Single Phase AC-DC Hybrid Boost-SEPIC (HBS) Converter for Improver Power Quality at High Duty Cycle and HBS Converter with Three Phase Inverter Integrated with a LCL Filter

A THESIS SUBMITTED TO THE ACADEMIC FACULTY IN PARTIAL FULFILLMENT OF THE REQUIREMENT FOR THE DEGREE OF BACHELOR OF SCIENCE IN TECHNICAL EDUCATION IN ELECTRICAL AND ELECTRONIC ENGINEERING

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CHAPTER 1

Abstract

Modern day devices often use an AC source as input even though they are operated with DC voltage. In order to have a suitable and flexible DC output, an AC-DC converter is used. However the conventional converters are not suited for high voltage output without sacrificing conversion efficiency. In this paper a new topology of Hybridized Boost-SEPIC (HBS) converter is proposed. This converter is capable of delivering output voltage as high as 1255V at high conversion efficiency. Maximum power factor of 0.97 and minimum THD of 9.94% is ensured by current mode PI controller.

The need of renewable energy is on the rise especially the use of solar energy. Solar energy usually provides with DC power. In order to harvest solar energy effectively, the HBS converter is also integrated with a three phase inverter, with an LCL filter to provide AC supply.

CHAPTER 2

Introduction

2.1 Fundamentals of Power Electronics

This chapter gives a description and overview of power electronic technologies including a description of the fundamental systems that are the building blocks of power electronic systems. Technologies that are described include: power semiconductor switching devices, converter circuits that process energy from one DC level to another DC level, converters that produce variable frequency from DC sources, principles of rectifying AC input voltage in uncontrolled DC output voltage and their extension to controlled rectifiers, converters that convert to AC from DC (inverters) or from AC with fixed or variable output frequency (AC controllers, DC–DC–AC converters, matrix converters, or cyclo- converters). The chapter also covers control of power converters with focus on pulse width modulation (PWM) control techniques.

2.2 Definition, History, Applications and Trends of Power Electronics

Power electronics (PE) experienced tremendous growth after the introduction of the first solid-state power switch, the silicon controlled rectifier (SCR) in 1957. Today, almost all of the technologies that require control of power control utilize PE technology. This chapter will give the reader an overview on the field of PE.

Power electronic circuits are used to control the power conversion from one or more AC or DC sources to one or more AC or DC loads, and sometimes with bidirectional capabilities. In most power electronics systems, this conversion is accomplished with two functional modules called the control stage and the power stage. Figure 2.1 shows the topology for a single source and single load converter application that includes a power processor (the power stage) and a controller (the control stage). The converter, handles the power transfer from the input to output, or vice versa, and is constituted of power semiconductor devices acting as switches, plus passive devices (inductor and capacitor). The controller is responsible for operating the switches according to specific algorithms monitoring physical quantities (usually voltages and currents) measured at the system input and or output.

The modern PE era began in 1957. It was during that year the first commercial thyristor, or Silicon Controlled Rectifier (SCR), was introduced by General Electric Company. The SCR, started replacing the mercury arc rectifiers, invented in 1902, and the later developed thyratron (invented in 1923) and ignitron (invented in 1931), allowed the commercialization of several industrial circuits conceived during the 1920s and 1940s (like the cyclo-converter, the chopper, and the parallel inverter) as well as the Graetz bridge conceived in 1897.

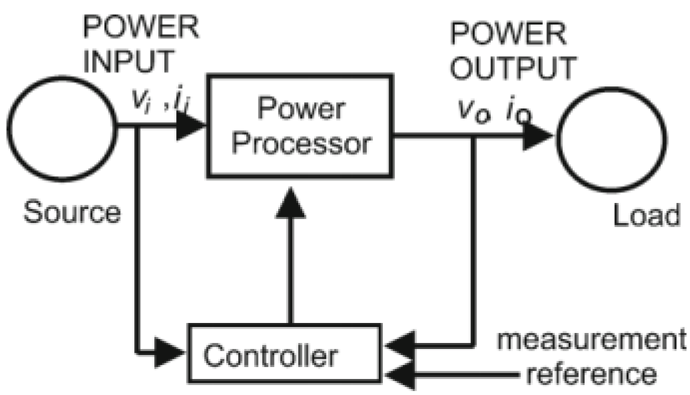


Fig. 2.1 A general power electronic system

The SCR was the only available power device for more than 25 years after its invention (and still is very useful for extremely high power applications). Since it is very difficult to impose turn-off conditions for SCR’s, faster devices, with higher voltage and current capabilities, with better controllability were developed, including the bipolar junction transistor (BJT) invented in 1970. The BJT was used in applications from low to medium power and frequency and now is considered obsolete. The metal oxide semiconductor field effect transistor (MOSFET) was invented in 1978 and is used for power electronic switching applications of low power and high frequencies. The gate turnoff thyristor (GTO), is used in applications from medium to high power and from low to medium frequencies. The insulated gate bipolar transistor (IGBT) developed in 1983 is used in applications from low to medium power and frequency. The integrated gate commutated thyristor (IGCT) invented in 1997 is used in applications from medium to high power and from low to medium frequencies.

Through the use of this switching technology power electronics systems can operate in the range from few watts up to GW, with frequency range from some 100 Hz up to some 100 kHz, depending on the power handled [1]. The advent of microelectronics and computer control made it possible to apply modern control theory to PE and at same the time made possible very complex circuit functions. Therefore, the area of PE, became interdisciplinary, as indicated in Fig. 2.2. At the high power level, PE deals with static and rotating equipment for generation, transmission, and distribution handling large amount of power. For consumer electronic applications power converters and circuits are important for information processing, employing analog and digital circuits, or microprocessors including microcontrollers, digital signal processors (DSP), and field programmable gate arrays (FPGA). In the area of control, PE deals with stability and response characteristics in systems with feedback loops, based on classical or modern control. With the development of very large system integration (VLSI), ultra large system integration (ULSI), and other sophisticated computer-assisted designs; advanced control systems could be used to develop new power electronic topologies.

The development of devices and equipment able to individually or in combination convert efficiently electric energy from AC to DC, DC to DC, DC to AC, and AC to AC together with the changes that occurred in electrical power engineering has resulted in wide spread of PE in a large spectrum of applications.

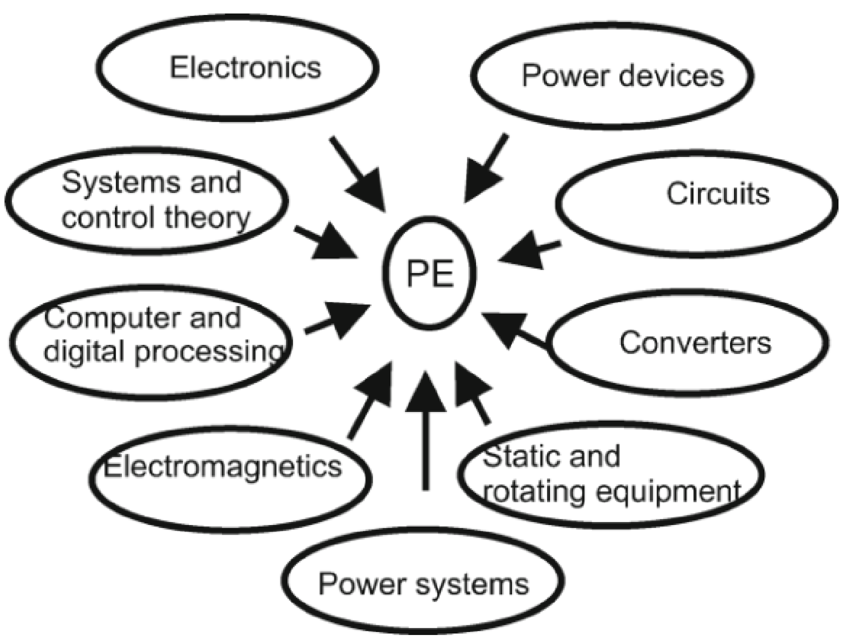


Fig 2.2 Power electronics and related topics

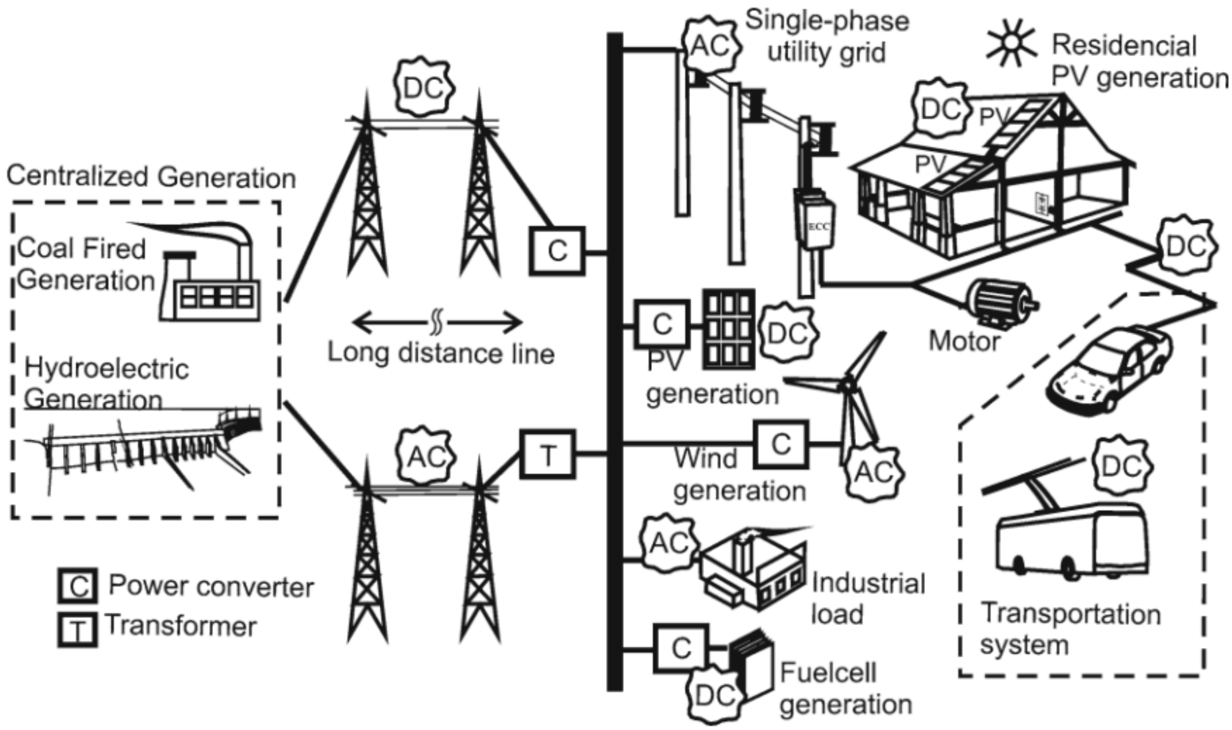


Fig. 2.3 Power electronics and electrical energy generation transmission, storage, and distribution

Figure 2.3 shows how electrical energy generation is distributed for the end-user, showing transmission, distribution, storage, renewable energy sources and users. In fact, nowadays PE is a key technology for all those sub-systems, and has spread in many applications, examples including:

- Residential: heaters, home appliances, electronic lighting, equipment sources;
- Commercial: heaters, fans, elevators Uninterruptible Power Supply (UPS), AC and DC breakers, battery chargers;
- Industrial: pumps, blowers, robots, inductive heaters, welding, machine drive, portable sources;
- Transportation: electrical and hybrid vehicles, battery chargers, railroad electric system;
- Utility systems: high voltage direct current, generators, reactive compensators, interface for photovoltaic, wind, fuel cells systems, Flexible AC Transmission Systems (FACTS) equipment;
- Aerospace: sources for spacecrafts, satellites, planes;

- Communication: sources, RF amplifiers, audio-amplifiers

  Power electronics will continue to be an enabling technology to address our future electricity needs. It is expected that new power devices for higher power, higher frequency, and lower losses will continue to be invented. Global energy concerns will provoke a large interest in the increase of the conversion efficiency and more application of PE in power quality, distributed generation, energy conservation, and smart grids. The integration of power and control circuitry into functional modules will result in systems solutions that are highly integrated into packaged products that will be both more reliable and affordable.

CHAPTER 3

Boost Converter

A boost converter (step-up converter) is a DC-to-DC power converter that steps up voltage (while stepping down current) from its input (supply) to its output (load). It is a class of switched-mode power supply (SMPS) containing at least two semiconductors (a diode and a transistor) and at least one energy storage element: a capacitor, inductor, or the two in combination. To reduce voltage ripple, filters made of capacitors (sometimes in combination with inductors) are normally added to such a converter's output (load-side filter) and input (supply-side filter).

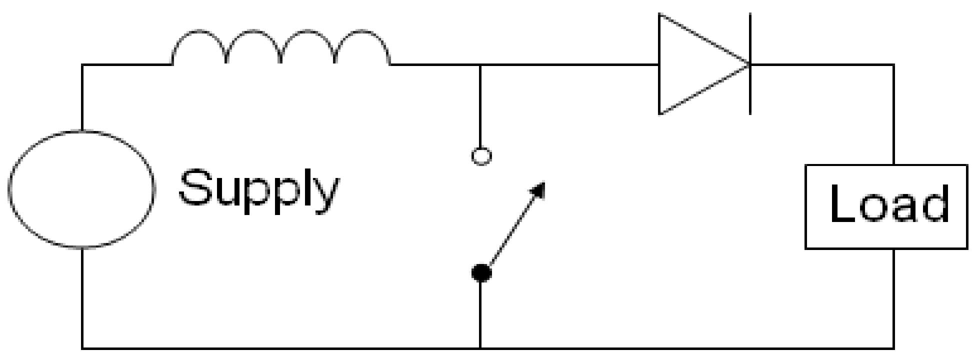


Figure 3.1 Boost converter

3.1 Overview

Power for the boost converter can come from any suitable DC sources, such as batteries, solar panels, rectifiers and DC generators. A process that changes one DC voltage to a different DC voltage is called DC to DC conversion. A boost converter is a DC to DC converter with an output voltage greater than the source voltage. A boost converter is sometimes called a step-up converter since it "steps up" the source voltage. Since power ($P = VI$) must be conserved, the output current is lower than the source current.

3.2 History

For high efficiency, the SMPS switch must turn on and off quickly and have low losses. The advent of a commercial semiconductor switch in the 1950s represented a major milestone that made SMPSs such as the boost converter possible. The major DC to DC converters were developed in the early 1960s when semiconductor switches had become available. The aerospace industry’s need for small, lightweight, and efficient power converters led to the converter’s rapid development.

Switched systems such as SMPS are a challenge to design since their models depend on whether a switch is opened or closed. R. D. Middlebrook from Caltech in 1977 published the models for DC to DC converters used today. Middlebrook averaged the circuit configurations for each switch state in a technique called state-space averaging. This simplification reduced two systems into one. The new model led to insightful design equations which helped the growth of SMPS.

3.3 Applications

Battery power systems often stack cells in series to achieve higher voltage. However, sufficient stacking of cells is not possible in many high voltage applications due to lack of space. Boost converters can increase the voltage and reduce the number of cells. Two battery-powered applications that use boost converters are used in hybrid electric vehicles (HEV) and lighting systems.

The NHW20 model Toyota Prius HEV uses a 500 V motor. Without a boost converter, the Prius would need nearly 417 cells to power the motor. However, a Prius actually uses only 168 cells and boosts the battery voltage from 202 V to 500 V. Boost converters also power devices at smaller scale applications, such as portable lighting systems. A white LED typically requires 3.3 V to emit light, and a boost converter can step up the voltage from a single 1.5 V alkaline cell to power the lamp.

An unregulated boost converter is used as the voltage increase mechanism in the circuit known as the 'Joule thief'. This circuit topology is used with low power battery applications, and is aimed at the ability of a boost converter to 'steal' the remaining energy in a battery. This energy would otherwise be wasted since the low voltage of a nearly depleted battery makes it unusable for a normal load. This energy would otherwise remain untapped because many applications do not allow enough current to flow through a load when voltage decreases. This voltage decrease occurs as batteries become depleted, and is a characteristic of the ubiquitous alkaline battery. Since the equation for power is (

$P = V^2/R$), and R tends to be stable, power available to the load goes down significantly as voltage decreases.

3.4 Operation

The key principle that drives the boost converter is the tendency of an inductor to resist changes in current by creating and destroying a magnetic field. In a boost converter, the output voltage is always higher than the input voltage. A schematic of a boost power stage is shown in figure below.

