MASTER OF SCIENCE IN ELECTRICAL AND ELECTRONIC ENGINEERING

Design and Analysis of Cascaded Buck-Boost Zeta (CBBZ) Converters for Improved Efficiency at High Output Voltage

Department of Electrical and Electronic Engineering
Islamic University of Technology (IUT)
Board Bazar, Gazipur-1704, Bangladesh
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by

Mohammad Dehan Rahman

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IN

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LIST OF ABBREVIATIONS

DC	Direct Current
AC	Alternating Current
BJT	Bipolar Junction Transistor
MOSFET	Metal Oxide Semiconductor Field Effect Transistor
IGBT	Insulated Gate Bipolar Transistor
GTO	Gate Turn-Off Thyristor
THD	Total Harmonic Distortion
LED	Light Emitting Diode
SEPIC	Single Ended Primary Inductor Converter
PF	Power Factor
CBBZ	Cascaded Buck-Boost Zeta

ABSTRACT

Various types of power electronic converters are now frequently used in electric power system applications such as power converter, communication systems, grid-connected systems, DC power supply and so on. A DC-DC converter which provides different levels of output voltage is really essential and have a wide variety of applications. However, the traditional DC-DC converters are not adequate enough to make proper conversion without compromising performance. There is always a trade-off between efficiency and other performances. The attempt of attaining high voltage gain introduces unwanted harmonics, thus deteriorating the signal shape. The design of cascaded topologies can be used to overcome these problems. Even in cascaded DC-DC converter, the efficiency decreases as the duty cycle of the DC-DC converter increases. This decrease in efficiency is caused by conduction loss and due to circuit topology. To overcome such limitations, in this research a Cascaded Buck-Boost Zeta (CBBZ) converter is designed. In this research the proposed converter’s AC-DC and closed-loop topology is also analyzed. The proposed converter is expected to provide high output voltage with high efficiency in comparison to the conventional Buck-Boost, Zeta converter and other cascaded converters.

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1. Introduction

Chapter 1

Introduction

1.1 Introduction to DC-DC Converter:

In modern day power supply, the use of renewable energy has increased exponentially [1-5]. Many industrial applications require to convert a fixed voltage source to a variable source. This conversion can be achieved by using a DC-DC converter. The primary function of a DC-DC converter is to either step up or step down a DC voltage.

DC converters can be used for a wide range of applications. These power electronics circuits are used in motor control, trolley trucks, marine hoists, forklift trucks and mine haulers [6-7]. DC converters are also used for micro grid, LED lighting. It is also used to harvest maximum energy from photovoltaic system and wind turbines [8].

1.2 Literature Review

Various types of power electronic converters are now frequently used in electric power system applications such as power converter, communication systems, grid-connected systems, DC power supply and so on. [9] A DC-DC converter that provides different levels of output voltage is really essential and have a wide variety of applications. [10] However, the traditional DC-DC converters are unable to make proper conversion without compromising performance. There is always a trade-off between efficiency and performance. [11-12] For example- high voltage gain will deteriorate the signal and introduce total harmonic distortion shape. Trade-off is also visible among all the performance parameters of the DC-DC converters.

With the increasing development of daily electrical appliances such as devices in communication system, UPS, appliances to use renewable energy, systems that are grid-connected, electrical vehicles etc. the requirement of high power supply increases. [13] Sometimes the need of conversion of power supply from one DC form to another arises. But it is not so easy to get the accurate desire output using simple DC-DC converters. Sometimes to get proper output voltage, it may appear that the power factor has not met the demand, or THD is high. Conventional converters cannot obtain high efficiency in higher duty cycle as there are some leakage inductance and dependent parameters. Also higher duty cycle causes more conduction loss. So cascaded converters are brought to light to mitigate those problems to a minimum rate.

Cascaded converter is a unique approach to primarily increase the output voltage. These types of converters are used for high voltage applications. When such converters are used in AC-DC topology it improves the THD and power factor of the system.

Cascaded converter is a simple approach in increasing the voltage gain of the converters. In this arrangement two or more converters are arranged in a cascaded form to develop a new converter. [14] One such arrangement is to have two Boost converters in a cascaded form to construct a new converter. The schematic diagram of the converter is shown in Fig. 1.1. The voltage is quite small in the first half of the converter and can be operated in high frequency. Hence it can be used effectively for high power density operation. However the second half can be operated in low frequency, to have low switching loss. In such converters the duty cycle of the switches are independent of each other. To reduce circuit complexity, a common switch can be used for a cascaded Boost converter. [15] Such converters are known as quadratic Boost converter. The diagram of quadratic Boost converter is shown in Fig. 1.2. From the diagram it can be observed that the duty cycle of quadratic Boost converter is not independent.

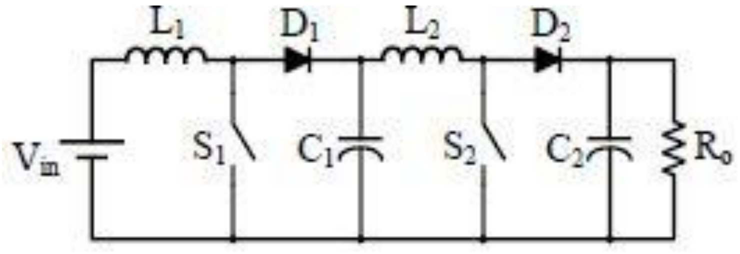


Fig. 1.1: Two cascaded Boost converter

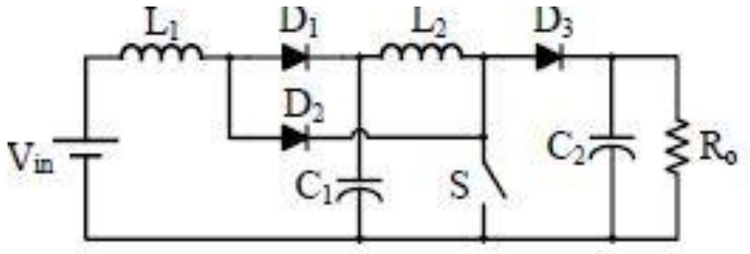


Fig. 1.2: Quadratic Boost converter

Another type of cascaded topology is hybrid cascaded topology. In this type of arrangement two different types of DC-DC converter are arranged in a cascaded form to develop a new cascaded converter, which is able to deliver high voltage gain. [16-17] Arrangements have also been done in such ways that quadratic Boost is in the first half, coupled inductor in the second stage and the output is connected in series. Such techniques are capable of delivering high voltage gain. Combination of quadratic Boost with voltage multiplier is also developed to achieve high voltage output. A general layout of such converters is shown in Fig. 1.3. Combination of different converters are utilized to design different cascaded converters. A general layout of such arrangement is shown in Fig. 1.4. Examples of such converters are SEPIC Boost and Boost Cuk converters.

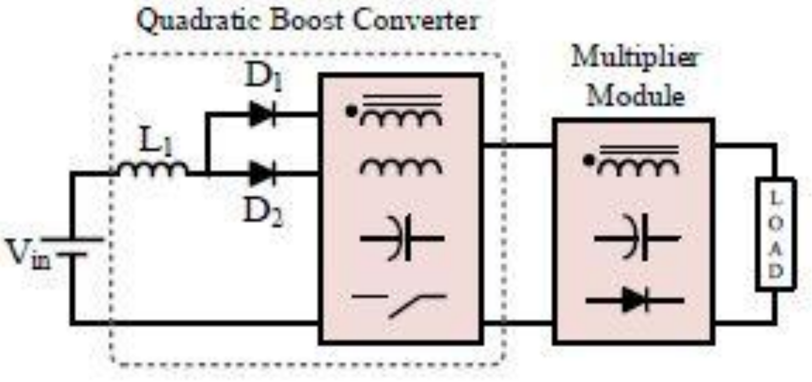


Fig. 1.3: Layout of quadratic hybrid Boost converter

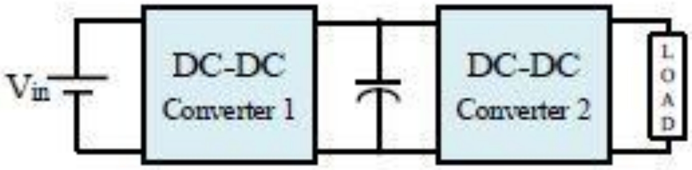


Fig. 1.4: Layout of cascaded connection of two different converters

Cascaded SEPIC Boost converter is hybrid cascaded converter in which SEPIC and Boost converter are arranged in a cascaded form. Such arrangement allows the converter to achieve higher voltage gain. The converter, due to its design is able to generate higher output voltage at different duty cycle. The converter is able to produce maximum voltage of about 900V and maximum efficiency about 97.8%.

