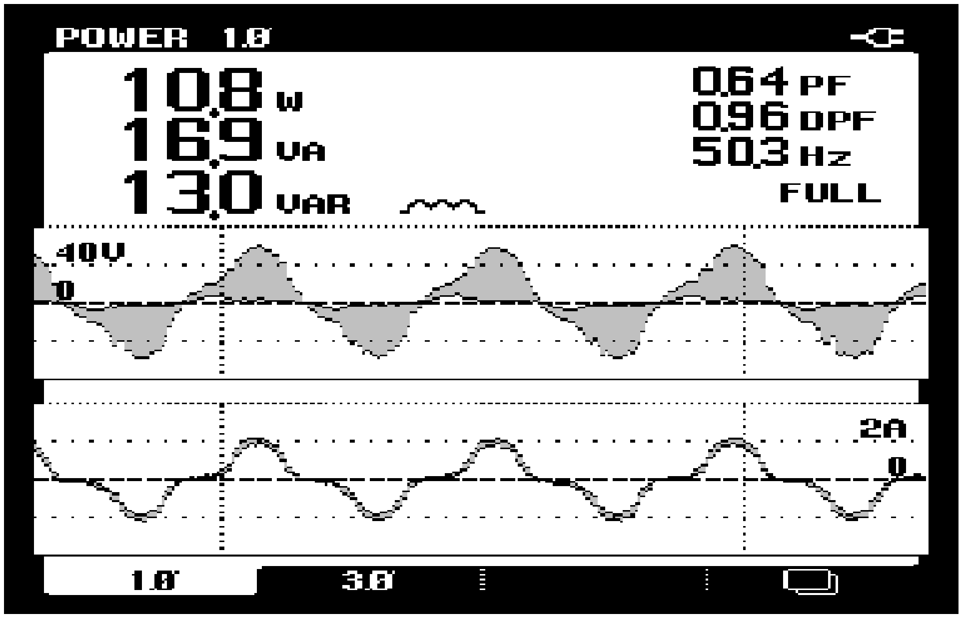


Figure 6.35: Power factor, Real power, Reactive Power, Apparent Power of Modified-2 Single Phase Ĉuk Rectifier for D = 0.7 From Power Quality Analyzer

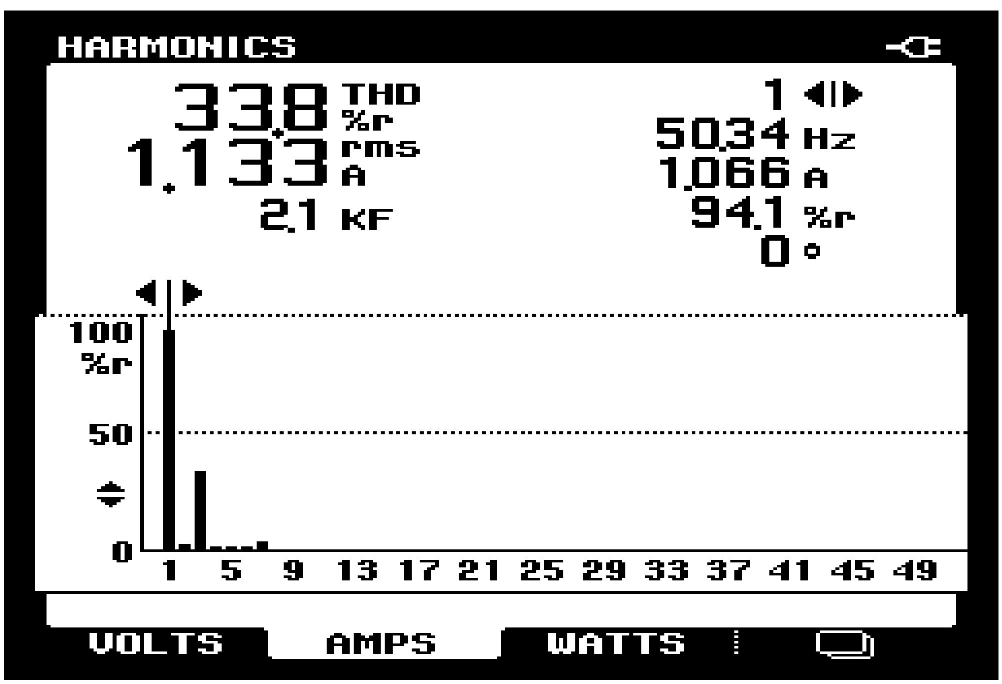


Figure 6.36: Spectrum of Input Current of Modified-2 Single Phase Ĉuk Rectifier for D = 0.7 From Power Quality Analyzer