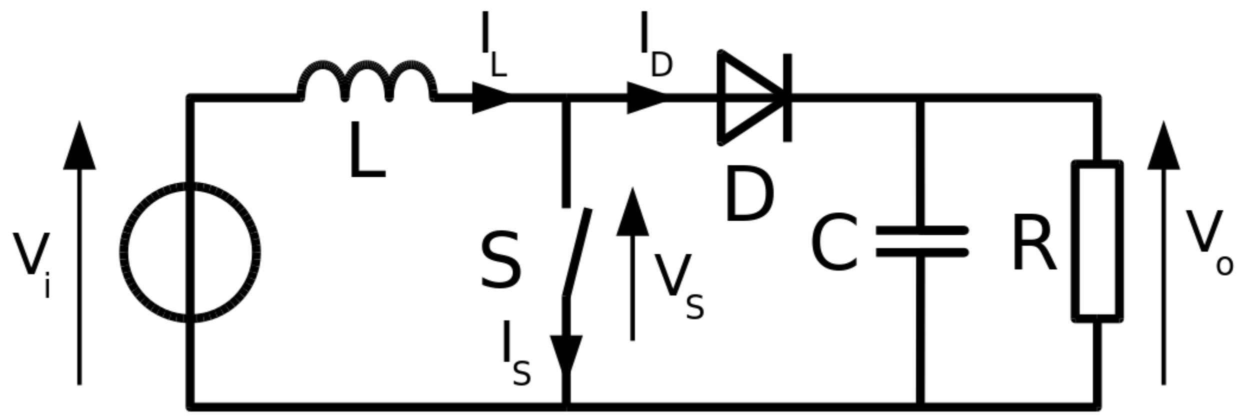


Figure 3.2 Schematic of Boost converter

a) When the switch is closed, current flows through the inductor in clockwise direction and the inductor stores some energy by generating a magnetic field. Polarity of the left side of the inductor is positive.
b) (b) When the switch is opened, current will be reduced as the impedance is higher. The magnetic field previously created will be destroyed to maintain the current towards the load. Thus the polarity will be reversed (means left side of inductor will be negative now). As a result, two sources will be in series causing a higher voltage to charge the capacitor through the diode D.

If the switch is cycled fast enough, the inductor will not discharge fully in between charging stages, and the load will always see a voltage greater than that of the input source alone when the switch is opened. Also while the switch is opened, the capacitor in parallel with the load is charged to this combined voltage. When the switch is then closed and the right hand side is shorted out from the left hand side, the capacitor is therefore able to provide the voltage and energy to the load. During this time, the blocking diode prevents the capacitor from discharging through the switch. The switch must of course be opened again fast enough to prevent the capacitor from discharging too much.

The basic principle of a Boost converter consists of 2 distinct states:

In the On-state, the switch S is closed, resulting in an increase in the inductor current;

In the Off-state, the switch is open and the only path offered to inductor current is through the flyback diode D, the capacitor C and the load R. This results in transferring the energy accumulated during the On-state into the capacitor.

The input current is the same as the inductor current as can be seen in figure below. So it is not discontinuous as in the buck converter and the requirements on the input filter are relaxed compared to a buck converter.

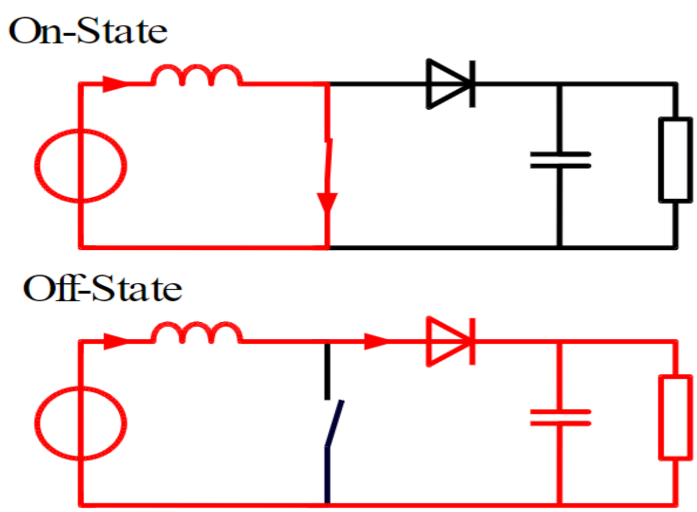


Figure 3.3 Current flow in on and off state

3.4.1 Continuous mode

When a boost converter operates in continuous mode, the current through the inductor (I_L) never falls to zero. Figure 3 shows the typical waveforms of currents and voltages in a converter operating in this mode. The output voltage can be calculated as follows, in the case of an ideal converter (i.e. using components with an ideal behavior) operating in steady conditions:

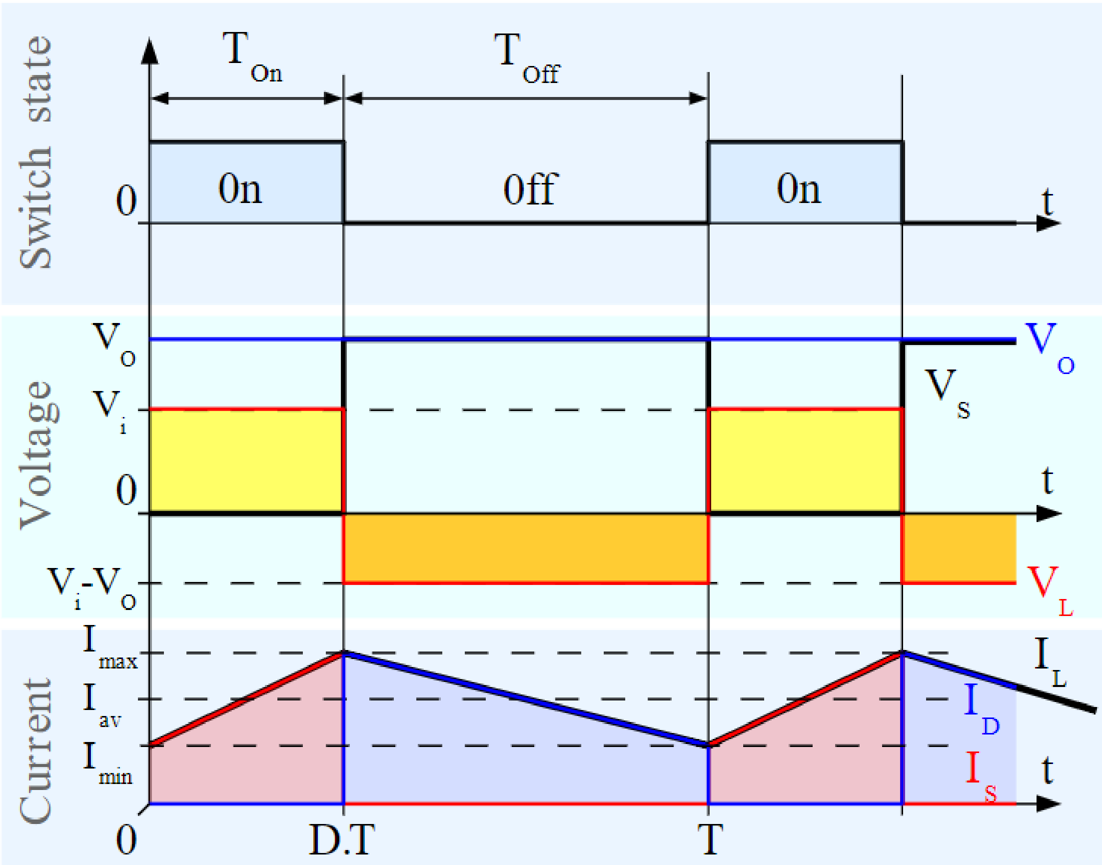


Figure 3.4 Switching, voltage and current graph for continuous mode

During the On-state, the switch S is closed, which makes the input voltage (V_i) appear across the inductor, which causes a change in current (I_L) flowing through the inductor during a time period (t) is given by the formula:

$$\frac{\Delta I_L}{\Delta t} = \frac{V_i}{L}$$

At the end of the On-state, the increase of I_L is therefore:

$$\Delta I_{L_{On}} = \frac{1}{L}\int_0^{DT} V_i dt = \frac{DT}{L} V_i$$

D is the duty cycle. It represents the fraction of the commutation period T during which the switch is On. Therefore, D ranges between 0 (S is never on) and 1 (S is always on).

During the Off-state, the switch S is open, so the inductor current flows through the load. If we consider zero voltage drop in the diode, and a capacitor large enough for its voltage to remain constant, the evolution of I_L is:

$$V_i - V_o = L\frac{dI_L}{dt}$$

Therefore, the variation of I_L during the Off-period is:

$$\Delta I_{L_{Off}} = \int_{DT}^{T} \frac{(V_i - V_o)\,dt}{L} = \frac{(V_i - V_o)\,(1-D)\,T}{L}$$

As we consider that the converter operates in steady-state conditions, the amount of energy stored in each of its components has to be the same at the beginning and at the end of a commutation cycle. In particular, the energy stored in the inductor is given by:

$$E = \frac{1}{2}LI_L^2$$

So, the inductor current has to be the same at the start and end of the commutation cycle. This means the overall change in the current (the sum of the changes) is zero:

$$\Delta I_{L_{On}} + \Delta I_{L_{Off}} = 0$$

Substituting the expressions yields:

$$\Delta I_{L_{On}} + \Delta I_{L_{Off}} = \frac{V_i DT}{L} + \frac{(V_i - V_o)\,(1-D)\,T}{L} = 0$$

This can be written as:

$$\frac{V_o}{V_i} = \frac{1}{1-D}$$

The above equation shows that the output voltage is always higher than the input voltage (as the duty cycle goes from 0 to 1), and that it increases with D, theoretically to infinity as D approaches 1. This is why this converter is sometimes referred to as a step-up converter.

Rearranging the equation reveals the duty cycle to be:

$$D = 1 - \frac{V_i}{V_o}$$

3.4.2 Discontinuous mode

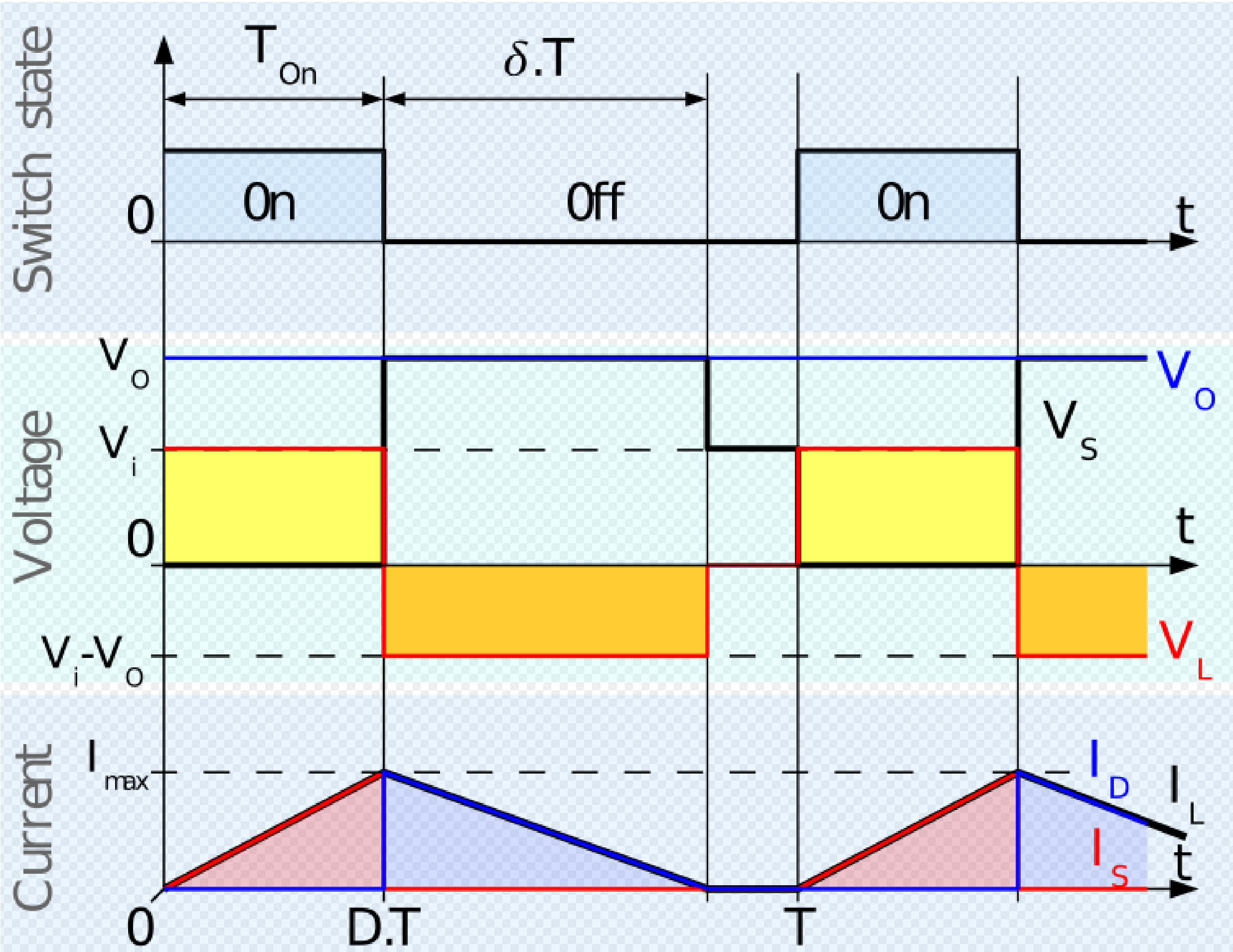


Figure 3.5 Switching, voltage and current graph for discontinuous mode

If the ripple amplitude of the current is too high, the inductor may be completely discharged before the end of a whole commutation cycle. This commonly occurs under light loads. In this case, the current through the inductor falls to zero during part of the period (see waveforms in figure). Although the difference is slight, it has a strong effect on the output voltage equation. The voltage gain can be calculated as follows:

As the inductor current at the beginning of the cycle is zero, its maximum value is

$$I_{L_{Max}} = \frac{V_i DT}{L}$$

During the off-period, I_L falls to zero

$$I_{L_{Max}} + \frac{(V_i - V_o)\,\delta T}{L} = 0$$

Using the two previous equations, δ is:

$$\delta = \frac{V_i D}{V_o - V_i}$$

The load current I_O is equal to the average diode current (I_D). As can be seen on figure 4, the diode current is equal to the inductor current during the off-state. Therefore, the output current can be written as:

$$I_o = \bar{I_D} = \frac{I_{L_{max}}}{2}\delta$$

Replacing I_{Lmax} and δ by their respective expressions yield:

$$I_o = \frac{V_i DT}{2L} \cdot \frac{V_i D}{V_o - V_i} = \frac{V_i^2 D^2 T}{2L\,(V_o - V_i)}$$

Therefore, the output voltage gain can be written as follows:

$$\frac{V_o}{V_i} = 1 + \frac{V_i D^2 T}{2LI_o}$$

Compared to the expression of the output voltage gain for continuous mode, this expression is much more complicated. Furthermore, in discontinuous operation, the output voltage gain not only depends on the duty cycle (D), but also on the inductor value (L), the input voltage (V_i), the commutation period (T) and the output current (I_O).

Substituting $I_O = V_O/R$ into the equation (R is the load), the output voltage gain can be rewritten as:

$$\frac{V_o}{V_i} = \frac{1 + \sqrt{1 + \frac{4D^2}{K}}}{2}$$

where $= \frac{2L}{RT}$.

CHAPTER 4

SEPIC Converter

The single-ended primary-inductor converter (SEPIC) is a type of DC/DC converter that allows the electrical potential (voltage) at its output to be greater than, less than, or equal to that at its input. The output of the SEPIC is controlled by the duty cycle of the control transistor.