Another hybrid cascaded converter is the Boost Cuk converter. The converter is designed by using Boost and Cuk converter. As a cascaded converter, it is capable of generating higher output voltage at different duty cycle. This is due to the converter having higher voltage gain.

The concept of cascaded converter is relatively new and has gained little attention. In this thesis a new cascaded Buck-Boost Zeta converter is developed.

Even in cascaded DC-DC converter, the efficiency decreases as the duty cycle of the DC-DC converter increases. [18-22] This decrease in efficiency is caused by conduction loss and circuit algorithm. To overcome such limitations, in this research a Cascaded Buck-Boost Zeta (CBBZ) converter will be designed and analyzed. The proposed converter is expected to provide high voltage output with high efficiency in comparison to the conventional Buck-Boost, Zeta converter and other cascaded converters.

1.3 Proposed Methodology

For significant contribution on the subject matter, the problems relating to the topic are identified. Conventional DC-DC converters suffer from efficiency loss when duty cycle increases. Furthermore, for AC-DC topologies, THD and Power Factor are quite high and controller is required to improve such parameters. Thus based on the stated limitations, the proposed converter will be designed. After developing the converter, its performance are compared with conventional Buck-Boost and Zeta converter. The simulated results of the converters are collected and compared. The simulations are run on PSIM software. The converters have been simulated for different duty cycles and then a comprehensive theoretical analysis has been made. The output results (efficiency, THD, Power Factor and output voltage) are collected and compared. To make a comprehensive analysis, the proposed DC-DC converter is used to design a closed loop and an AC-DC topology.

i. Existing problems relating to current DC-DC converter topologies have been studied.
ii Based on the limitations, a cascaded converter will be designed.
iii. The designed converter is compared and analyzed with Buck-Boost and Zeta converter.
iv. The efficiency and the output voltage of the converters are noted at different duty cycles.

v. The results are compared between cascaded Buck-Boost Zeta converter and the existing converters (Buck-Boost and Zeta converter).

vi. The proposed converter will be used to design a DC-DC closed loop feedback and AC-DC converter topology.

1.4 Outline of the Thesis

The book is organized in the following chapters

Chapter 1: Represents the basic information of DC-DC converters.

Chapter 2: Represents the performance parameters.

Chapter 3: Represents the Cascaded Buck-Boost Zeta converter.

Chapter 4: Represents the results of the converters.

Chapter 5: Represents conclusion and future work.

Chapter 2

Power Electronics DC-DC Converter

2.1 Classification of DC-DC converters

Switched mode DC-DC converter originated with the introduction of pulse width modulation (PWM). The DC-DC converter changes the input voltage to a desired output voltage. The DC-DC converter can either step-up or step-down the input voltage. The study of converters received attention with the introduction of semiconductor switches. Due to semiconductor switches, the DC-DC converter experienced a steady performance advancement. Switches such as BJT, MOSFET, and GTO greatly augmented the advancement of DC-DC converter. The step-up and step-down operation of the DC-DC converter depends on the duty cycle. For converters such as Buck-Boost, SEPIC and Cuk converter if the duty cycle is greater than 50%, then the converter will perform step-up operation. If duty cycle less 50% the step-down operation. Converters such as Buck and Boost converter perform step-down and step-up operation irrespective of duty cycle.

DC-DC converter is a power electronic circuit which can be used to produce variable DC voltage. Based on output voltage polarity, DC converter can be classified in two types [23]:

1. Inverted converter
2. Non-inverted converter

Inverted converter: Inverted converters are types of converter whose output voltage polarity is inverted when compared with the input voltage source. Such converters include Buck-Boost, Cuk and ZETA converter.

Non-inverted converter: The DC converters, which produce the same output voltage polarity as that of input voltage are called non-inverted converter. Examples of such converters are Buck, Boost and SEPIC converter.

DC converters can be further classified into four types based on circuit arrangement and usage [24]

1. Isolated converter
2. Soft switching converter

3. Bidirectional converter
4. Cascaded converter

Isolated converter: Isolation is an important method when using DC-DC converter. It electrically separates input and output side. Isolation provides safety and a reliable power supply with reduced noise. The decrease in noise is achieved by breaking of ground loops. Isolation is done by using a coupled inductor or a transformer. However isolation does increase the converter size, cost and reduces efficiency [24].

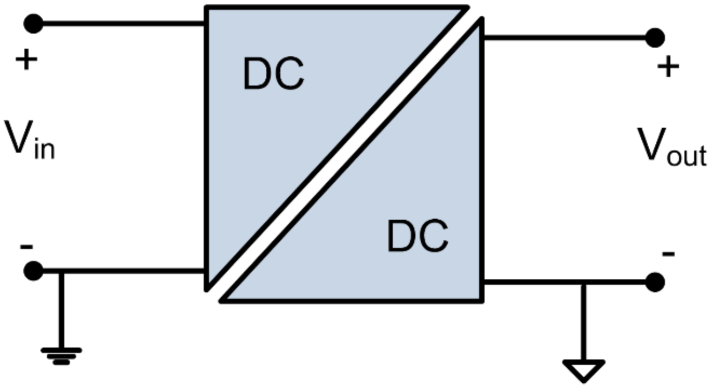


Fig. 2.1: Isolated converter

Soft switching: Soft switching refers to the method of switching based on the relation between voltage and current. A simple method of controlling switches is by using hard switching. But in this method, the switching loss is very high. Switching loss occurs due to the intersection of voltage and current (Fig. 2.2). Thus to avoid, this soft switching technique is used [24].

Switching loss is significantly reduced by using soft switching converters. This loss reduction is obtained by using a LC resonant circuit to switch on and off the switching device at zero current (zero current switching) or voltage (zero voltage switching). Due to this adjustment, the converter can operate at high frequency with decreased switching loss.

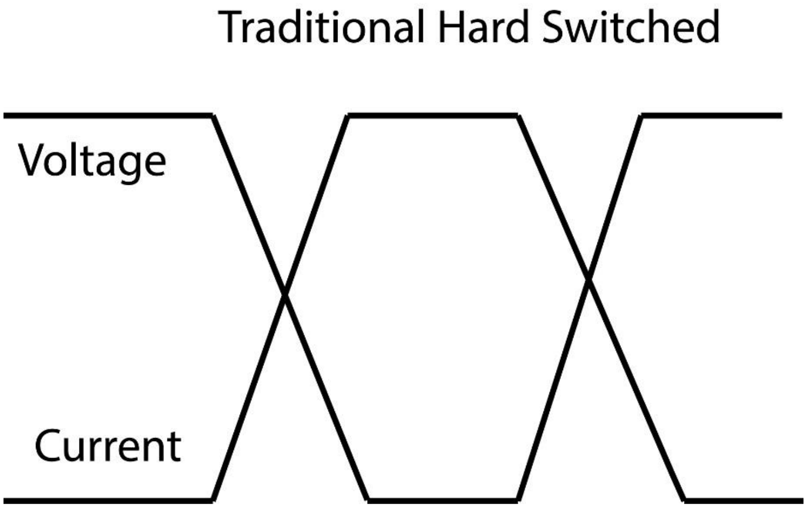


Fig. 2.2: Hard switching waveform

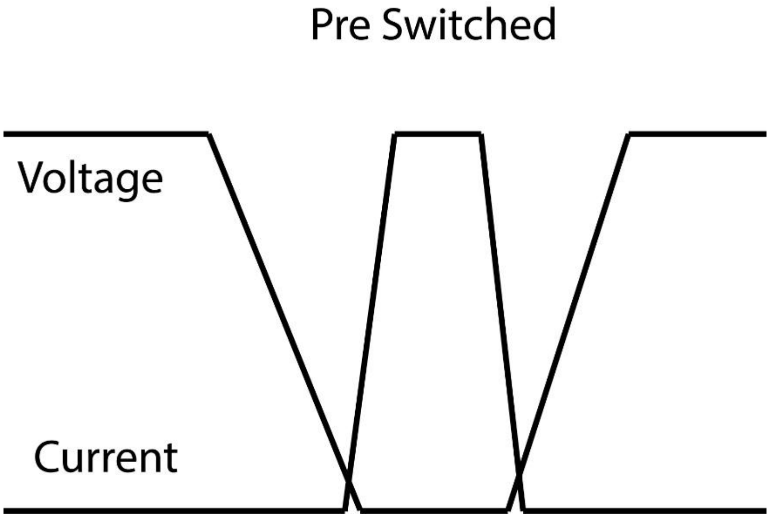


Fig. 2.3: Soft switching waveform

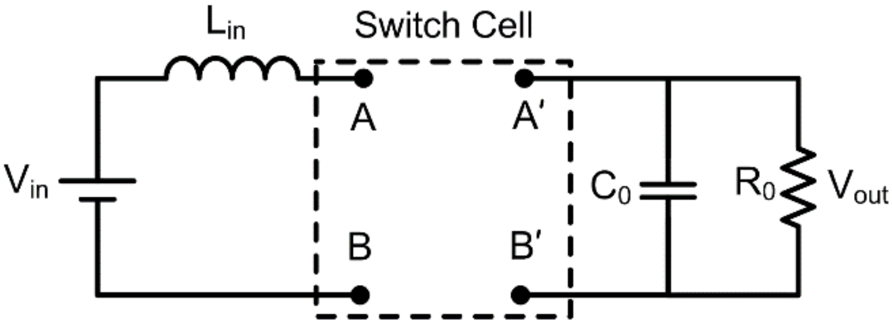


Fig. 2.4: Soft-switching converter

Bidirectional converter: Conventional DC converter are used as unidirectional converter. In such converters, the power flow is unidirectional. However the converter can be modified to make bidirectional power flow [24]. This modification can be done by using bidirectional switches. Fig. 2.5 shows the schematic of a bidirectional converter.