Table 6.3: Comparison of experimental results of performance between proposed Modified-1 and Modified -2 configurations of AC-DC converter

Configuration		Modified - 1			Modified - 2		
Duty Cycle		0.3	0.5	0.7	0.3	0.5	0.7
Gain	Theoretical	0.61	1.41	3.30	0.61	1.41	3.30
	Simulated	1.14	2.56	4.77	1.14	2.56	4.77
	Experimental	1.07	1.6	2.35	0.8	1.65	2.68
Efficiency (%)	Simulated	98.48	98.44	98.19	98.49	98.45	98.19
	Experimental	75.29	84.7	65.86	90	80.12	74.07
THD (%)	Simulated	52.93	46.16	24.05	52.93	46.16	23.94
	Experimental	42.4	50.3	37.2	35	50.9	33.8
Power Factor	Simulated	0.87	0.88	0.82	0.87	0.88	0.82
	Experimental	0.84	0.74	0.64	0.87	0.74	0.64

From Table 6.1 it is evident that proposed Modified -1 and Modified -2 single phase AC-DC converter switched within bridge have almost similar voltage gain, efficiency, THD and power factor with variation of duty cycle. Modified -2 will be better choice as it uses less circuit component (three inductors used in design). Sometimes it is not necessary to connect the inductor at the input side because secondary windings of transformer of power supply can do the similar work of input inductor. Hence, Modified -2 configuration is cost effective. For further improved results proper feedback controller must be used with the rectifier. The results obtained experimentally show some deviation from theoretically simulated results. In practical implementation of the topologies, due to non-ideal components of the circuits the characteristics of the circuits slightly differ from the mere theoretical analysis.

Chapter 7
Conclusion

7.1 Summary of the Thesis

The conventional single phase output switched boost and Ĉuk rectifiers have been studied at first. The input current was found non sinusoidal pulsating and the THD was high. In this thesis, four different configurations of single phase AC-DC converters based on Ĉuk topologies have been proposed. The configurations are input switched output-bridge, input switched output-bridgeless configuration-1 and configuration-2, modified -1 and modified -2 switched within bridge single phase AC-DC rectifier. To get less input current THD, improved power factor and high efficiency the converters are designed carefully to operate in both buck and boost region. The results are as expected from the designs. But input current THD are not in acceptable range and power factor deteriorates at high duty cycle. For improved power factor and lower input current THD and also to regulate the output voltage of the rectifier, proper feedback controller is designed in this thesis theoretically and studied by simulation. With change of ± 20Ω of l00Ω load the output voltage is regulated at a fixed level of output voltage. The feedback controller parameters are same for all the configurations which are included in this thesis with only a single gain change parameter (which is variable) used when operating as buck or boost converter. The design of the controller gives it versatility for using it to different configurations. PFC controller of the rectifier, was able to keep input current THD below 10% and power factor of the circuits above 0.9. The proposed configurations give better performance than the conventional ones. Among the proposed configurations, Modified -1 and Modified – 2 AC-DC converter switched within bridge give best performance in terms of input current THD, power factor and efficiency and also show better performance than the conventional output switched boost and Ĉuk rectifiers.

7.2 Future Work

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

- The four different configurations of single phase Ĉuk rectifiers can be designed for three phase rectifiers also.
- Proper feedback controller designed for three phase rectifiers of four configurations will be able to give regulated output voltage, lower input current THD, improved power factor of the circuit. If the design of the controller is made in such a way that the controller parameters are same for all the proposed configurations of three phase rectifier, then complexity of the circuitry will be reduced and will be easier for practical implementation of the configurations.
- During the investigation of this work operation of power circuits of this proposed topologies were implemented in a low voltage and low current prototype modules. The results of the prototypes are presented in the thesis in the form of typical waveforms, spectrums and power quality analyzer recording. However, the circuits were not implemented with feedback controllers due to non-availability of appropriate ICs and sensors. In future work proposed circuits may be designed, fabricated and tested at practical operating voltages and currents with proper feedback circuits.

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