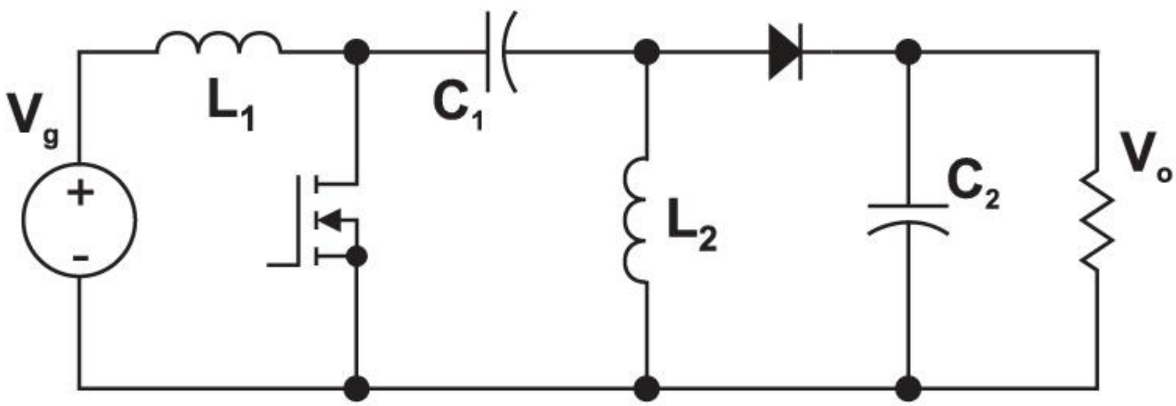


Figure 4.1 SEPIC converter

A SEPIC is essentially a boost converter followed by a buck-boost converter, therefore it is similar to a traditional buck-boost converter, but has advantages of having non-inverted output (the output has the same voltage polarity as the input), using a series capacitor to couple energy from the input to the output (and thus can respond more gracefully to a short-circuit output), and being capable of true shutdown: when the switch is turned off, its output drops to 0 V, following a fairly hefty transient dump of charge.

The architecture is very similar to a boost converter. However, with a boost converter there is a dc path that flows through the inductor and rectifier diode into the output capacitor meaning the output voltage can never be lower than the input voltage. With a SEPIC converter, =A capacitor breaks this dc path enabling the output of a SEPIC converter to start from 0V.

Another benefit of the SEPIC converter is that it can also act as a low noise buck converter. The conventional buck converter has sharp edges on the input current that can interfere with circuitry connected to the input voltage. With the SEPIC converter, the input inductor slows down the input current edges thus providing a lower noise buck regulator solution.

4.1 Applications

SEPICs are useful in applications in which a battery voltage can be above and below that of the regulator's intended output. For example, a single lithium ion battery typically discharges from 4.2 volts to 3 volts; if other components require 3.3 volts, then the SEPIC would be effective.

A buck converter regulates a high voltage into a smaller voltage, so input voltage is greater than output voltage. For example, for a car charger for a cell phone, 12 V is converted down to 5 V. On the other hand, a boost converter regulates a small voltage into a higher voltage, so input voltage is smaller than output voltage. For example, an LED driver with a 3 V input converts to a 9 V output. A SEPIC converter combines those functions and allows a circuit to have flexible input voltages with a stable output voltage

Typical SEPIC applications include the following:

1) Battery-operated equipments and handheld devices
2) NiMH chargers
3) LED lighting applications
4) DC power supplies with a wide range of input voltages

4.2 Circuit operation

The schematic diagram for a basic SEPIC is shown in below. As with other switched mode power supplies (specifically DC-to-DC converters), the SEPIC exchanges energy between the capacitors and inductors in order to convert from one voltage to another. The amount of energy exchanged is controlled by switch S1, which is typically a transistor such as a MOSFET. MOSFETs offer much higher input impedance and lower voltage drop than bipolar junction transistors (BJTs), and do not require biasing resistors as MOSFET switching is controlled by differences in voltage rather than a current, as with BJTs.

4.3 Continuous mode

A SEPIC is said to be in continuous-conduction mode ("continuous mode") if the current through the inductor L1 never falls to zero. During a SEPIC's steady-state operation, the average voltage across capacitor C1 (VC1) is equal to the input voltage (Vin). Because capacitor C1 blocks direct current (DC), the average current through it (IC1) is zero, making inductor L2 the only source of DC load current. Therefore, the average current through inductor L2 (IL2) is the same as the average load current and hence independent of the input voltage.

Looking at average voltages, the following can be written:

$$V_{IN} = V_{L1} + V_{C1} + V_{L2}$$

Because the average voltage of VC1 is equal to VIN, VL1 = −VL2. For this reason, the two inductors can be wound on the same core. Since the voltages are the same in magnitude, their effects of the mutual inductance will be zero, assuming the polarity of the windings is correct. Also, since the voltages are the same in magnitude, the ripple currents from the two inductors will be equal in magnitude.

The average currents can be summed as follows (average capacitor currents must be zero):

$$I_{D1} = I_{L1} - I_{L2}$$

When switch S1 is turned on, current IL1 increases and the current IL2 goes more negative. (Mathematically, it decreases due to arrow direction.) The energy to increase the current IL1 comes from the input source. Since S1 is a short while closed, and the instantaneous voltage VL1 is approximately VIN, the voltage VL2 is approximately −VC1. Therefore, the capacitor C1 supplies the energy to increase the magnitude of the current in IL2 and thus increase the energy stored in L2. The easiest way to visualize this is to consider the bias voltages of the circuit in a dc state, then close S1.

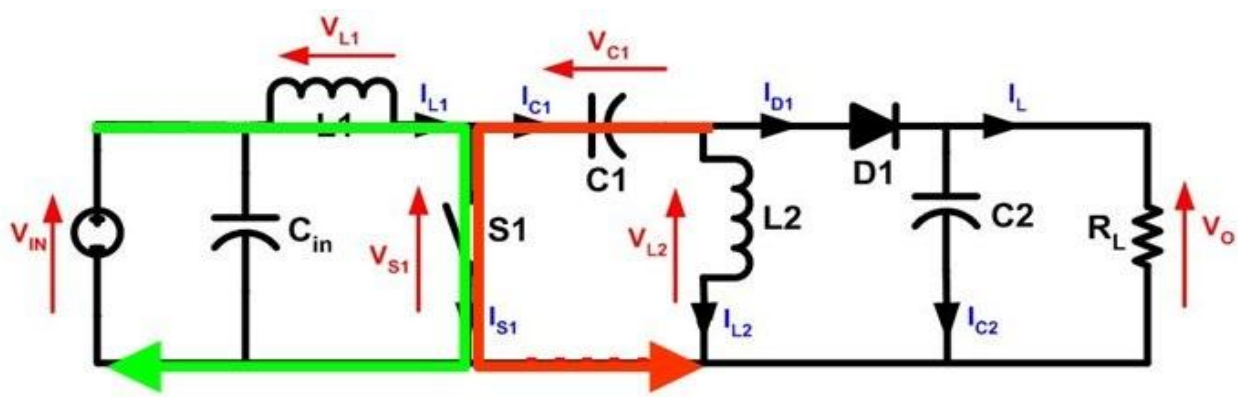


Figure 4.2 Current flow when switch is on

When switch S1 is turned off, the current IC1 becomes the same as the current IL1, since inductors do not allow instantaneous changes in current. The current IL2 will continue in the negative direction, in fact it never reverses direction. It can be seen from the diagram that a negative IL2 will add to the current IL1 to increase the current delivered to the load. Using Kirchhoff's Current Law, it can be shown that ID1 = IC1 - IL2. It can then be concluded, that while S1 is off, power is delivered to the load from both L2 and L1. C1, however is being charged by L1 during this off cycle, and will in turn recharge L2 during the on cycle.

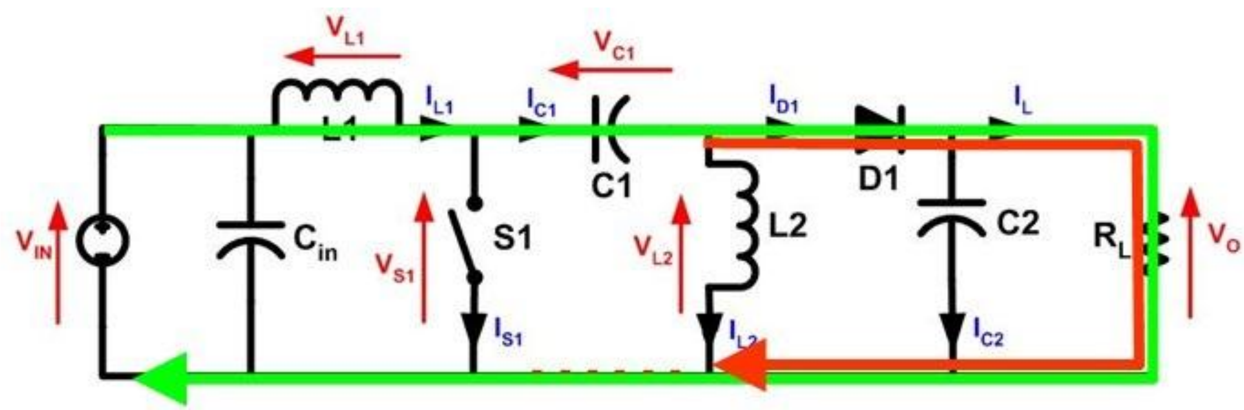


Figure 4.3 Current flow when switch is off

Because the potential (voltage) across capacitor C1 may reverse direction every cycle, a non-polarized capacitor should be used. However, a polarized tantalum or electrolytic capacitor may be used in some cases, because the potential (voltage) across capacitor C1 will not change unless the switch is closed long enough for a half cycle of resonance with inductor L2, and by this time the current in inductor L1 could be quite large.

The capacitor CIN is required to reduce the effects of the parasitic inductance and internal resistance of the power supply. The boost/buck capabilities of the SEPIC are possible because of capacitor C1 and inductor L2. Inductor L1 and switch S1 create a standard boost converter, which generates a voltage (VS1) that is higher than VIN, whose magnitude is determined by the duty cycle of the switch S1. Since the average voltage across C1 is VIN, the output voltage (VO) is VS1 - VIN. If VS1 is less than double VIN, then the output voltage will be less than the input voltage. If VS1 is greater than double VIN, then the output voltage will be greater than the input voltage.

The evolution of switched-power supplies can be seen by coupling the two inductors in a SEPIC converter together, which begins to resemble a Flyback converter, the most basic of the transformer-isolated SMPS topologies.

4.4 Reliability and efficiency

The voltage drop and switching time of diode D1 is critical to a SEPIC's reliability and efficiency. The diode's switching time needs to be extremely fast in order to not generate high voltage spikes across the inductors, which could cause damage to components. Fast conventional diodes or Schottky diodes may be used.

The resistances in the inductors and the capacitors can also have large effects on the converter efficiency and output ripple. Inductors with lower series resistance allow less energy to be dissipated as heat, resulting in greater efficiency (a larger portion of the input power being transferred to the load). Capacitors with low equivalent series resistance (ESR) should also be used for C1 and C2 to minimize ripple and prevent heat build-up, especially in C1 where the current is changing direction frequently.

4.5 Disadvantages

Like the buck–boost converter, the SEPIC has a pulsating output current. The similar Ćuk converter does not have this disadvantage, but it can only have negative output polarity, unless the isolated Ćuk converter is used.

Since the SEPIC converter transfers all its energy via the series capacitor, a capacitor with high capacitance and current handling capability is required.

The fourth-order nature of the converter also makes the SEPIC converter difficult to control, making it only suitable for very slow varying applications.

In order to overcome the disadvantages of conventional converters, in the next chapter, a new topology based on cascaded configuration will be discussed.

CHAPTER 5

Single Phase AC-DC Hybrid Boost-SEPIC (HBS) Converter for Improved Power Quality at High Duty Cycle

5.1 Introduction

In day to day life electronic devices are used in grid-connected systems, communication systems, power supply systems etc. Devices also operate in variable voltage levels. A converter that facilitates the capability of different level of operating voltage is essential for versatile use. But not all converters are able to make conversion properly without compromising performance. There is always a tradeoff between necessity and performance. High voltage gain will cause for a deterioration of signal shape (THD). Tradeoff is also visible among performance parameters of the converters. For example, improving power factor tends to decrease the efficiency. [14] These limitations can be addressed introducing cascaded converter topologies. [2 - 7]

Higher voltage conversion can be achieved using cascaded Boost-SEPIC converter. The proposed circuit will provide higher RMS voltage upto 90% duty cycle. The overall efficiency goes down slightly as the duty cycle rises in conventional converter.[8] Again increasing duty cycle causes conduction losses and serious reverse-recovery problem in diodes.[9][10] Also Boost converter can operate with lower voltage level of MOSFET. Boost converter also gives output with lower distortion which makes the circuit manage the THD level as low as possible. [11][12][13]

In this paper a new topology is introduced – Hybrid Boost SEPIC (HBS), which will be used to change the voltage level by varying the duty cycle. The proposed converter is a cascaded Boost and SEPIC converter. The converter is designed to obtain higher RMS voltage levels at different duty cycles with appreciable low THD.

5.2 CONVENTIONAL CONVERTERS

5.2.1 CONVENTIONAL BOOST CONVERTER

Most commonly used AC-DC converter are boost converters which consists of a bridge rectifier, followed by a DC-DC Boost converter. The converter is capable of supplying high voltage.

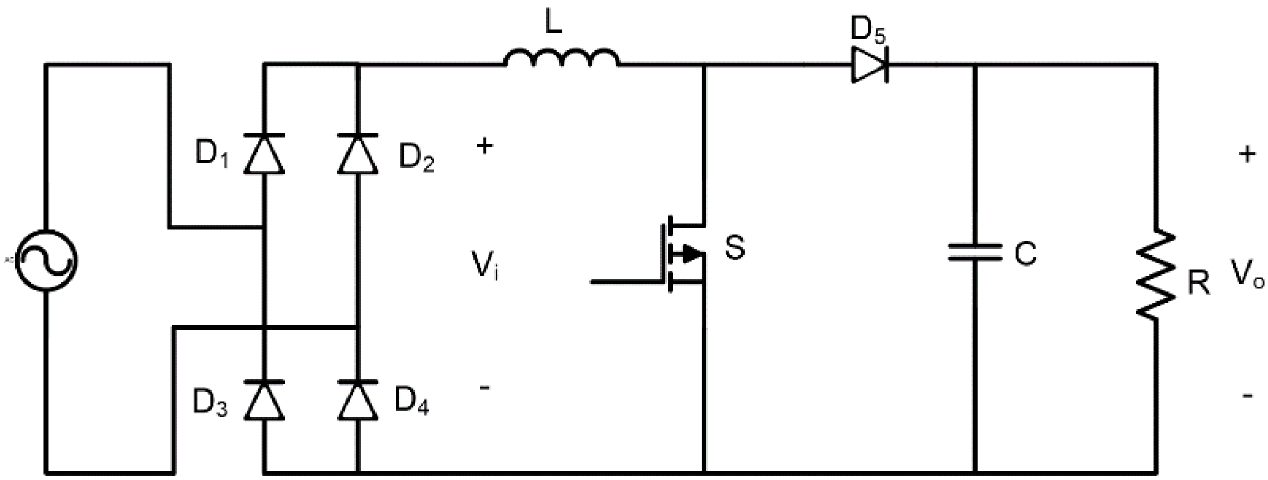


Fig. 5.1 Conventional Boost converter

The voltage gain of Boost converter is given as,

$$\frac{V_{o_1}}{V_o} = \frac{1}{1-D}$$

5.2.2 CONVENTIONAL SEPIC CONVERTER

DC-DC S a bridge rectifier for SEPIC converter is followed by a bridge rectifier forms the conventional AC-DC SEPIC converter. DC-DC SEPIC converter is designed as an extension of boost converter and by adding a buck-boost converter with it, the output of which is non-inverting.