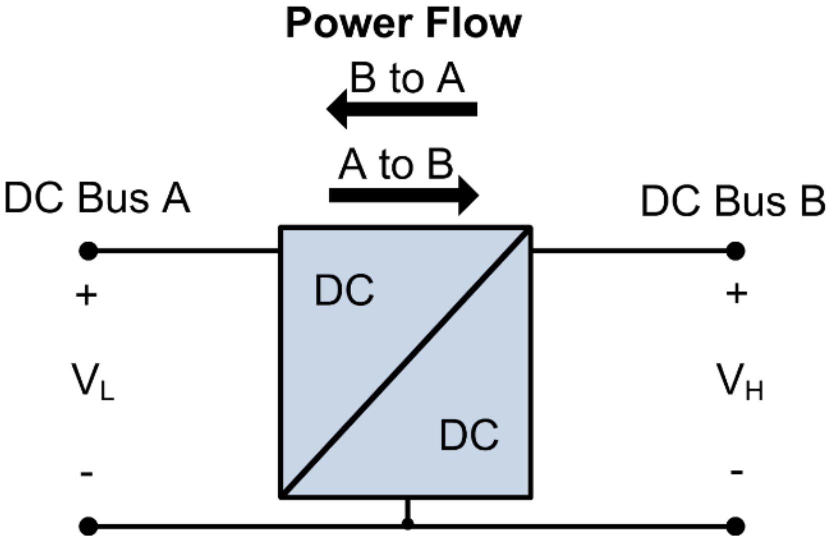


Fig. 2.5: Bidirectional converter

Cascaded converter: DC converters are also used for high voltage applications. However, for high voltage application, the efficiency of the converter decreases. Thus to circumvent this problem, cascaded converters are used [24].

Cascaded topology is a method of connecting two converters to obtain a high voltage ratio while preserving high efficiency.

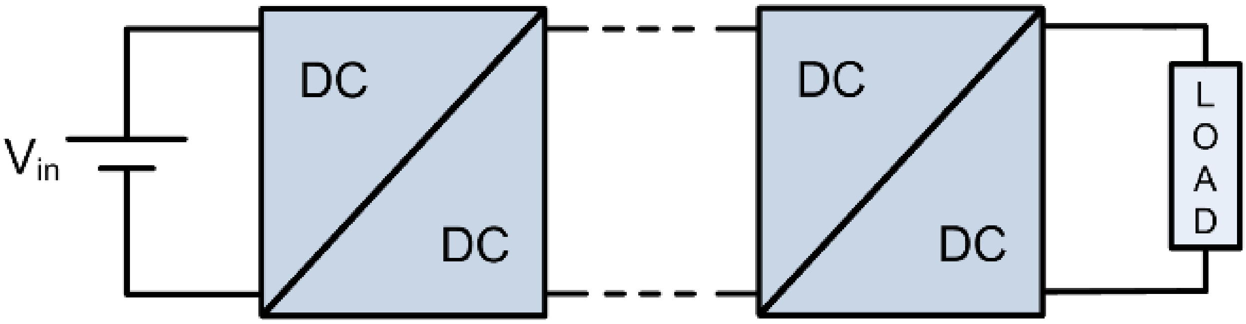


Fig. 2.6: Cascaded converter

Switching mode regulators are types of DC converter, which convert unregulated DC voltage to regulated DC voltage. The regulation is done by a switching device (BJT, IGBT, MOSFET), controlled by a PWM at a high frequency. There are four basic topologies of switching regulators:

1. Buck regulator
2. Boost regulator
3. Buck-Boost regulator
4. CUK regulator

Buck Regulator

Buck regulator is a power electronic converter which only step downs the input DC voltage i.e. output voltage is always less than input voltage [25]. The circuit diagram is shown in Fig. 2.7.

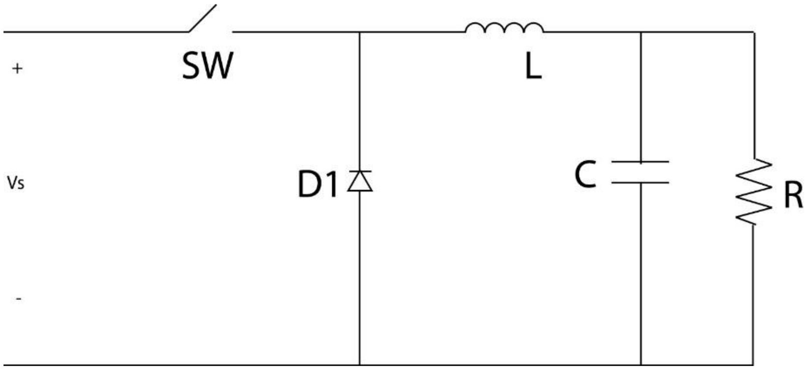


Fig. 2.7: Buck regulator

The circuit operation of the Buck regulator can be divided into two modes. Mode 1 (Switch on state) and Mode 2 (Switch off state). When the switch is on, current flows through inductor L. The current rises as it flows through inductor L, capacitor C and resistor R. When the switch is off, the inductor L discharges. Thus current flows through capacitor C and load R. The current returns back to the inductor via diode D1.

The average output voltage of Buck regulator is

$$Vo = Vs\frac{t1}{T} = DVs$$

Boost Regulator

The DC input voltage in a Boost regulator is always stepped up, irrespective of duty cycle [25]. The circuit diagram of the Boost converter is shown in Fig. 2.8.

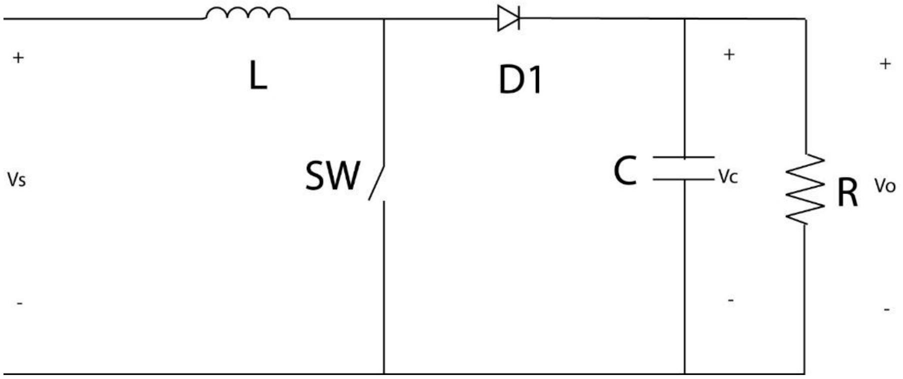


Fig. 2.8: Boost regulator

The circuit operation can be shown in two modes. Mode 1 when switch is on and Mode 2 when switch is off. In Mode 1, when the switch is on, current flows through the inductor L and through the switch SW. During this time input current rises. In Mode 2, the switch is closed. During this time the current flows through inductor L, diode D1, capacitor C and load R. During this time the inductor current falls until the switch is turned on again.

The average output voltage of Boost regulator is

$$Vo = Vs\frac{T}{t2} = \frac{Vs}{1 - D}$$

Buck-Boost Regulator

A Buck-Boost regulator can either step-up or step-down the input DC voltage, depending on the duty cycle. If the duty cycle is less than 50%, then the voltage will step-down [25]. On the other hand, if the duty cycle is greater than 50%, the voltage will step-up. It is sometimes also called inverting regulator. The circuit diagram of the regulator is shown below.