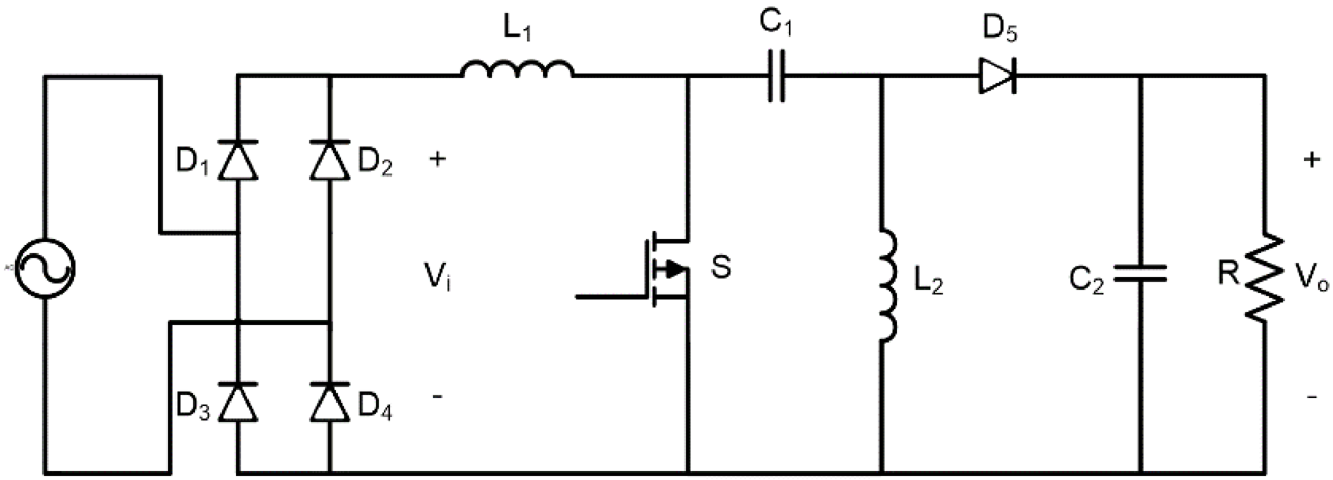


Fig. 5.2 Conventional Sepic converter

The voltage gain of SEPIC converter is given as,

$$\frac{V_{o_2}}{V_o} = \frac{D}{1-D}$$

5.3 PROPOSED CIRCUIT AND OPERATION

The proposed circuit, HBS converter is a combination of the Boost and SEPIC converter. The proposed HBS converter consists of six diodes (D1-D6), three capacitors (C0-C2), two inductors (L0-L1), a load resistor (RL), and a switch (MOSFET).

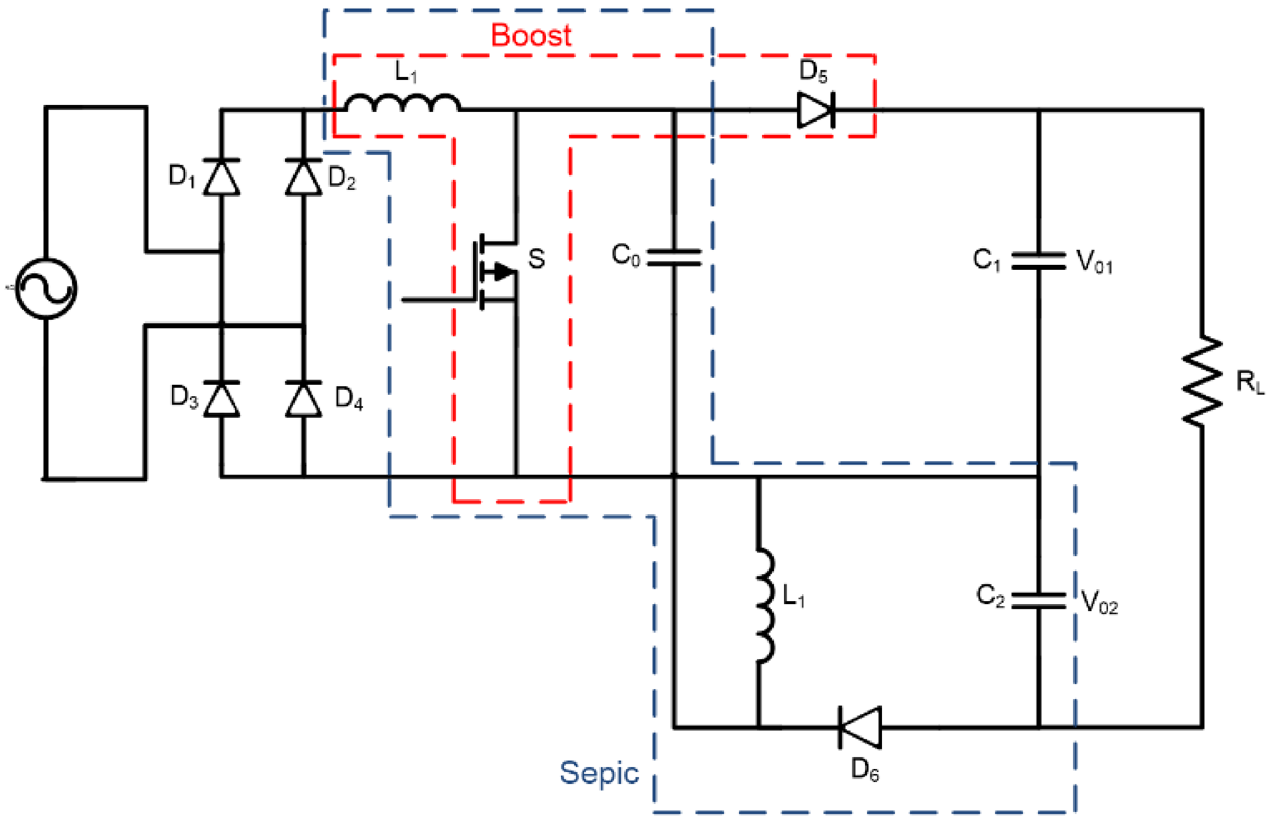
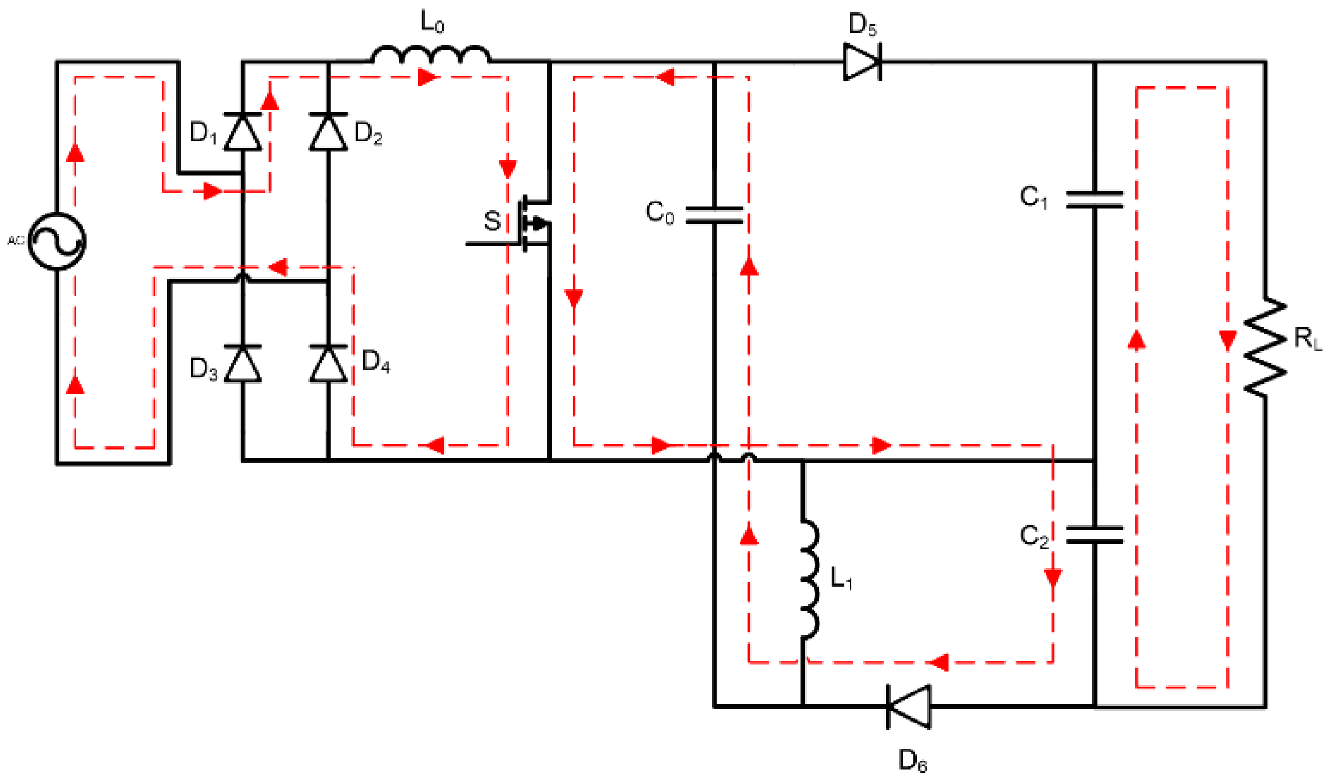
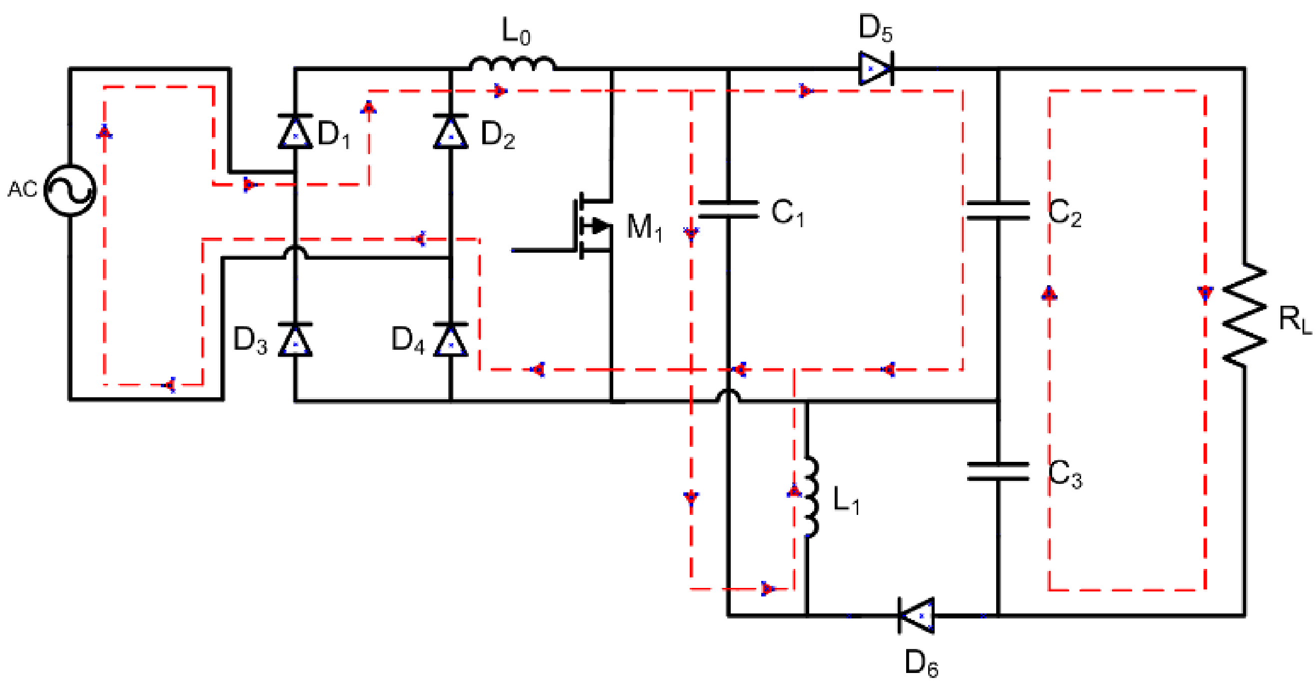


Fig. 5.3 Proposed HBS converter

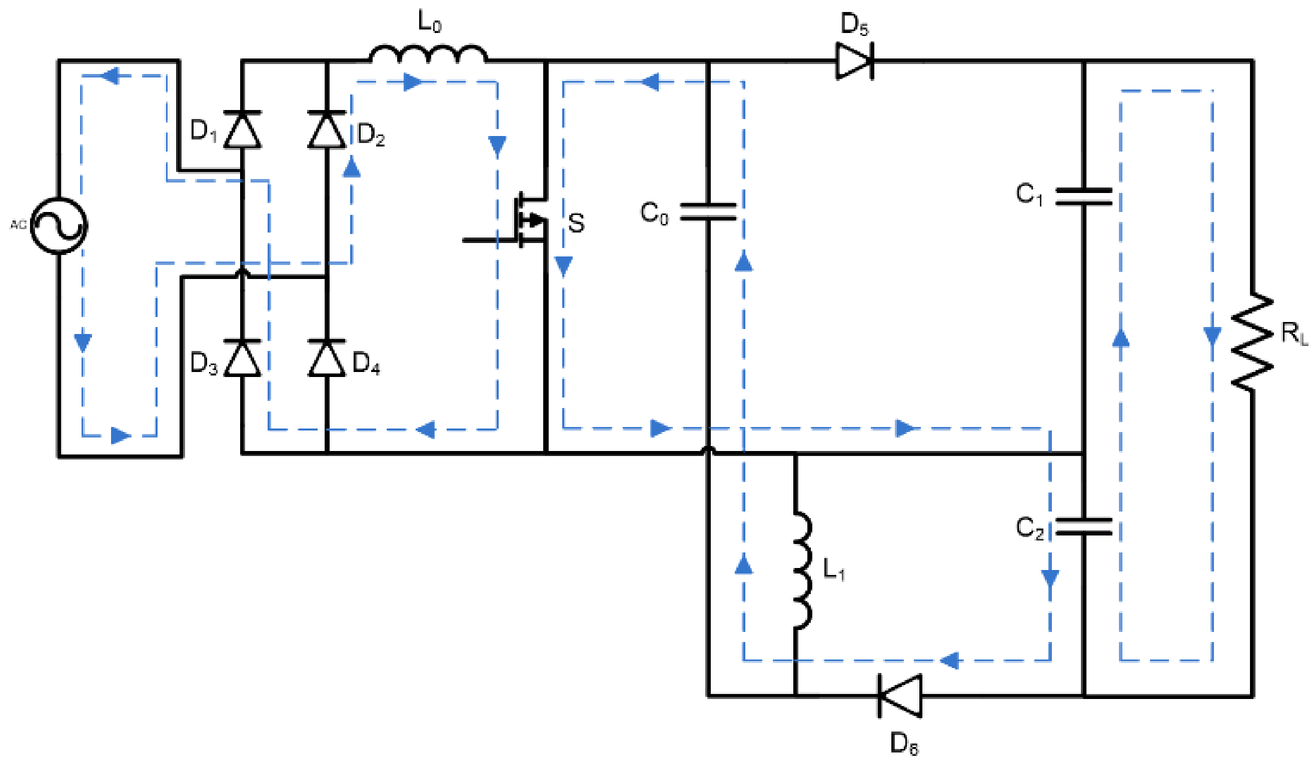
The mode 1 of operation which is TON of the positive half cycle of line frequency is illustrated in Fig 5.4(a). The mode 2, TOFF of positive half cycle of line frequency is shown in Fig 5.4(b). Similarly TON and TOFF of negative half cycle if line frequency is shown in Fig 5.4(c) and Fig 5.4(d) respectively.


L0
D5
D1
D2
S
C0
C1
AC
RL
D3
D4
C2
L1
D6

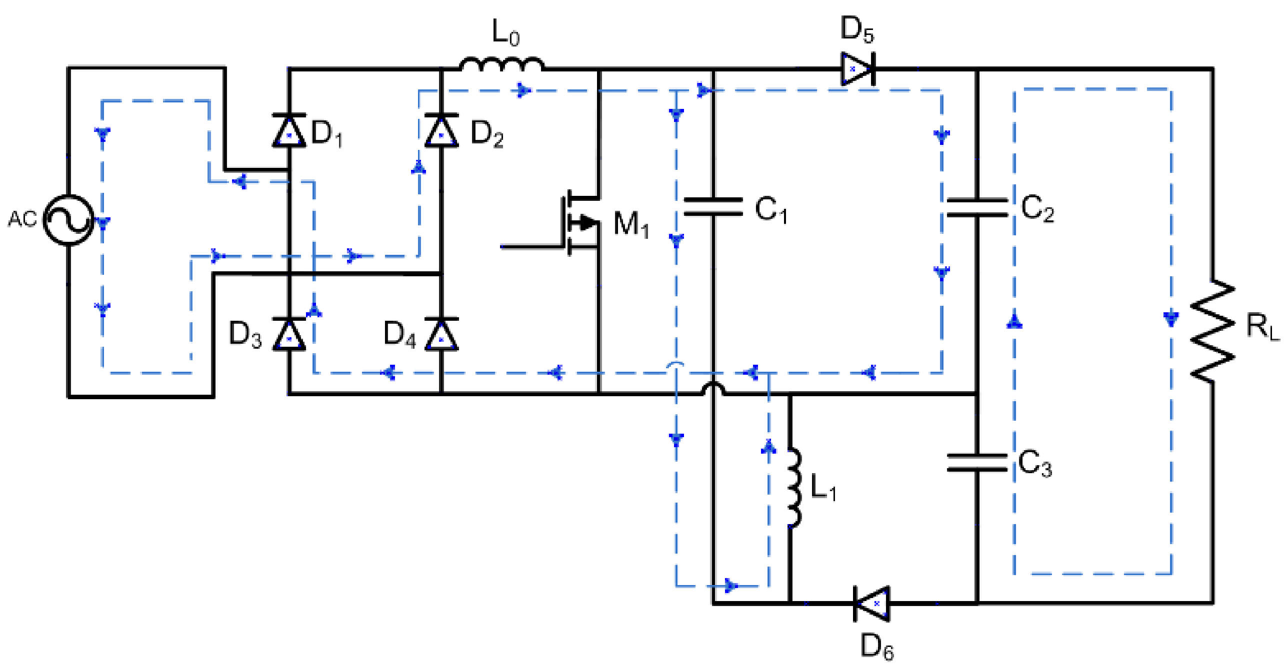
(a)


L0
D5
AC
D1
D2
M1
C1
C2
RL
D3
D4
L1
C3
D6

(b)



(c)



(d)

Fig. 5.4 Principle of operation of the proposed AC-DC HBS converter (a) Mode 1 (b) Mode 2 (c) Mode 3 (d) Mode 4

Capacitors C1 and C2, both supply energy to the load. When the switch is off capacitor C0 and C1 is charged by the source, while C2 supplies energy to the load. When the switch is on then C2 is charged by the capacitor C0 and C1 supplies energy to the load.

The overall estimated voltage gain of the circuit is given below.

$$V_o = V_{o_1} + V_{o_2}$$

$$V_o = \frac{1}{1-D}V_o + \frac{D}{1-D}V_o$$

$$V_o = (\frac{1}{1-D} + \frac{D}{1-D})V_o$$

$$V_o = \left(\left|\frac{1+D}{1-D}\right|\right)V_o$$

$$V_o = GV_o$$

$$\text{G} = \text{Gain} = \frac{1+D}{1-D}$$

5.4 CLOSED LOOP TO IMPROVE POWER FACTOR AND THD

In an attempt to improve the input power factor and input current THD, a PI controller is implemented in current mode control. The actual induction current is compared with the scaled rectified reference current generated from the input voltage. Successive approximation was used to choose the scale factor of the reference current which eventually provided the desired output.

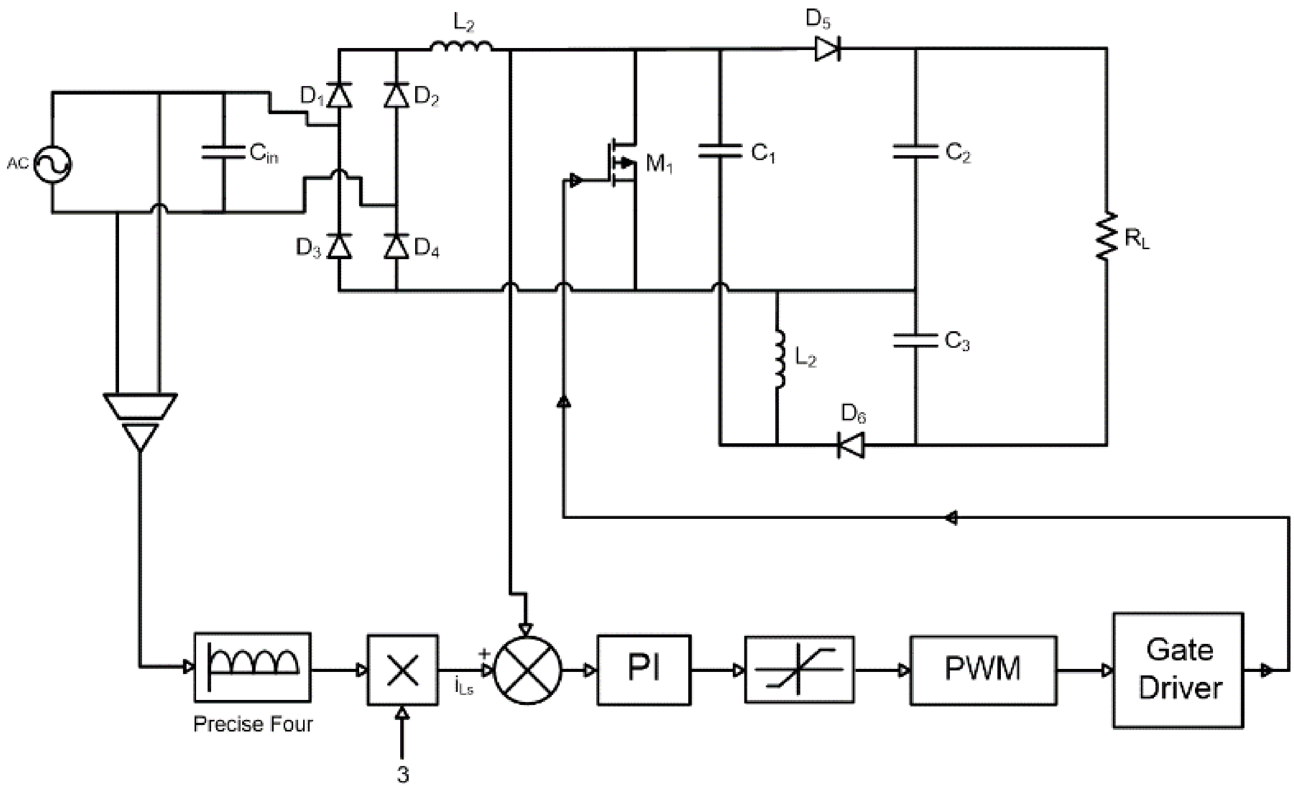


Fig. 5.5 Close loop implementation of the proposed HBS converter using PI controller

5.5 SIMULATION RESULTS

For simulation purposes, the following set of data were used in the proposed HBS circuit, as well as the Boost and SEPIC converter.

Parameter	Value
Input voltage	325V
Input frequency	50 Hz
Capacitor (C0,C1, C2)	200uF, 500uF, 500uF
Inductor (L0, L1)	5mH, 500mH
Load resistor (RL)	100 ohm

TABLE 5.1 Design parameters

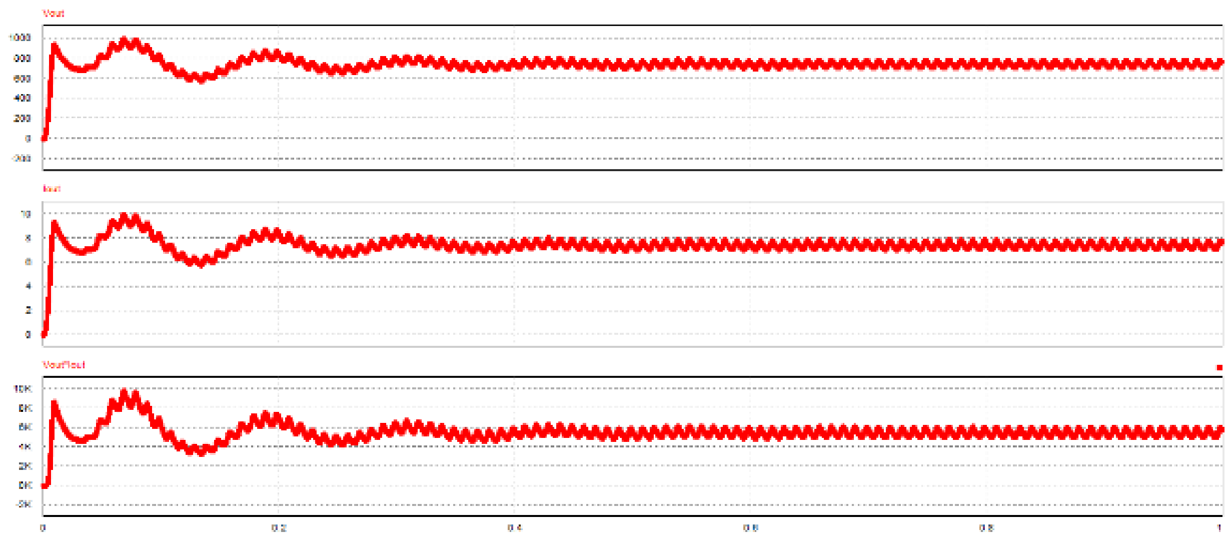


Fig. 5.6 Output voltage, current and power of the proposed open loop HBS converter for 50% duty cycle

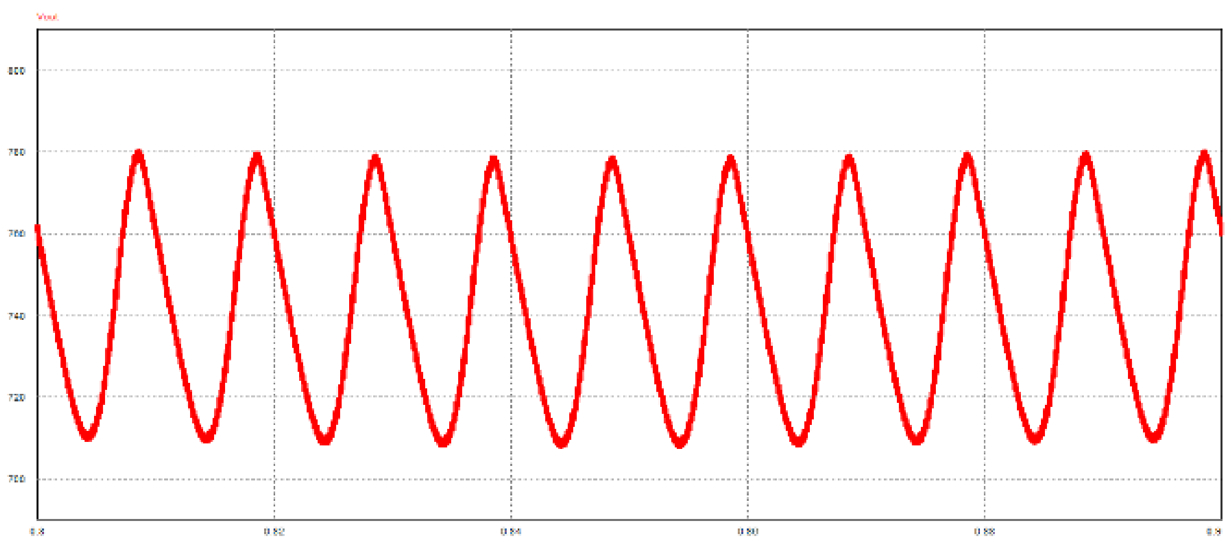


Fig. 5.7 Output voltage of the proposed open loop HBS converter simulated from 0.4s – 0.5s

For comparison, the proposed circuit was compared with the conventional Boost and SEPIC converter.

5.5.1 Conversion Efficiency

It can be observed from Fig. 9 that the proposed converter has greater efficiency then conventional SEPIC converter. Initially the efficiency of boost converter is slightly higher than the proposed converter but after 0.6 duty cycle the efficiency of the proposed circuit is higher. As duty cycle increases the efficiency of the SEPIC converter also increases but it is still less than the efficiency of the proposed converter.

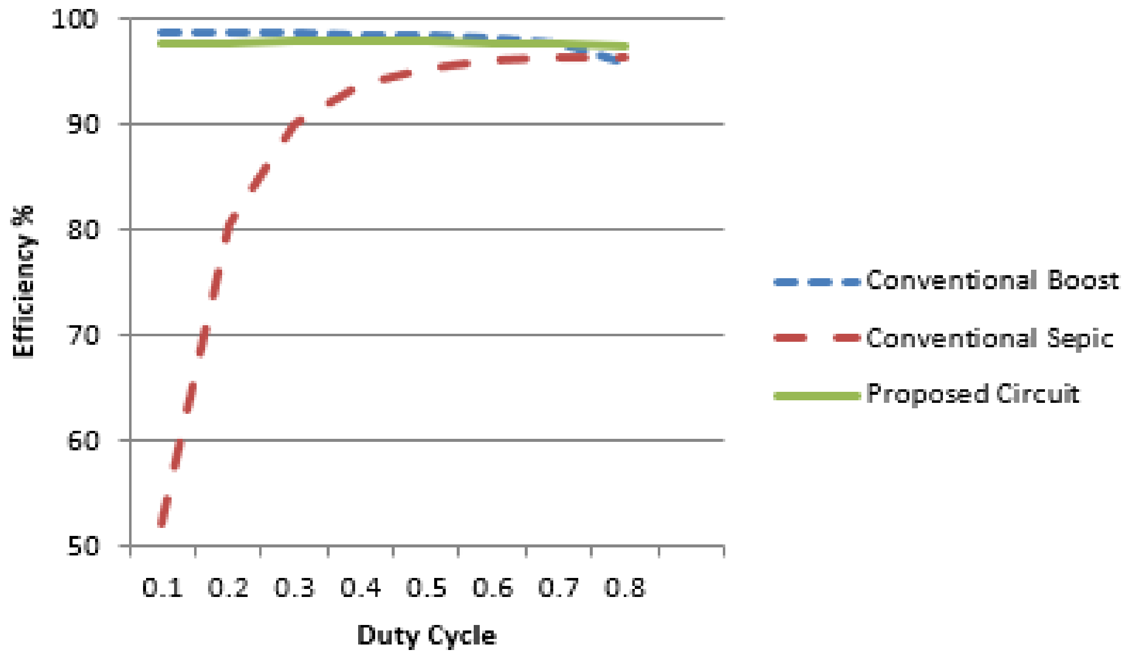


Fig. 5.8 Efficiency comparison

5.5.2 Input Power Factor

The proposed circuit has higher input power factor than the conventional SEPIC converter. It can be observed from Fig. 10 that the input power factor of the SEPIC converter increases when duty cycle increases but it is still less than the input power factor of the proposed converter.

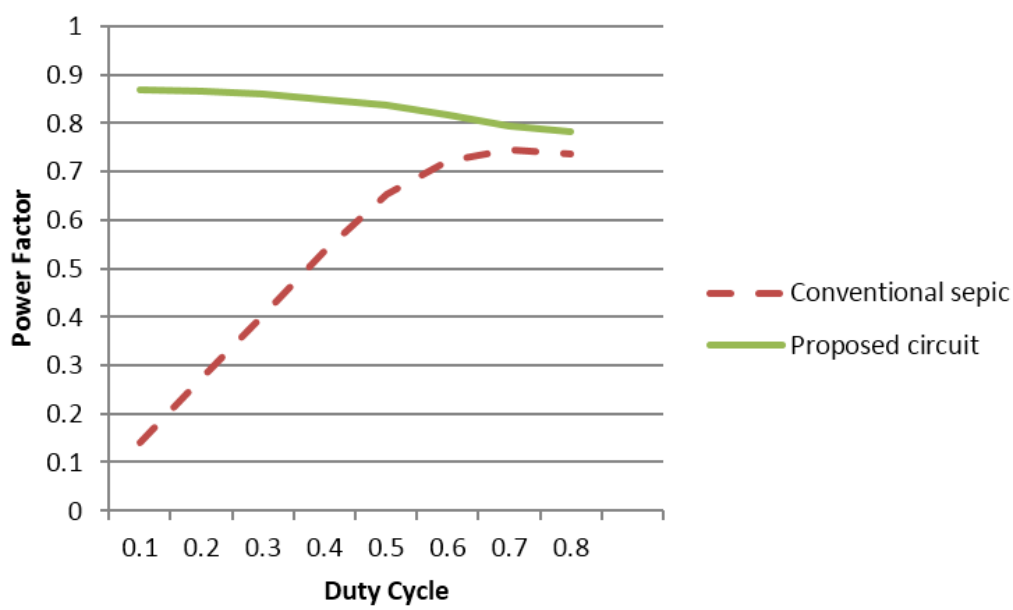


Fig. 5.9 Input Power Factor comparison

5.5.3 Input Current THD

Total Harmonic distortion of the proposed converter is less when compared with the conventional boost and SEPIC converter as shown in Fig. 11. However THD of the proposed converter increases after 0.7 duty cycle.