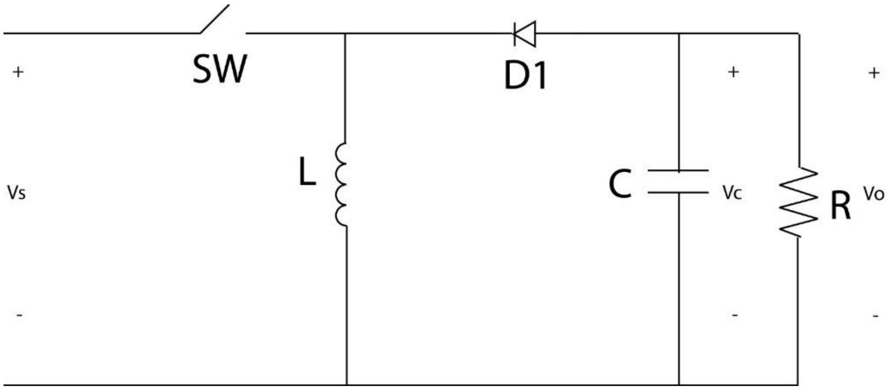


Fig. 2.9: Buck-Boost regulator

Similar to Buck and Boost regulator, the Buck-Boost regulator's circuit operation is divided into two modes. During Mode 1 the switch is on and during Mode 2 the switch is off. When the switch is on, diode D1 operates in reverse bias. Current flows through inductor L and switch SW. When the switch is turned off, the current flows through L, D1, C and R. The inductor discharges and energy is transferred to the load. During this time inductor current decreases until switch is turned on again.

The average output voltage of Buck-Boost regulator is

$$Vo = -\frac{VsD}{1-D}$$

Cuk Regulator

The Cuk regulator is capable of step-up and step-down operation, similar to the Buck-Boost regulator. When the duty cycle is less than 50%, the input voltage is stepped down. When the duty cycle is greater than 50%, the step-up operation occurs [25]. Fig. 2.10 shows the circuit diagram of the Cuk regulator. Cuk regulator has inverted polarity.

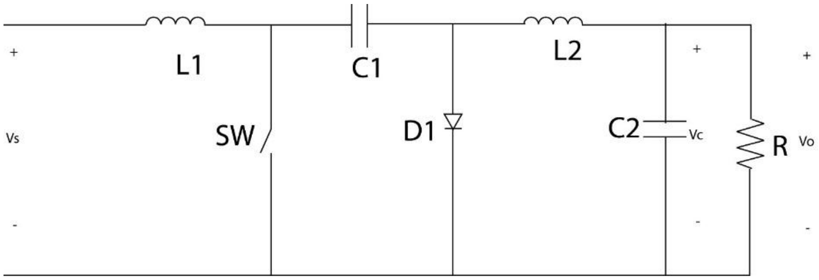


Fig. 2.10: Cuk regulator

Cuk regulator operates in two mode. Mode 1 and Mode 2. When switch is on, inductor current rises. Simultaneously the capacitor C1 voltage reverse biases the diode D1. The capacitor C1 discharges in the circuit formed by load, L2, C2 and C1. In the Mode 2, the switch is turned off. Current flows through inductor L1, capacitor C1. Inductor L2 discharges and transfers energy to load R.

The average output voltage of Cuk regulator is

$$Vo = -\frac{VsD}{1-D}$$

2.2 Performance Parameters

DC-DC converters operate in DC to provide required functionality for an outcome. The effectiveness of a DC-DC converter depends on some DC parameters. For AC-DC converter, the converter performance depends on some AC parameters. The design of any new DC-DC, AC-DC converter needs to be validated with the following parameters.

- Efficiency
- Power Factor
- Total Harmonic Distortion
- Output Voltage

2.2.1 Efficiency

Efficiency is used to describe the energy that a certain system can extract and make useful from its energy source. Such systems include power plants, engines, and turbines. Any system that uses energy from a fuel or primary flow has a certain efficiency associated with it. If energy output and input are expressed in the same units, efficiency is a dimensionless number

Efficiency is an important parameter, when a new converter is designed. It is defined as the ratio of output and input power. It signifies the amount of power, which is transferred from input to output side. Hence if efficiency is less, then output power is not equal to input power. This signifies that there is power wasted in the circuit. It is desirable to have minimum wasted power. This ensures maximum power transfer from input to output side. Efficiency can be defined as

$$\eta = \frac{output\ power}{input\ power}$$

2.2.2 Power Factor

Power factor of an AC power system is defined as the ratio of the real power absorbed by the load to the apparent power flowing in the circuit. It is a dimensionless quantity ranging from 0 to 1. Power factor of less than one indicates the voltage and current are not in phase, reducing the average product of the two. Real power is the instantaneous product of voltage and current and represents the capacity of the electricity for performing work. Apparent power is the product of RMS current and voltage. Due to energy stored in the load and returned to the source, or due to a non-linear load that distorts the wave shape of the current drawn from the source, the apparent power may be greater than the real power.

Power Factor is a parameter which is associated with AC topology of the converters. When designing AC-DC or AC-AC converter, power factor has to be considered. Improving the PF can maximize current-carrying capacity, improve voltage to equipment, and reduce power losses. Power factor is defined as

$$PF = \cos \theta$$

The value of real power can be defined as

$$Real\ power = VI \cos \theta$$

From the above equation is can stated that real power is directly proportional to power factor. Thus it is ideal to have a unity power factor.

The above equation of power factor is for purely sinusoidal waveforms. When the waveforms are affected by THD then power factor also changes. So when a new AC-DC converter is designed the power factor is kept as high as possible.

2.2.3 Total Harmonic Distortion

Another important factor to be considered when designing an AC-DC or AC-AC converter is total harmonic distortion (THD). It is an important aspect of the system and it should be kept as low as possible. Lower THD improves the system significantly. Decreased THD in the system ensures higher power factor, lower current peak and higher efficiency.

The formula of power factor as mentioned above is true only when both voltage and current are completely sinusoidal. Hence if THD increases the power factor decreases. The value of THD can be calculated by using the following formula.

$$THD = \frac{\sqrt{\sum_{k\neq 1} I_{k\_rms}^2}}{I_{1\_rms}}$$

Here I_{k_rms} is defined as

$$I_{k\_rms} = \sqrt{I_{dc}^2 + \sum_{k=2}^{\infty} I_{k\_rms}^2}$$

So taking THD into consideration the equation of power factor can be rewritten as

$$PF = \cos\theta \times \sqrt{\frac{1}{1 + THD^2}}$$

In the above equation $\sqrt{\frac{1}{1+THD^2}}$ is known as distortion factor. Thus the equation of power factor can be written as

$$PF = \cos\theta \times \ Distortion\ Factor$$

2.2.4 Output Voltage

The output voltage is the voltage released by a device, such as a voltage regulator or a generator. Voltage regulators maintain constant voltage levels. Electricity generators use a fuel source, such as sunlight, coal or nuclear energy, to power spinning turbines, which interact with magnets to generate electricity. A conductor carries the output voltage to various destinations, such as homes and businesses. Semiconductor mediums conduct voltage.

For any converter design, a major parameter to be considered is the converter’s ability to provide reliable output voltage. If the system demands high voltage (e.g. 600V-1.5K), then the converter must be designed in such a way that the required voltage could be provided. Cascaded or interleaved converters are used for such high voltage applications. Similarly if the systems demands, then the designed converter should be able to provide low voltage (less than 20V. Usually measured in mV).

Chapter 3

Proposed Cascaded Buck-Boost Zeta Converter (CBBZ)

3.1 Importance of Cascaded DC-DC converter

The power electronics converters can be classified as rectifier, DC to DC converter, AC to AC converter and inverter. Devices are also seen operating in different voltage levels. A converter that provides different levels of output voltage is really essential and have a wide variety of applications. However, the traditional converters are unable to make proper conversion without performance compromisation. There is always a tradeoff between efficiency and performance. For example- high voltage gain will deteriorate the signal and introduce total harmonic distortion. In a traditional converter, the efficiency decreases as the duty cycle of the converter increases. [26] This decrease in efficiency is caused by conduction loss and reverse-recovery problem in diodes. [27-28] Conduction loss and reverse-recovery increases as duty cycle increases. However with the help of cascaded topologies such drawbacks can be overcame. [29-35]

The aim of this research is develop a Cascaded Buck-Boost Zeta (CBBZ) converter, which is used to provide a much higher output voltage in comparison to the conventional Buck-Boost and Zeta converter. High voltage output and high efficiency can be obtained using this Cascaded Buck-Boost Zeta topology. Due to presence of dual output capacitor, output voltage ripple decreases which increases the overall efficiency. [36] Conventional Buck-Boost reaches an output voltage level of 400V whereas the cascaded Buck-Boost Zeta provides almost twice the output voltage. The efficiency of the proposed converter is also higher up to 70% duty cycle when compared with traditional Buck-Boost and Zeta converter. A comparative analysis is done on the proposed converter. Its performance on DC-DC, AC-DC, and closed loop feedback topology is also analyzed. [37-42]

3.2 Circuit topology

In this topology, a cascaded converter is proposed by using Buck-Boost and Zeta converter as base, as illustrated in Fig. 3.1. The proposed converter is able to provide high voltage gain. When compared with conventional converters, the efficiency of the proposed converter is higher, despite having more components. The presented topology consists of switch M_1 and inductor L_1, which are common for both Buck-Boost and Zeta converter. Diode D_1 and capacitor C_1 are the remaining electrical components of Buck-Boost converter. Similarly diode D_2, inductor L_2, and capacitors C_2 and C_3 form the remaining part of the Zeta converter. Resister R_1 acts as load for the converter.