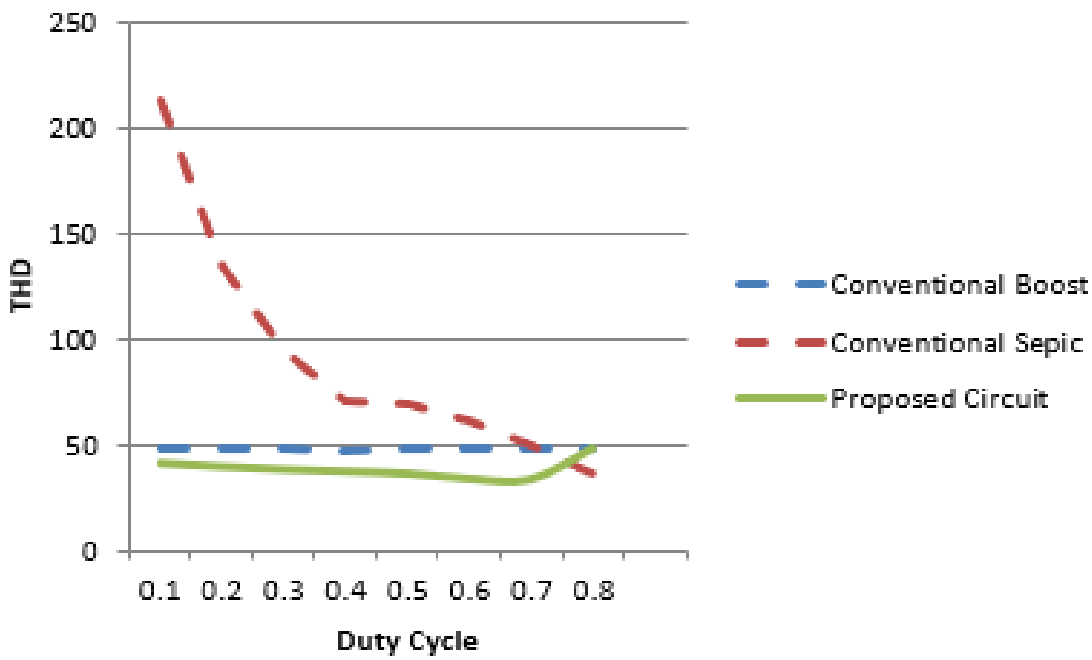


Fig. 5.10 THD comparison

5.5.4 RMS Output Voltage

As illustrated in Fig. 12 VRMS of the proposed converter is higher than the conventional Boost and SEPIC converter. It can also be observed that VRMS of the proposed, as well as the conventional converter increases with increase in duty cycle

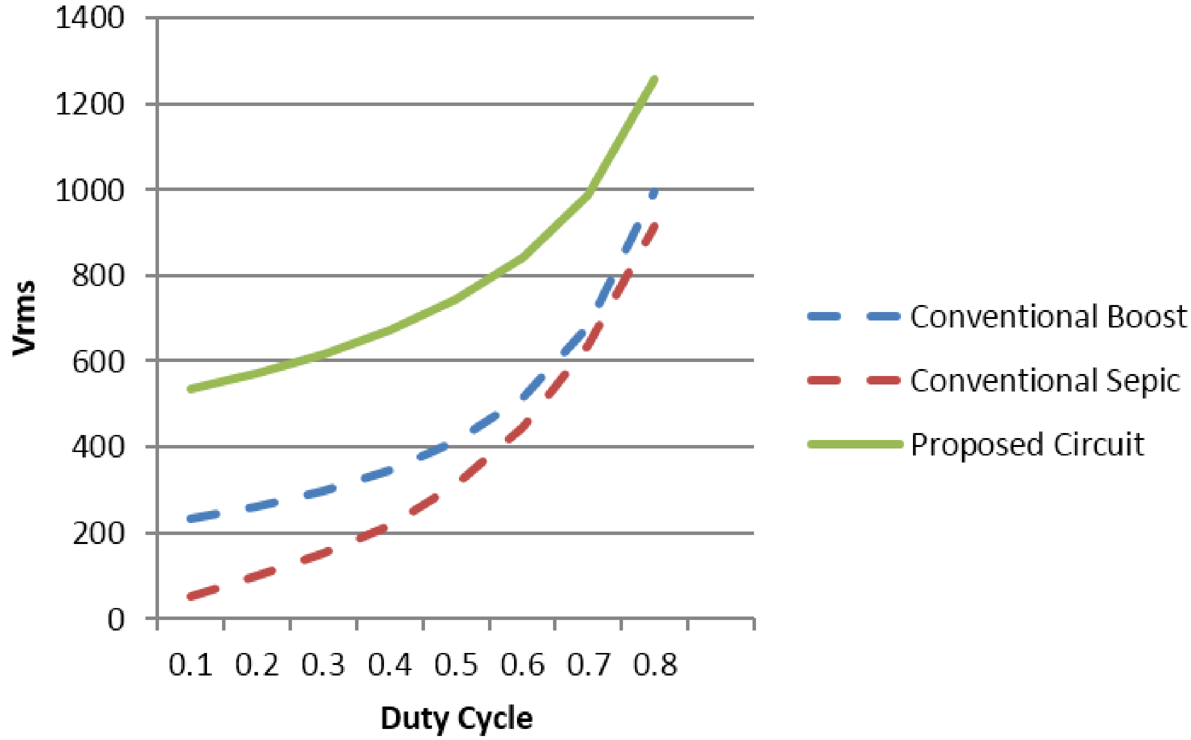


Fig. 5.11 VRMS comparison

Implementation of current mode PI controller significantly improved the input current THD and input power factor with negligible reduction in converter efficiency.

Parameters	Proposed HBS converter (open loop)	Proposed HBS converter (closed loop)
Efficiency (%)	97.8	97.1
THD (%)	39.03	9.94
Power factor	0.86	0.97

TABLE 5.2 Open and closed loop comparison

The effect of change in switching frequency on input current THD and conversion efficiency are also observed keeping 50 duty cycle.

5.5.5 Input current THD vs Switching Frequency

From Fig 13, it can be observed minimum THD is achieved around 25Khz of switching frequency.

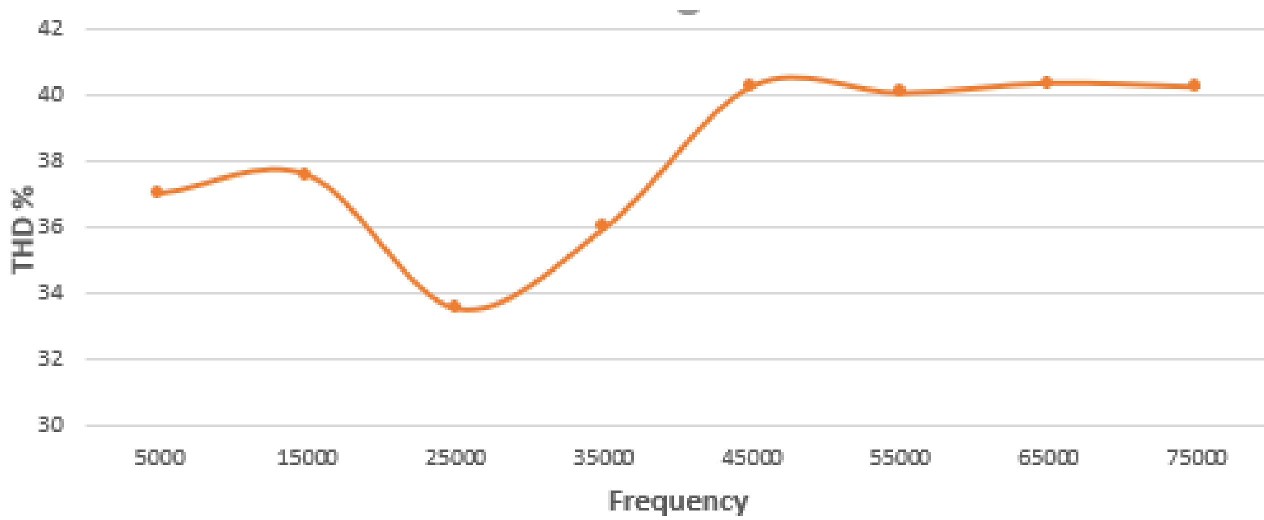


Fig. 5.12 Input THD comparison with switching

5.5.6 Efficiency Comparison with Switching Frequency

As illustrated in Fig 14 conversion efficiency seems to increase at high switching frequency.

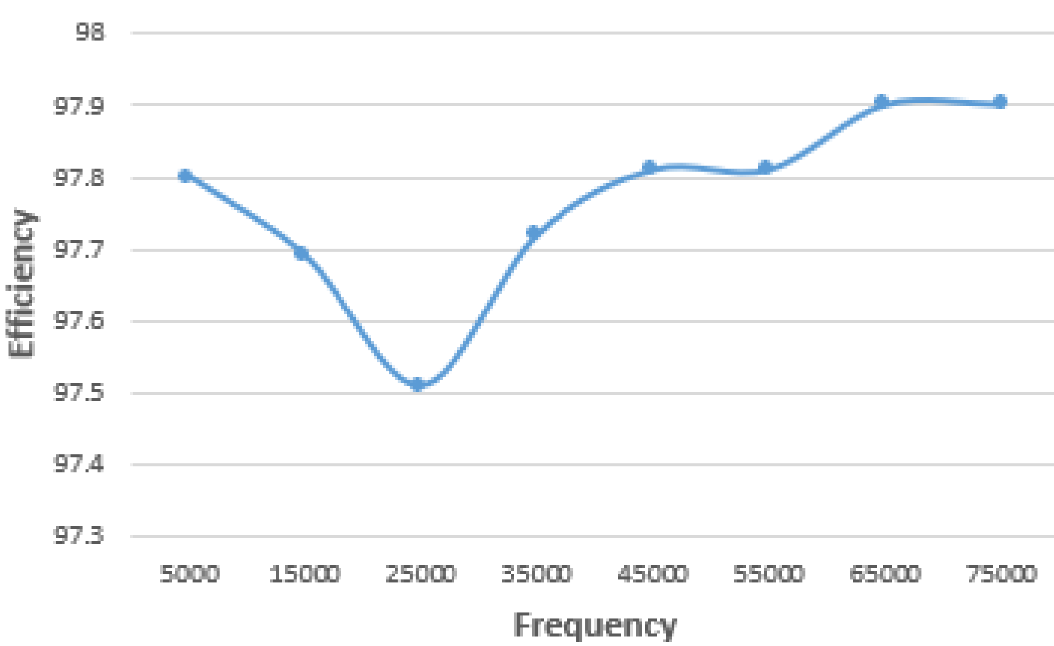


Fig 5.13 Efficiency comparison with switching frequency

CHAPTER 6

Modified Boost SEPIC Converter Integrated with a Three Phase Inverter Transformerless Topology

6.1 Introduction

Sources of energy can be grouped into two general categories. Renewable and non-renewable energy. Non-renewable energy sources such as coal, petroleum and fossil fuels have been an integral part of energy production for many years. Even today, these sources play a key role in generating energy. But these sources are being exhausted aggressively. In order to maintain the continuous production of energy, the use of renewable energy such as solar energy must be explored. Non-renewable sources are associated with pollution, most commonly CO_2 emission, which solar energy bypasses. However the problem lies, that solar energy is acquired in the form of DC power, whereas the power grid, along with other home appliances use AC power. This problem can be remedied by using a converter with a three phase inverter, LCL filter topology

In this paper a cascaded converter is used in conjunction with a three phase inverter and a LCL filter. Boost SEPIC converter is used to change the output voltage level by varying the duty cycle. Then a three phase converter is used to convert the DC output of the converter to AC and send it to the grid. However the inverter output is not sinusoidal. The voltage shape is square. To convert it to sinusoidal a LCL filter is used.

6.2 Proposed Topology and Operation

The proposed circuit is a combination of a hybrid boost SEPIC converter, integrated with a 3 phase inverter along with a LCL filter.

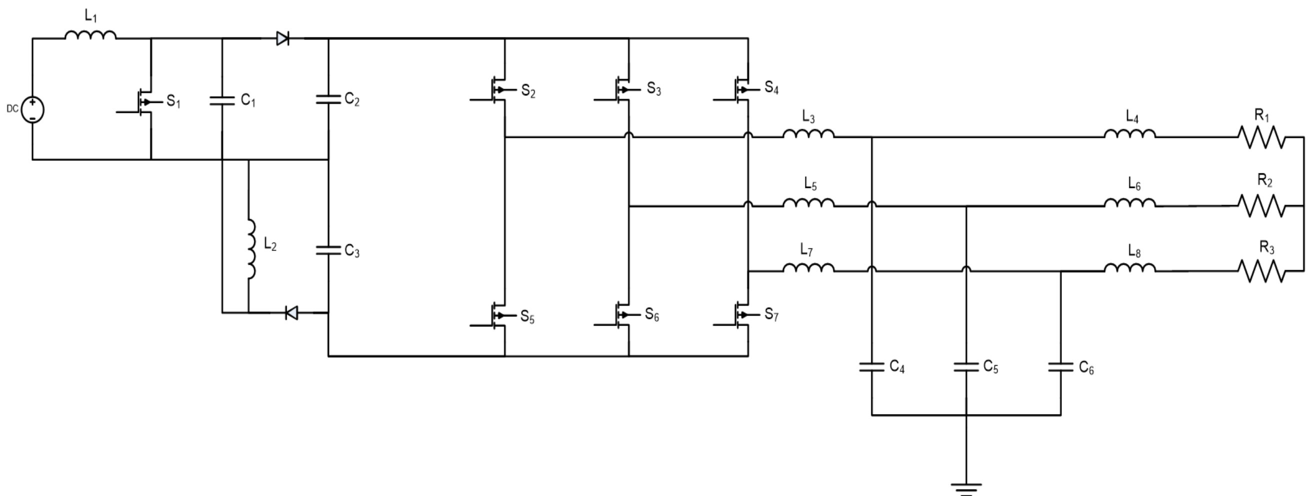


Figure 6.1 Proposed HBS converter integrated with three phase inverter

In the chapter four, the working operation of the HBS converter was discussed.

The working operation of the three phase inverter can be divided to three modes. In mode 1 (0° to 60°) the switches S2, S4 and S6 are on and the rest of the switches are off. The current flows via switch S2, and passes through load R1. Due to switch S4, current pass though the load R3. Now due to KCL both the current will pass through the load R2, and via switch S6 will return to the source.

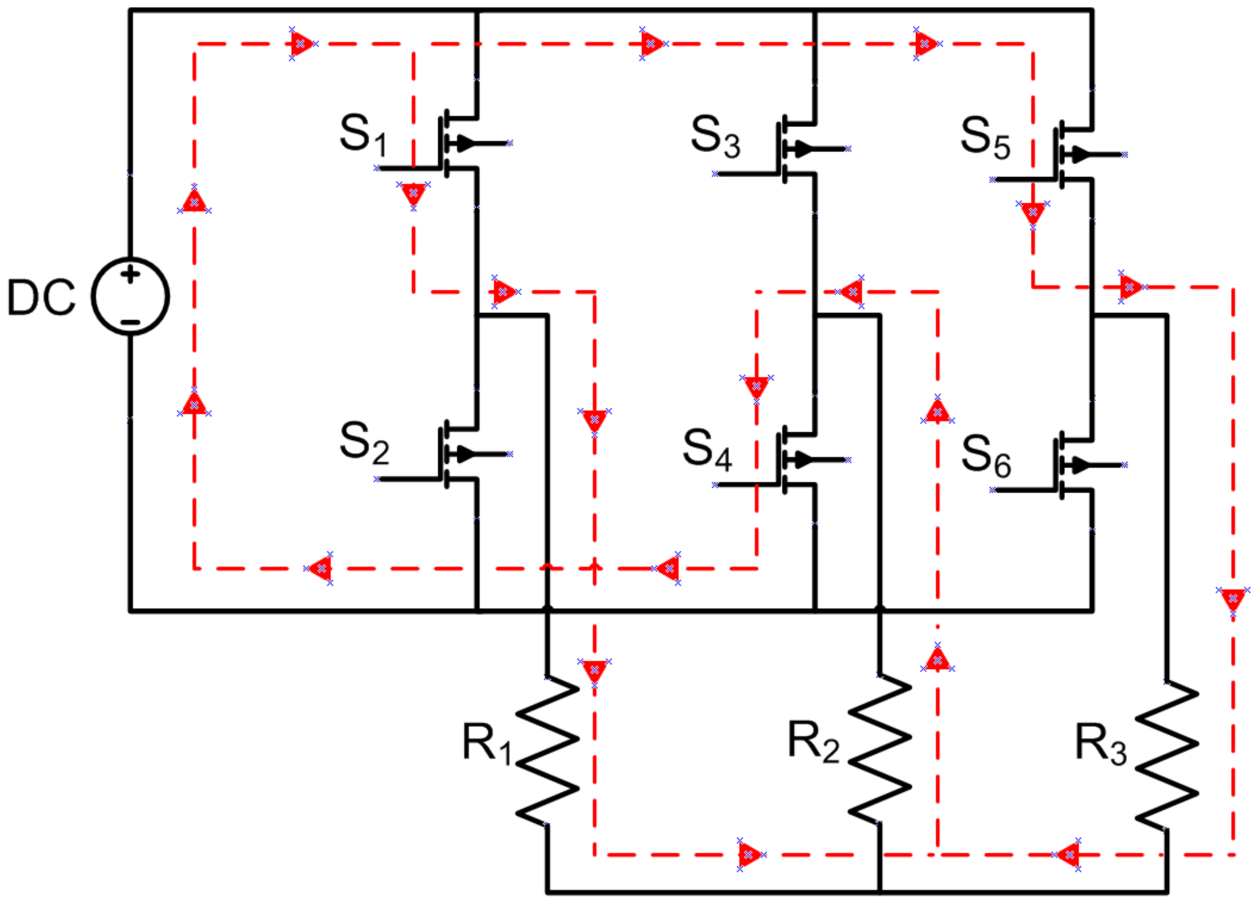


Figure 6.2 Mode 1 of the three phase inverter operation

In mode 2(60° to 120°) the switches S2, S6 and S7 are on and the rest of the switches are off. The current flows via switch S2, and passes through load R1. Now due to KCL the current will divide and pass through the load R2, R3 and via switch S6 and S7 respectively and will return to the source.