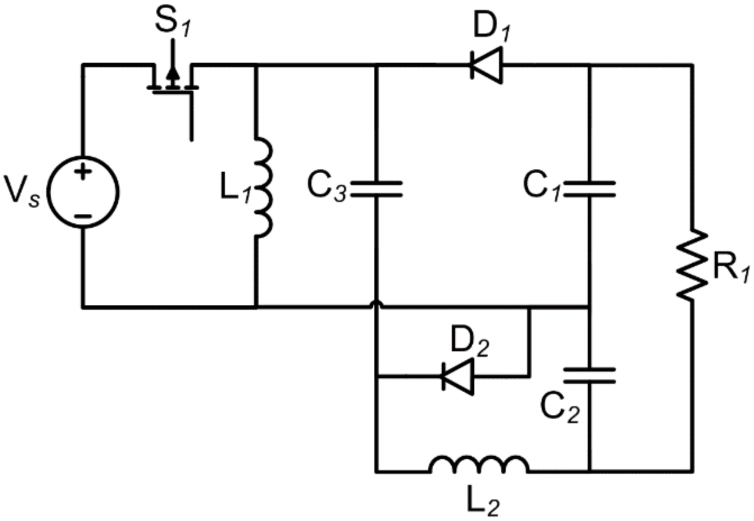


Fig. 3.1: Proposed converter

3.3 Circuit Operation

In this section, the current flow of the proposed circuit is shown as performed in PSIM software. The overall current flow of the converter for on-switching and off-switching is shown in Fig. 3.2.

During mode 1 (when the switch is on), inductor L_1 gets charged. Simultaneously capacitors C_2, C_3 and inductor L_2 gets charged. During mode 2 (when the switch is off), inductor L_1 discharges and follows the pathway of capacitor C_1 and diode D_1. Simultaneously capacitor C_3 and inductor L_2 also discharges. C_3 discharges through inductor L_1 and diode D_2. Inductor L_2 discharges through capacitor C_2 and diode D_2. The ripple in the output voltage is reduced by capacitors C_1 and C_2, thus ensuring constant voltage. The duty cycle formula of the proposed converter is expressed as

$$V_{o1} = \text{Output voltage of Buck-Boost} = \frac{-D}{1-D} V_i$$

$$V_{o2} = \text{Output voltage of Zeta} = \frac{-D}{1-D} V_i$$

$$V_o = V_{o1} + V_{o2}$$

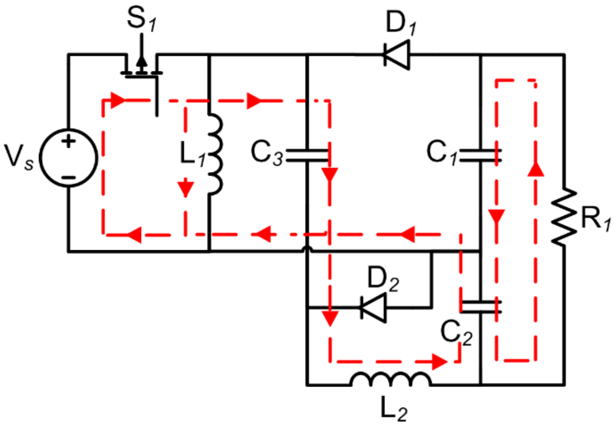
$$V_o = \frac{-D}{1-D}V_i + \frac{-D}{1-D}V_i$$

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

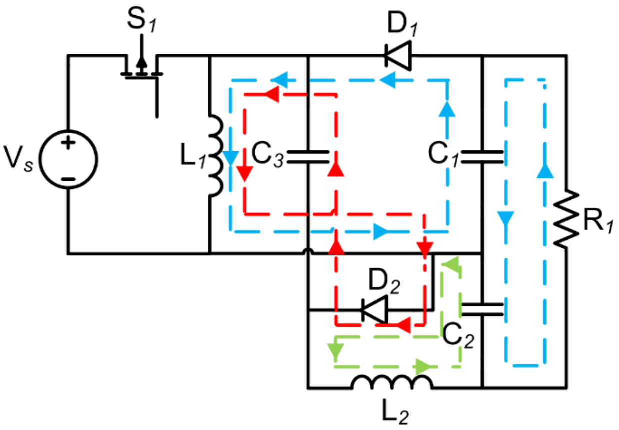
$$V_o = \frac{-2D}{1-D}V_i$$

From the derived equation the overall voltage gain of the DC-DC converter is

$$G = \frac{-2D}{1-D}$$



(a) Mode 1 (On State)



(b) Mode 2 (Off State)

Fig. 3.2: Cascaded Buck-Boost Zeta converter current diagram

3.4 Applications of the proposed converter

In recent years, the practical applications of converter have increased, making it an important part of the power system [42-48]. Converter has a versatile usage, ranging from HVDC, speed control, motor control and so on. The proposed converter, with its improved working performance, can be used for practical applications. The converter can be implemented with an AC-DC and closed loop topology, backed up by theoretical simulation done in PSIM.

3.5 AC-DC Topology

The proposed converter can be implemented in an AC-DC topology, as illustrated in Fig. 3.3. In order to implement such a system, the proposed converter is integrated with an AC source and a full-wave rectifier. With the use of a full-wave rectifier, the AC input voltage is converted to DC output.

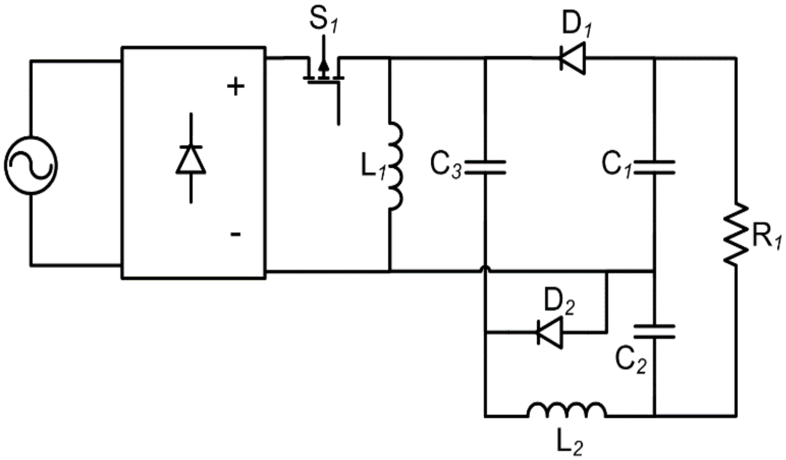


Fig. 3.3: AC-DC Cascaded Buck-Boost Zeta converter

3.6 Closed Loop Feedback

The performance of the proposed converter can be further augmented by using a closed loop feedback topology. The implementation of the PI controller is done to improve efficiency of the converter. The gain and time constant of the PI block is set at 0.8 and 0.0001 respectively. Comparison is made between the output current and a scaled reference current. Successive approximation is used to choose the scale factor which is set at 1.5 of the reference current which eventually provided the desired output. After the PI block a limiter is used to set the maximum and minimum value, which will be given to the comparator. From the comparator a switching signal goes to the switch S_1, controlling the converter. The closed loop controller significantly enhances the performance parameter of the proposed converter, delivering an efficiency as high as 99.67. The circuit topology is shown in Fig. 3.4.

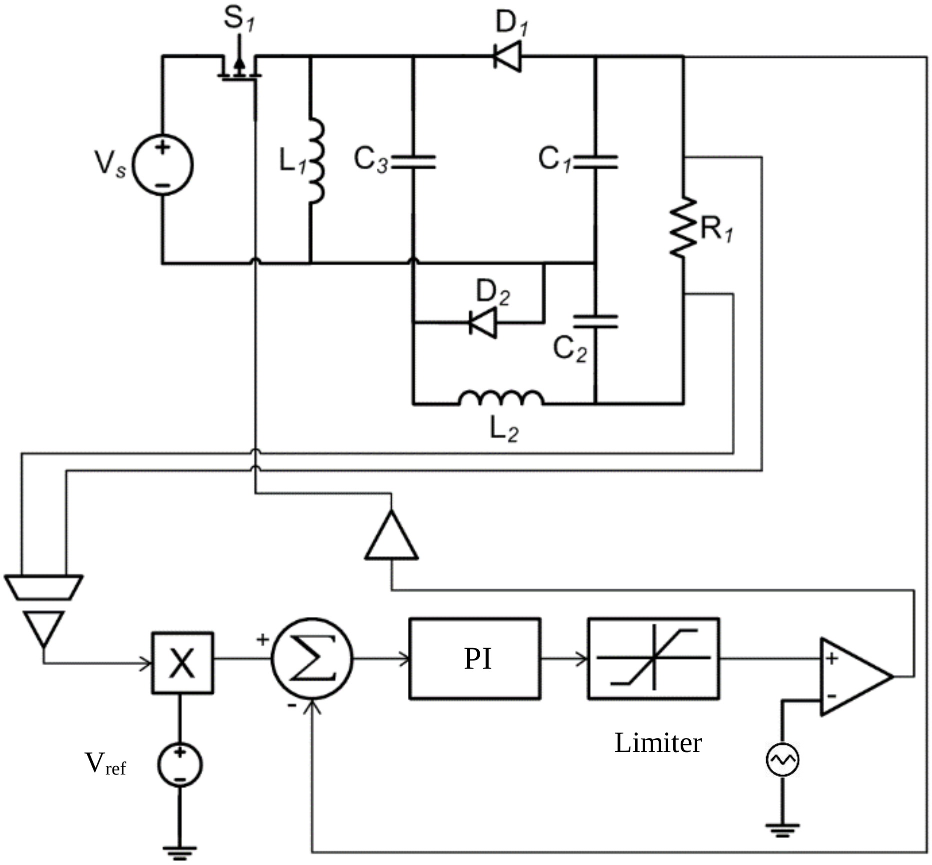


Fig. 3.4: Closed Loop Feedback topology for DC-DC Converter

Chapter 4

Simulation Results

4.1 Comparative Analysis

A comparative analysis between the proposed converter with conventional converters, along with recent published cascaded converters are shown. Table 4.1 shows the component comparison between the proposed and conventional converters. From the table it can be observed that al the converters have the same number of switches. Buck-Boost converter has the least number of components when compared with conventional Zeta and proposed converter. The proposed converter has two inductors, three capacitors and two diodes.

Table 4.2 shows the comparison between the proposed and recent converters. All the converter have same number of switches. When the table is analyzed, it can be observed that all the converters have same number of components. The simulation assumptions used are also illustrated in this section. Comparative analysis of the circuit DC-DC, AC-DC and closed loop is shown here, followed by frequency and load analysis of the proposed converter.

Table 4.1: Component comparison between proposed and conventional converter

	Proposed converter	Buck-Boost converter	Zeta converter
Switches	1	1	1
Inductors	2	1	2
Capacitors	3	1	2
Diodes	2	1	1

Table 4.2: Component comparison between proposed, cascaded SEPIC Boost and integrated Boost-CUK converter

	Proposed converter	Cascaded SEPIC Boost converter [27]	Integrated Boost CUK converter [26]
Switches	1	1	1
Inductors	2	2	2
Capacitors	3	3	3
Diodes	2	2	2

4.2 Simulation Assumptions

For theoretical analysis, the following assumptions were made.

- The components used were all ideal.
- Input voltage is considered as ideal source.
- For simulation, the following values were used using PSIM:

Frequency = 10 KHz
L_1 = 50mH
L_2 = 50mH
C_1 = 500uF
C_2 = 500uF
C_3 = 10uF
R_1 = 100 Ω

4.3 DC-DC Topology

4.3.1 Output Analysis

Fig. 4.1 and 4.2 shows the input and output voltage of the proposed DC-DC converter at 50% duty cycle.