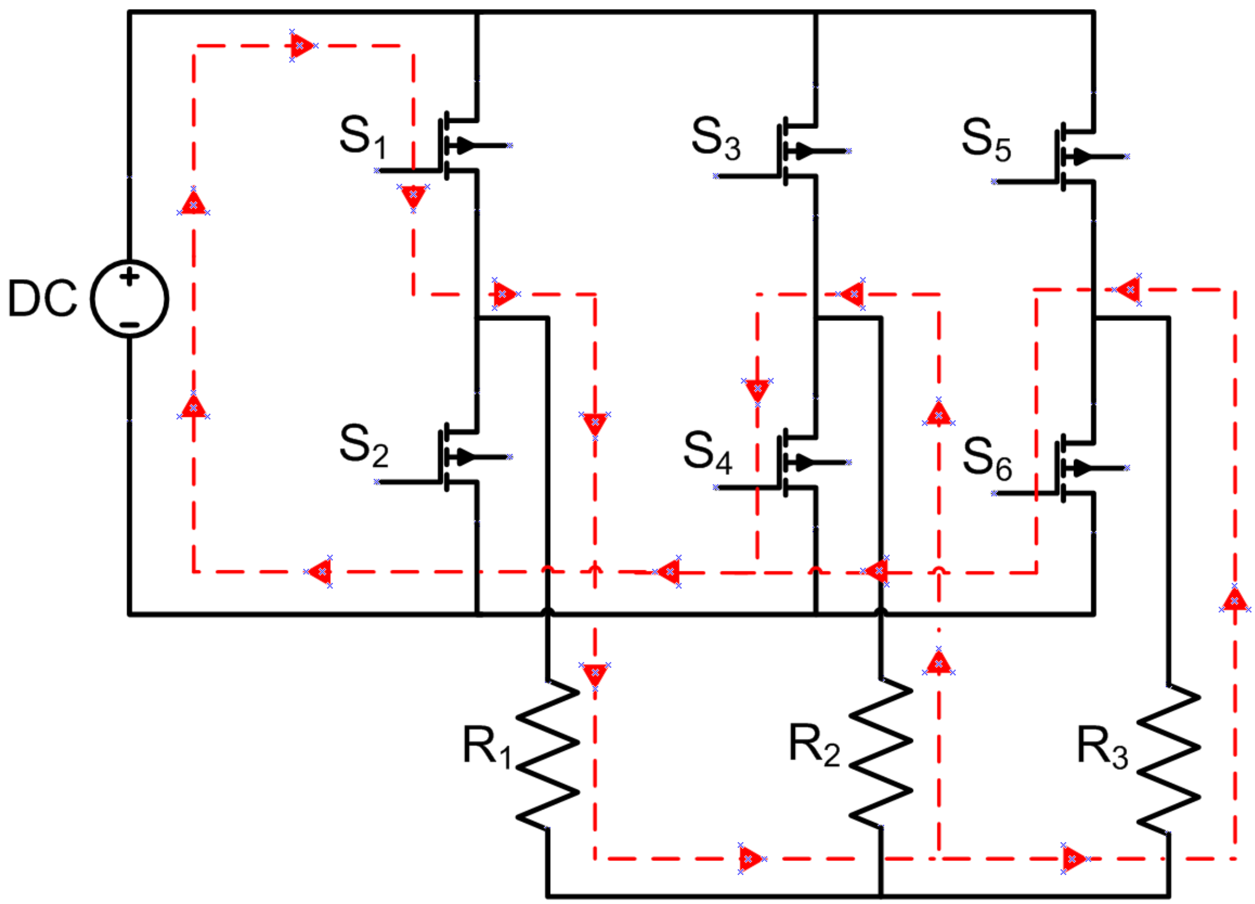


Figure 6.3 Mode 2 of the three phase inverter operation

In mode 3(120° to 180°) the switches S2, S3 and S7 are on and the rest of the switches are off. The current flows via switch S2 and passes through load R1. Due to switch S3, current pass through the load R2. Now due to KCL both the currents will pass through the load R3 and via switch S7 will return to the source.

After 180°, switch 2 is off. Like switch 2 other switches also work in a similar manner.

However, after this the output voltage will a square wave. To acquire sinusoidal wave a LCL filter is applied before the load.

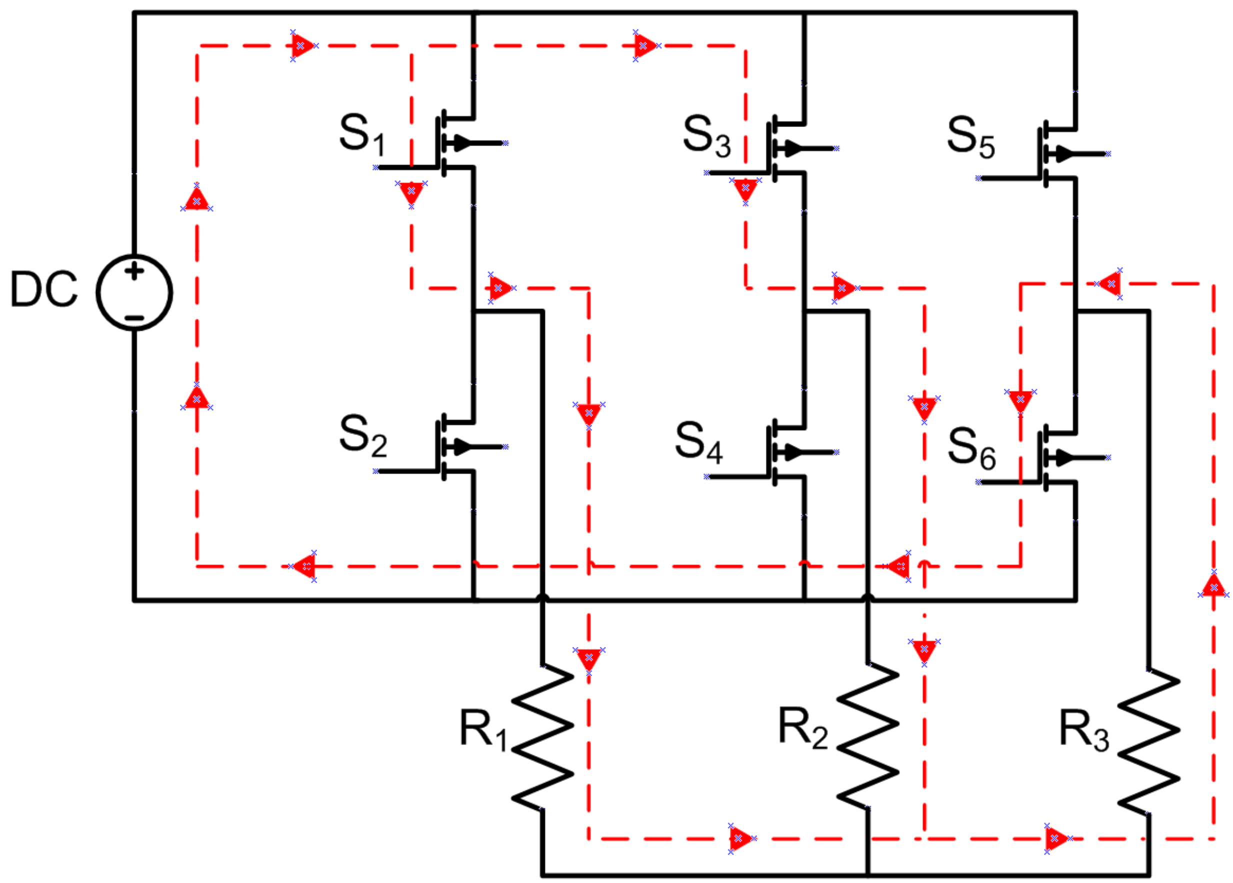


Figure 6.4 Mode 3 of the three phase inverter operation

6.3 Theoretical Setup

All the switches used in the three phase inverter conducted at 180°. The circuit simulation at first was conducted using a resistive load, capacitive load and inductive load. Value of resistive load used was 100Ωs, capacitive load used was 1uFand inductive load was 1mH. All the circuit simulation was done in PSIM.

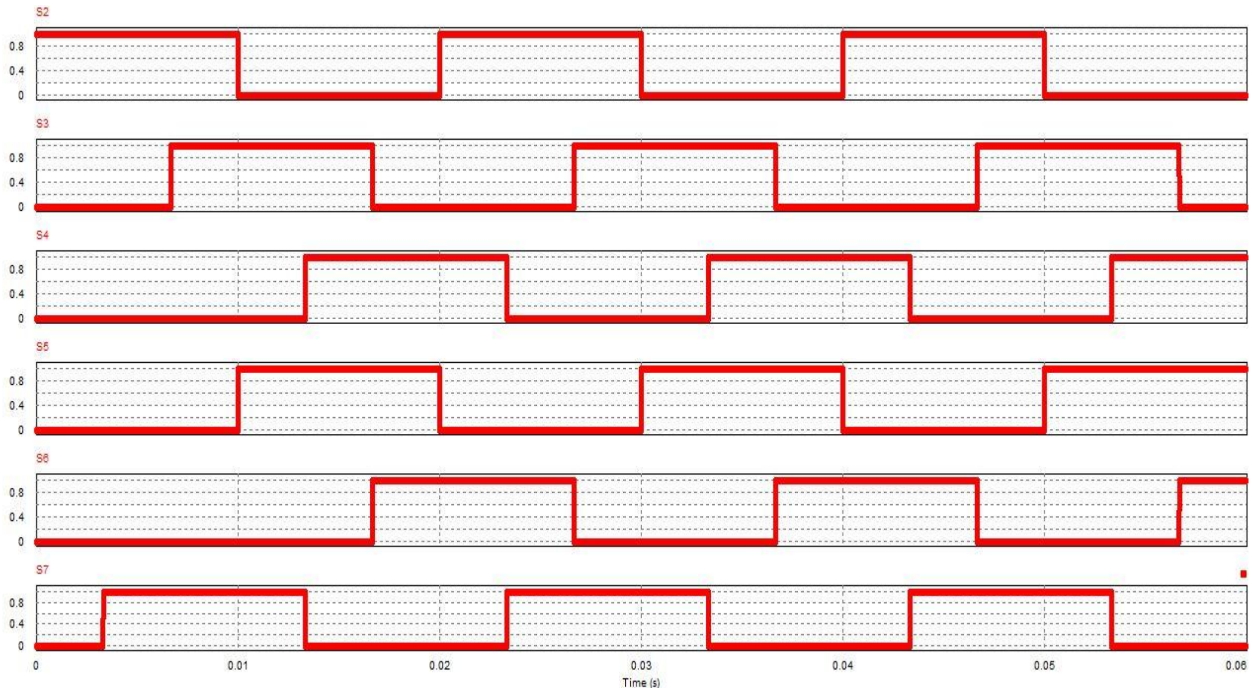


Figure 6.5 Switching pattern of the three phase inverter

6.4 Results

6.4.1 Resistive load

6.4.1.1 Efficiency

The duty cycle of the converter is increased from 10% to 70 %. From the graph below it can be observed that as the duty cycle increases the efficiency of the proposed circuit decreases, although the decrease of the efficiency is not so much. The range of the efficiency is from 92.42% to 92%.

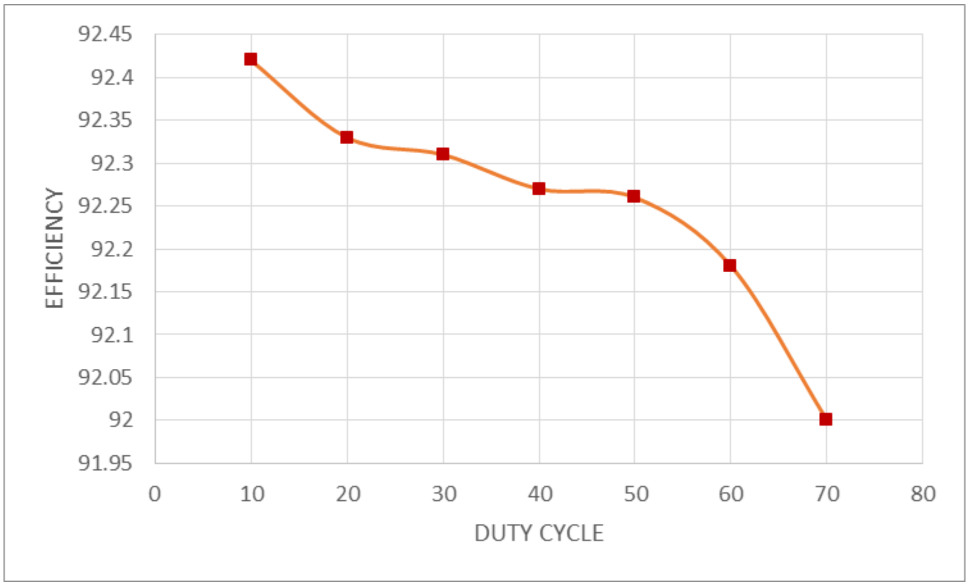


Figure 6.6 Efficiency curve of a resistive load

6.4.1.2 THD

Since the output of the proposed circuit is three phase, thus it is split into R, Y and B. From the graphs below it can be observed that initially THD of R decreases. However it increases at peaks at around 38% duty cycle and then decreases, For Y, the THD increases and peaks at around 30% and then decreases. For B, the THD decreases to its lowest value at around 25%, then it reaches its peak at around, 40% and them it decreases again.