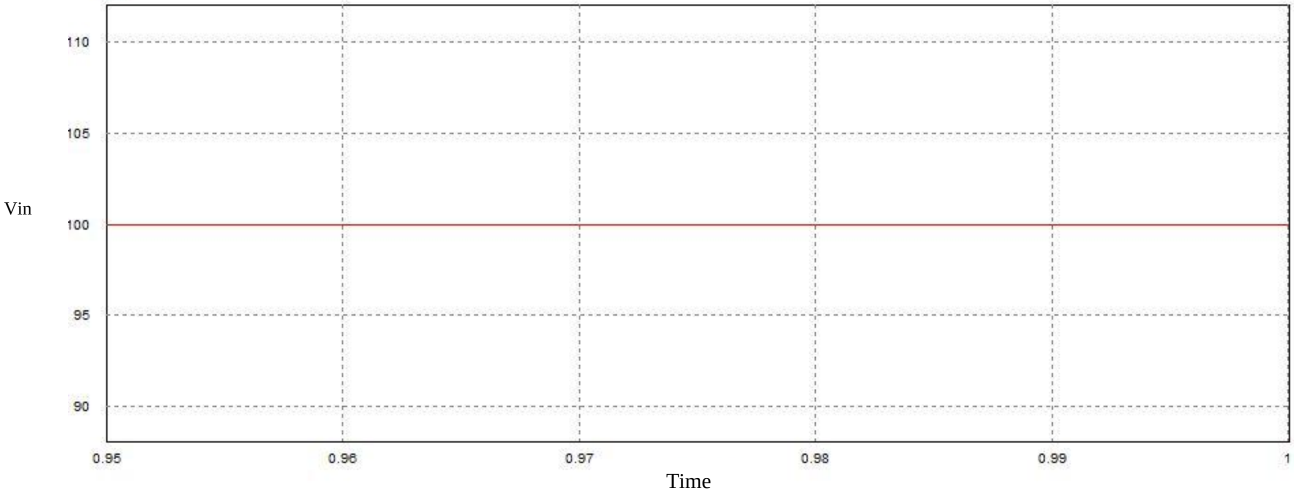


Fig. 4.1: Input voltage of DC topology at 50% duty cycle

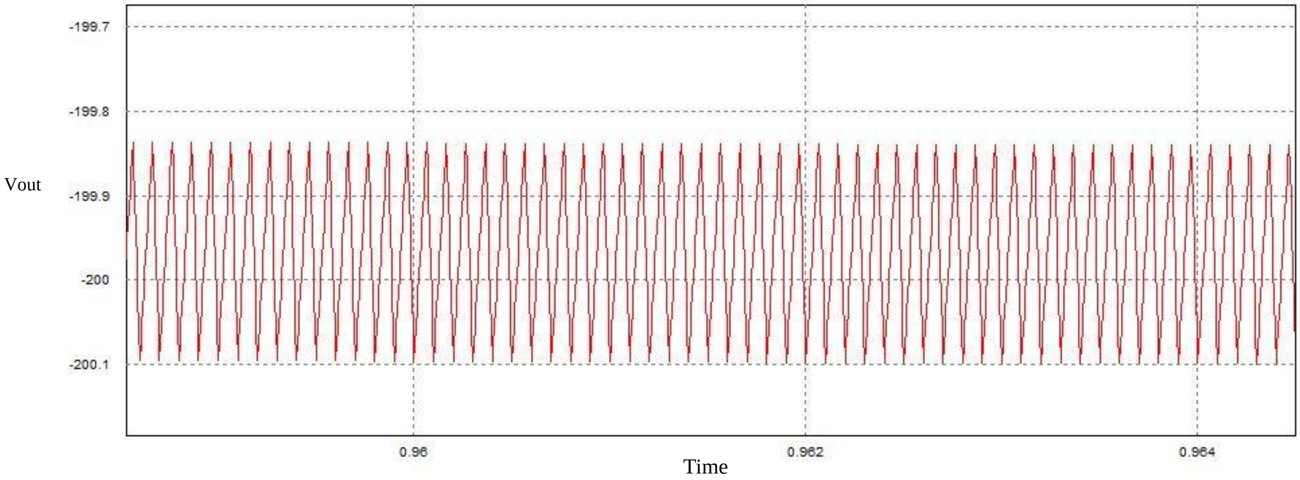


Fig. 4.2: Output voltage of DC topology at 50% duty cycle

4.3.2 Efficiency Comparison

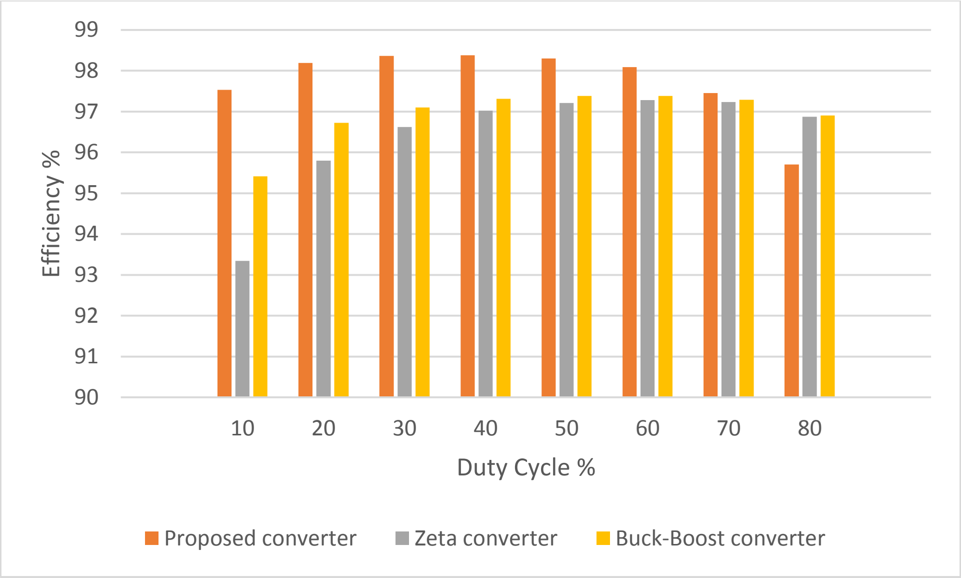
When compared with conventional Buck-Boost and Zeta converter, the proposed converter has higher efficiency as shown in Table 4.3. From the table it can be seen that the duty cycle of the converters are increased from 10 to 80%. Due to increase in duty cycle, the efficiency of the converters are also changes. The efficiency of the proposed DC-DC converter increases and peaks at 40% duty cycle, with an efficiency of 98.38%. After that the efficiency decreases to 95.7% at 80% duty cycle. Zeta converter experiences its lowest efficiency at 10% duty cycle with a value of 93.34%, as duty cycle increases, efficiency of Zeta converter also increases and peaks at 97.28% at 60% duty cycle. For the Buck-Boost converter, as duty cycle increases, the efficiency of the converter also increases and has maximum efficiency at 97.38%.

The bar diagram in Fig. 4.3(a) shows that the efficiency bar diagram of the converters. From the diagram it can be observed that the efficiency of the proposed converter towers over conventional Zeta and Buck-Boost converter. The difference between them however decreases, as duty cycle increases. At 80% duty cycle, it can be observed that the efficiency of the proposed converter is slightly lower than the conventional converters.

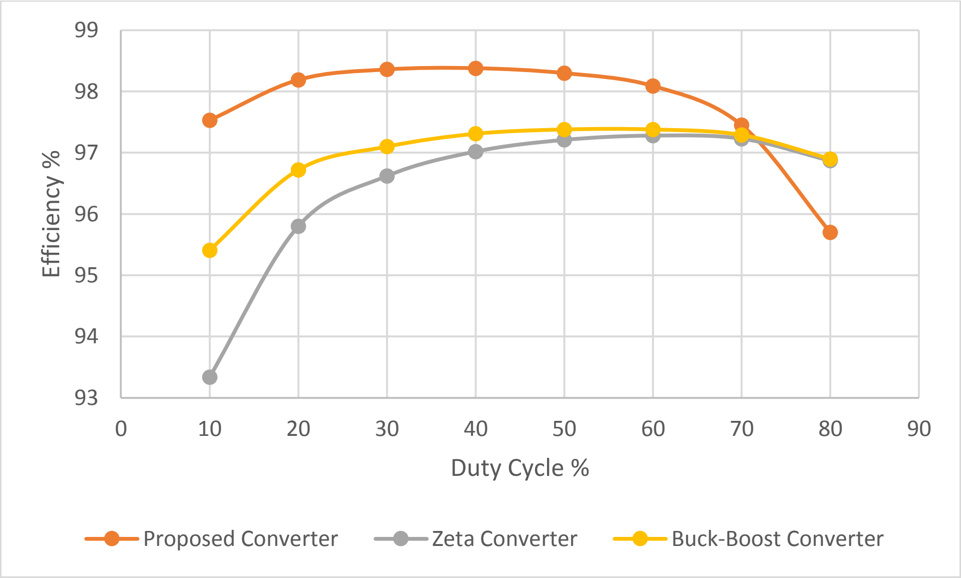
The graph in Fig. 4.3(b) illustrates the efficiency trajectory of the converters. Initially it can be observed that the efficiency of the proposed converter increases and have maximum value at 40% duty cycle. After that the efficiency dips and at 80% duty cycle becomes less than conventional Zeta and Buck-Boost converter.

Table 4.3: Efficiency data for the proposed and conventional converters

Duty cycle (%)	Proposed converter (%)	Zeta converter (%)	Buck-Boost converter (%)
10	97.53	93.34	95.41
20	98.19	95.8	96.72
30	98.36	96.62	97.1
40	98.38	97.02	97.31
50	98.3	97.21	97.38
60	98.09	97.28	97.38
70	97.45	97.23	97.29
80	95.7	96.87	96.9



(a)



(b)

Fig. 4.3: DC-DC Efficiency comparison

4.3.3 Output Voltage Comparison

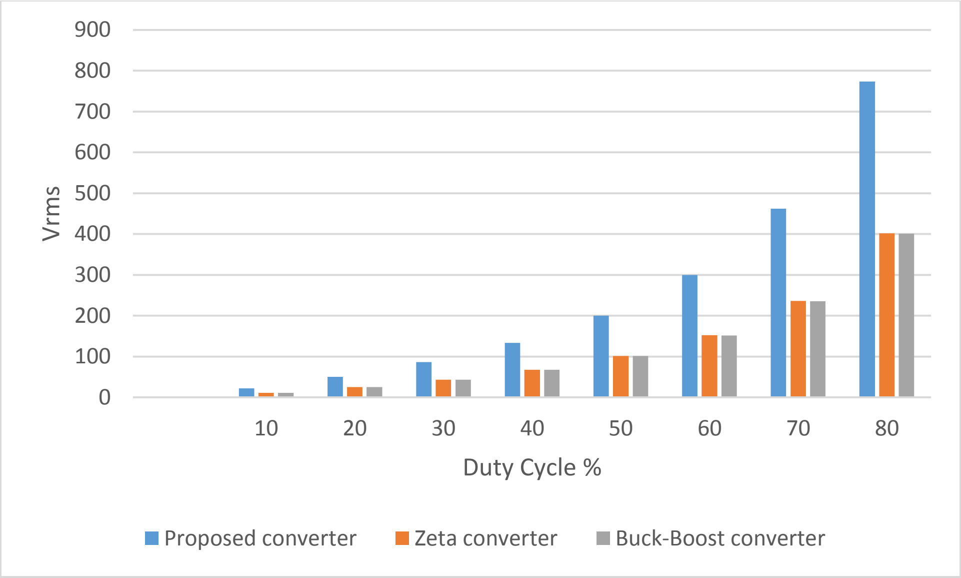
The proposed converter can deliver voltage at a higher level when compared with conventional Buck-Boost and Zeta converter. As shown in Table 4.4, the output voltage of the proposed converter increases with increase in duty cycle. At 10% duty cycle, the output voltage is at 22.38V. As the value of duty cycle is increased, the value of output voltage also increases and at 80% duty cycle the value reaches at 773.36V. From Table 4.4 it can be observed that the output voltage of the proposed converter is almost twice more than the conventional Zeta and Buck-Boost converter. The maximum output voltage of Zeta and Buck-Boost converter is 401.79V and 401.23V respectively.

From the bar diagram in Fig. 4.4(a), it can be observed that as duty cycle is increased, output voltage is also increased. However the rise in the proposed converter is much superior to conventional Zeta and Buck Boost converter.

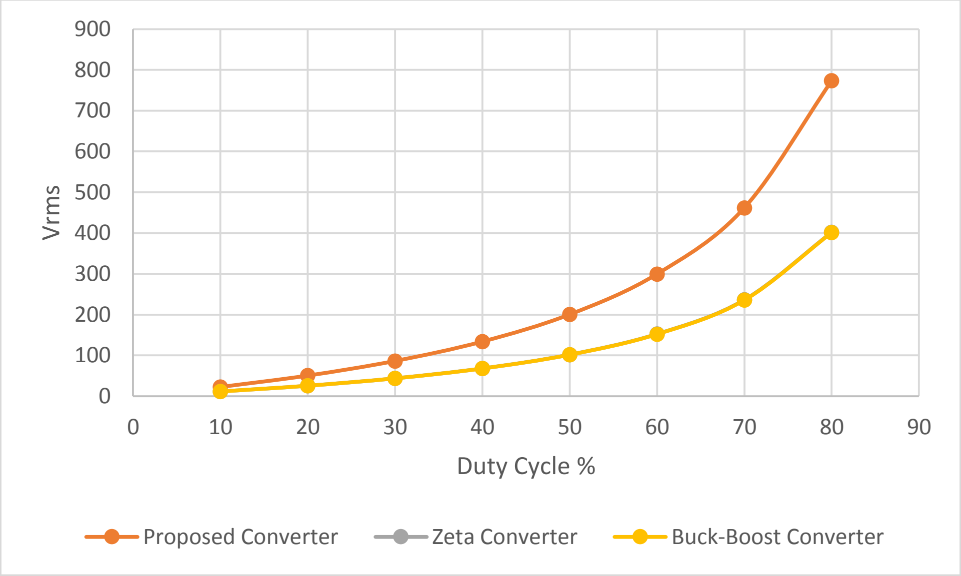
Fig. 4.4(b) illustrates the output voltage between the converters in a graphical form. From the graph it can be observed that as duty cycle increases, the output voltage of the proposed and conventional converters also increases. The increase in output voltage is an exponential rise for all the converters. However the increase in output voltage of the proposed converter is much higher than conventional Zeta and Buck Boost converter.