Figure 6.7 THD Ir

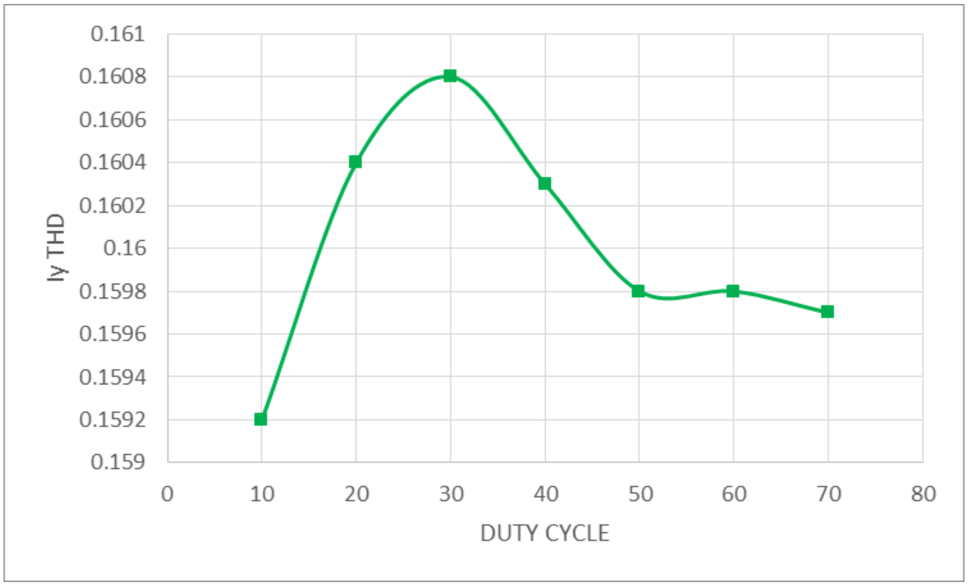


Figure 6.8 THD Iy

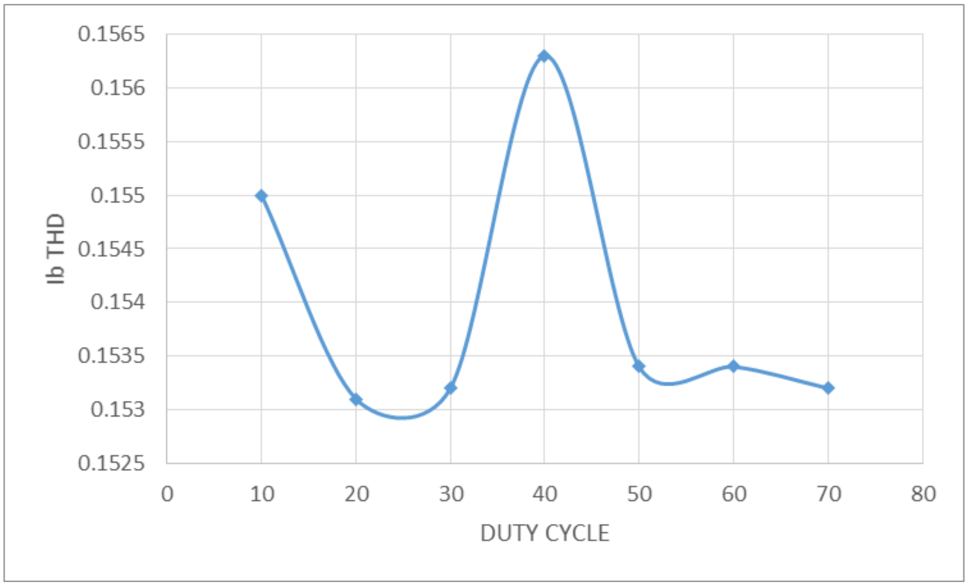


Figure 6.9 THD Ib

6.4.2 Capacitive Load

6.4.2.1 Efficiency

From the graph below it can be observed that for capacitive load the efficiency decreases from 92.38 to 92.17 as the duty cycle increases from 10% to 60%.

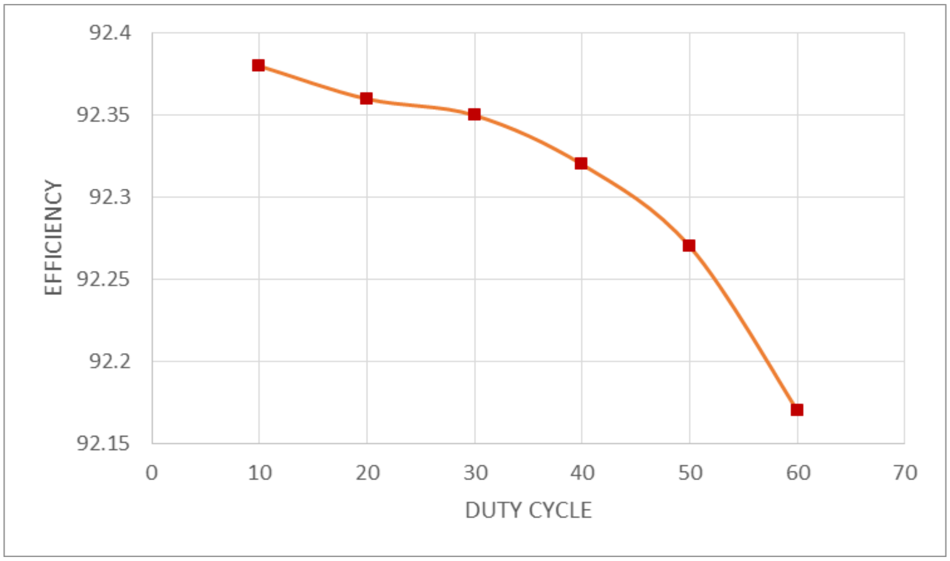


Figure 6.10 Efficiency curve of a capacitive load

6.4.2.2 THD

From the graphs below it can be seen that the THD of R increases as duty cycle increases to 21% and then decreases when THD increases to 41 % and then again the THD increases. For B, THD ranges from 0.1686 to 0.1673. For Y, THD ranges from 0.174 to 0.172.

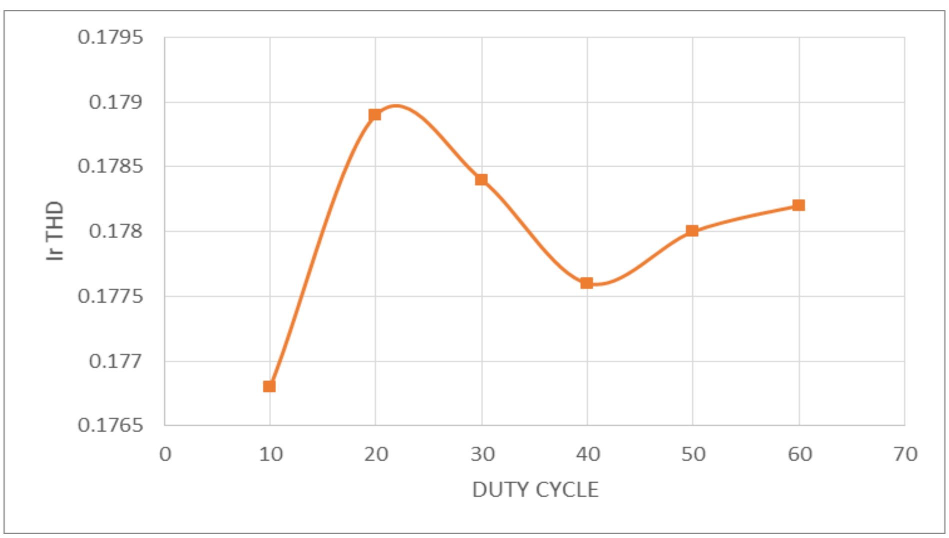


Figure 6.11 THD Ir

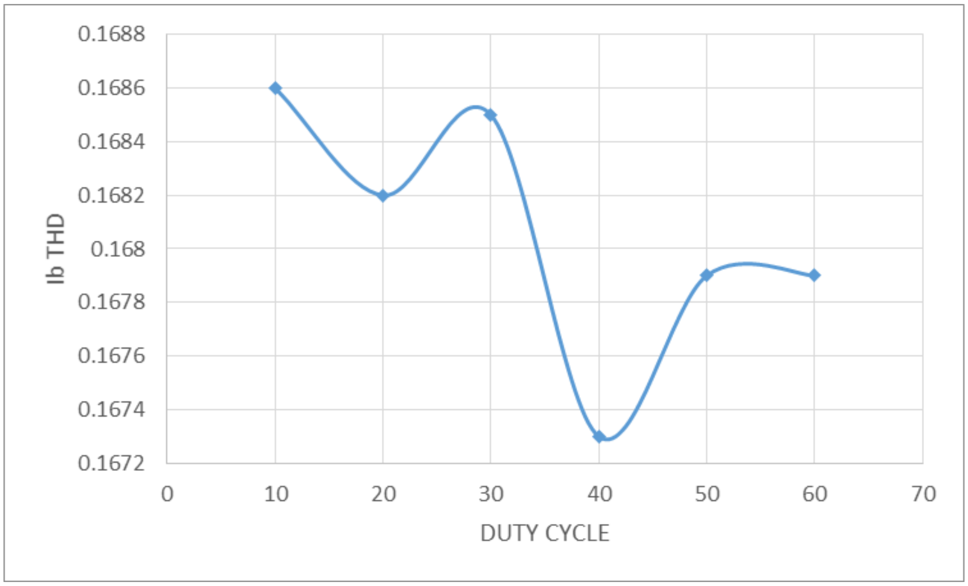


Figure 6.12 THD Ib

Figure 6.13 THD Iy

6.4.3 Inductive Load

6.4.3.1 Efficiency

From the graph below it can be it can be observed that the efficiency decreases from 92.4% to 92.1% as duty cycle increases from 10% to 70%.

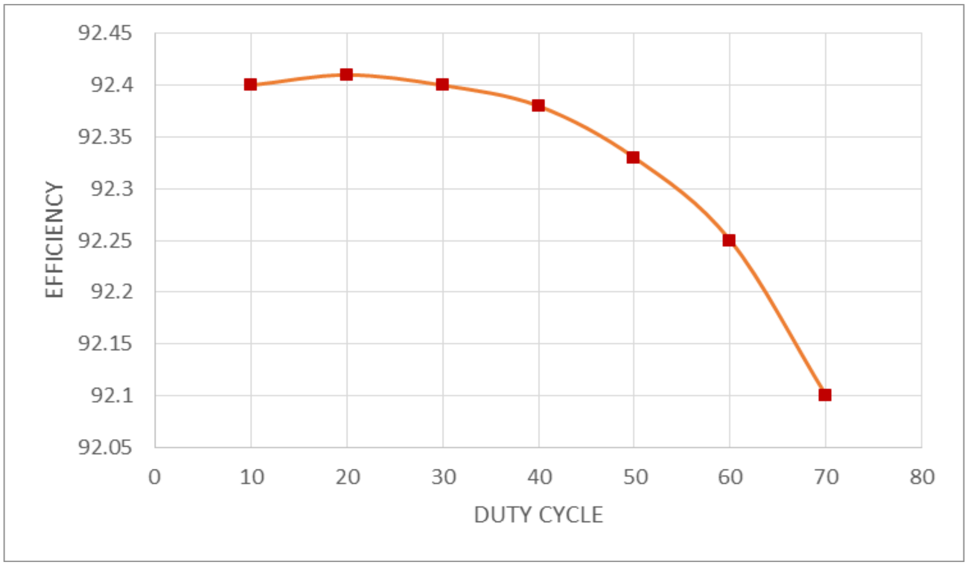


Figure 6.14 Efficiency curve of inductive load

6.4.3.2 THD

From the graphs below it can be seen that the THD of R ranges from 0.166 to 0.1613 for duty cycle of 10% to 70%. For B, THD ranges from 0.1686 to 0.1673. For Y, THD ranges from 0.174 to 0.172.

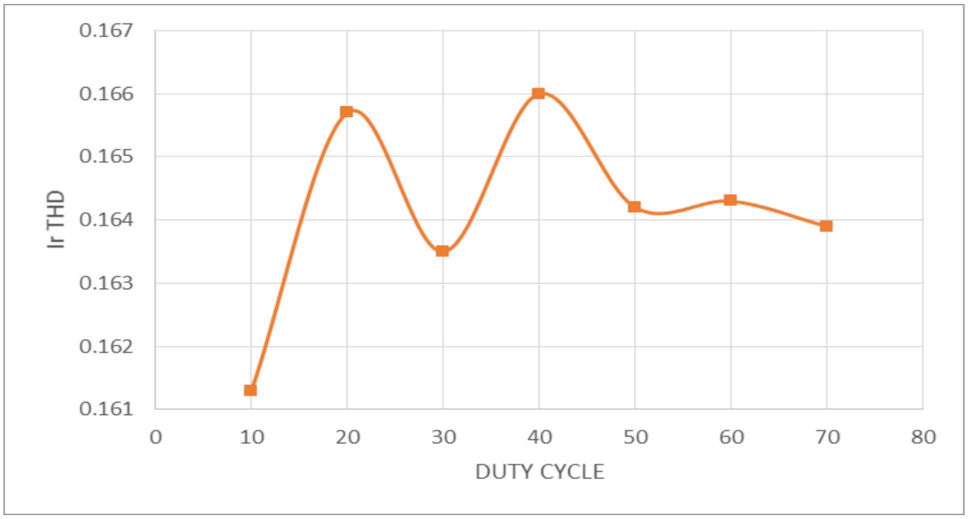


Figure 6.15 THD Ir

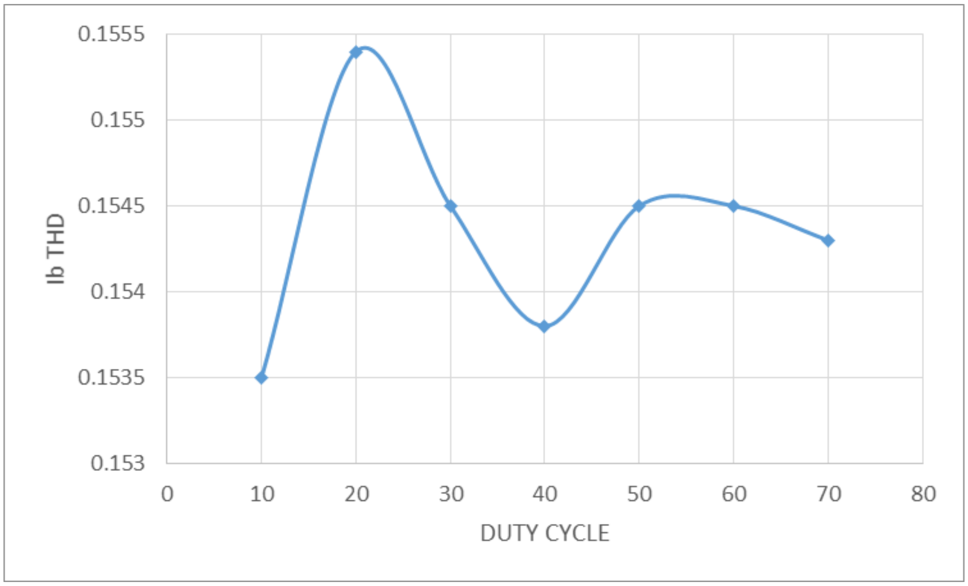


Figure 6.16 THD Ib

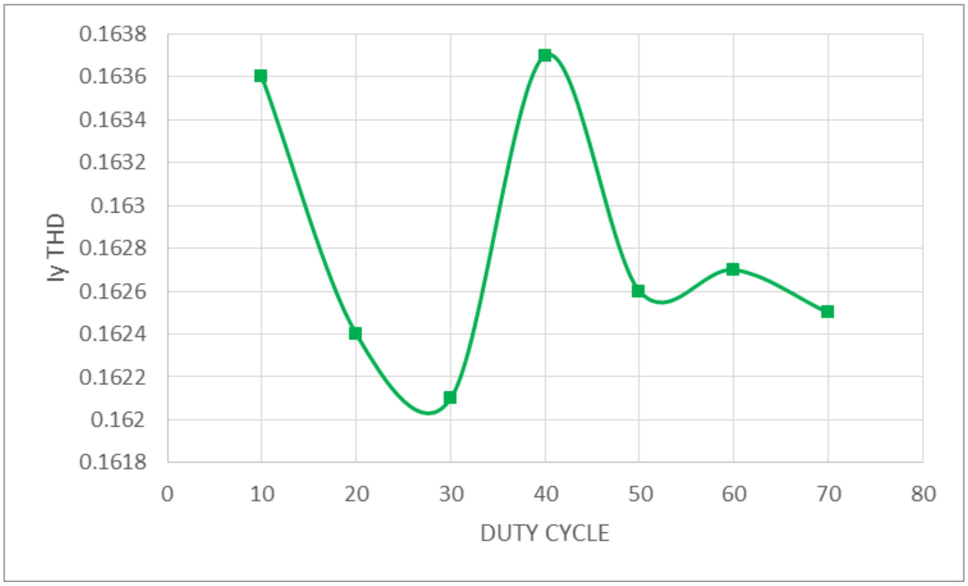


Figure 6.17 THD Iy

CHAPTER 7

Conclusion

The proposed MBS converter designed by cascading Boost and SEPIC converter to obtain the advantages of both the converters. The maximum efficiency the circuit can produce without any controller is 97.8%. However the THD was quite high which is brought down to 9.94% by using the PI controller. The power factor is also improved with the addition of the PI controller. The proposed MBS converter can be effectively used for high voltage DC application like DC micro grid, heater etc.

With the demand of solar energy on the rise, effective circuits are required to integrate the DC output with the grid. This is where HBS converter with a three phase inverter along with a LCL filter comes in usage, providing AC output with efficiency as high as 92.42% for resistive load, 92.38% for capacitive load and 92.4% for inductive load.

CHAPTER 8

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