Table 4.4: Output voltage data for the proposed and conventional converters

Duty Cycle (%)	Proposed converter (V)	Zeta converter (V)	Buck-Boost converter (V)
10	22.38	11.32	11.31
20	50.33	25.46	25.43
30	86.21	43.63	43.57
40	133.8	67.84	67.72
50	200.35	101.69	101.47
60	299.5	152.32	151.9
70	461.97	236.22	235.5
80	773.36	401.79	401.23



(a)



(b)

Fig. 4.4: DC-DC output voltage comparison

4.4 AC-DC Topology

4.4.1 Output Analysis

Fig. 4.5 and 4.6 shows the waveform of input and output voltage respectively. The waveforms are recorded at 50% duty cycle.

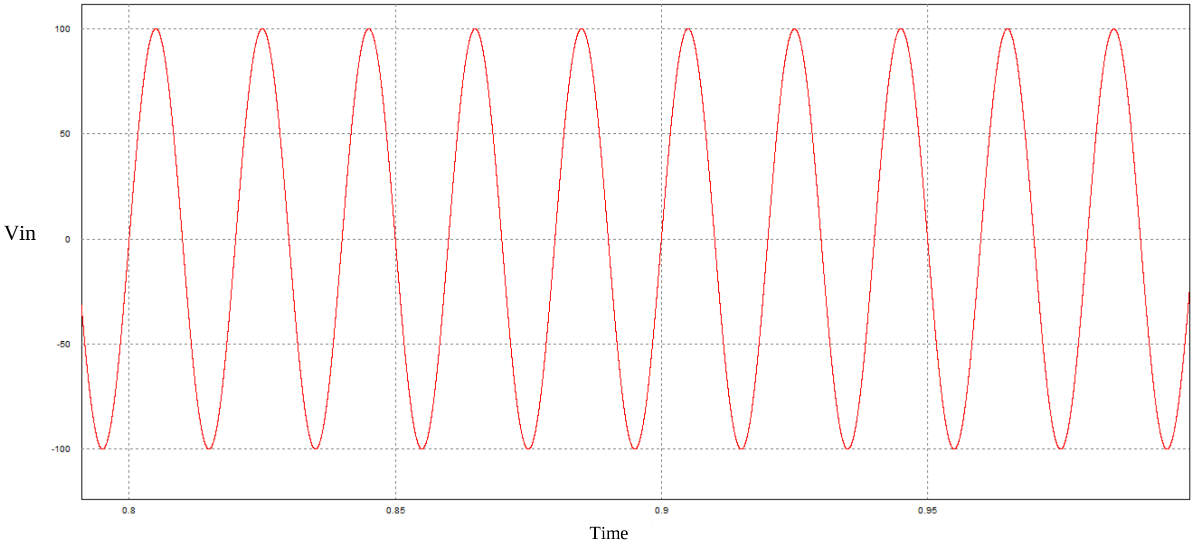


Fig. 4.5: Input Voltage of AC-DC topology from 0.8s to 1s

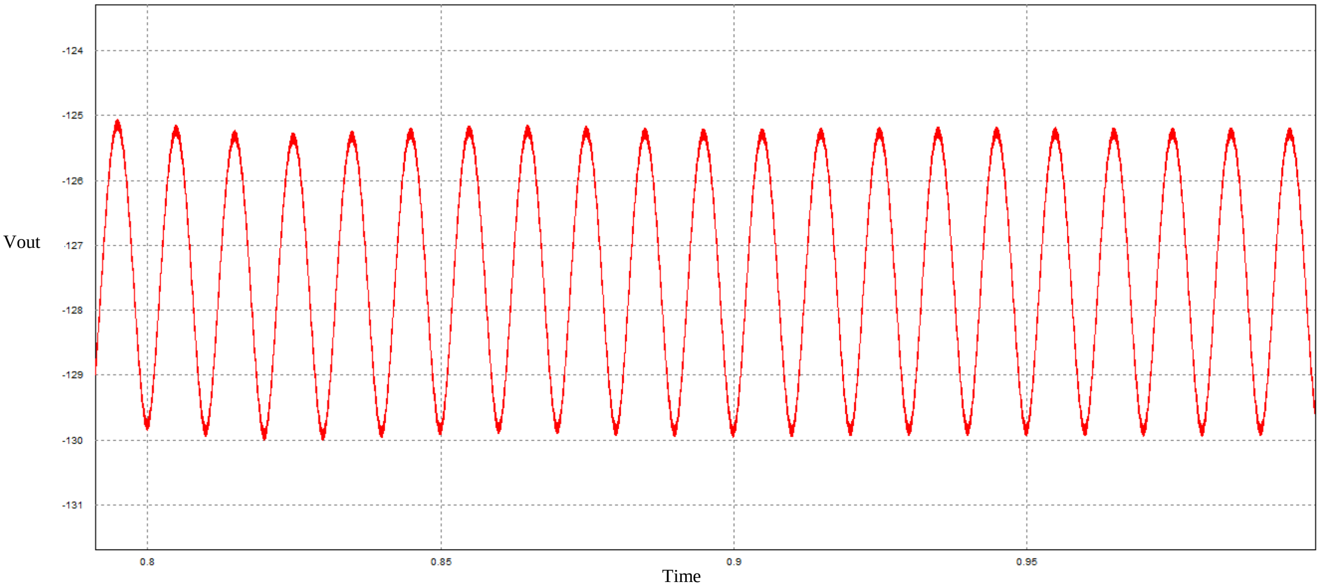


Fig. 4.6: Output Voltage of AC-DC topology at 50% duty cycle

4.4.2 Efficiency Comparison

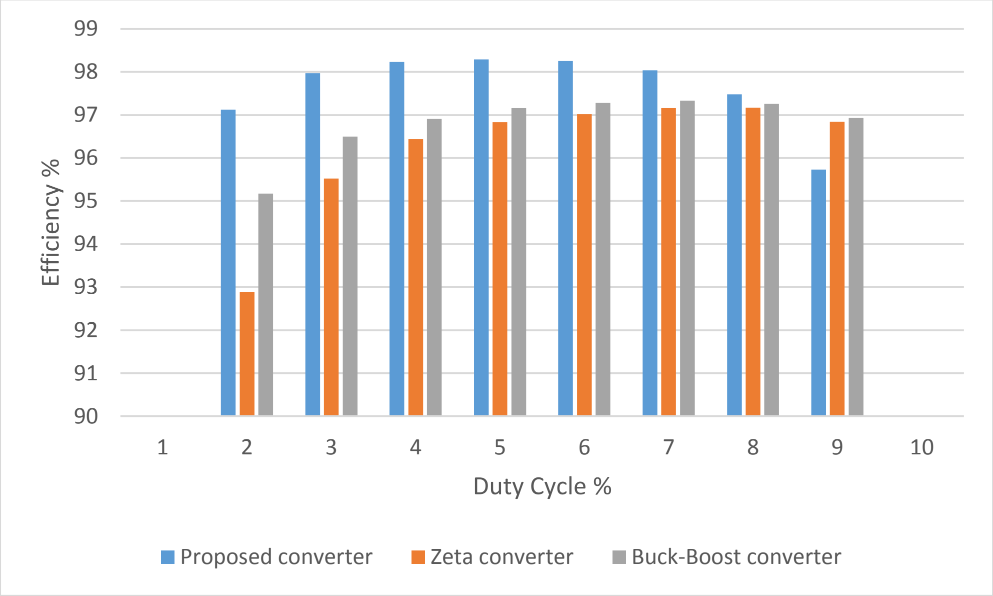
From Table 4.5 it can be observed that the efficiency of the proposed converter increases with increases in duty cycle. This trend is observed up to 40%, when the efficiency is maximum at 98.29%. After 40% duty cycle, the efficiency decreases to 95.73%. For Zeta converter, the minimum efficiency value is 92.88%. As duty increases, the efficiency value increases to 97.17%. For Buck Boost converter, minimum efficiency is 95.17% and the value increases to 97.33%.

Fig. 4.7(a) shows efficiency bar diagram of the converters. From the bar diagram it can be observed that initially the efficiency of the proposed AC-DC converter is significantly higher than the conventional AC-DC Zeta and Buck Boost converter. As duty cycle is increased, this difference between the efficiency reduces.

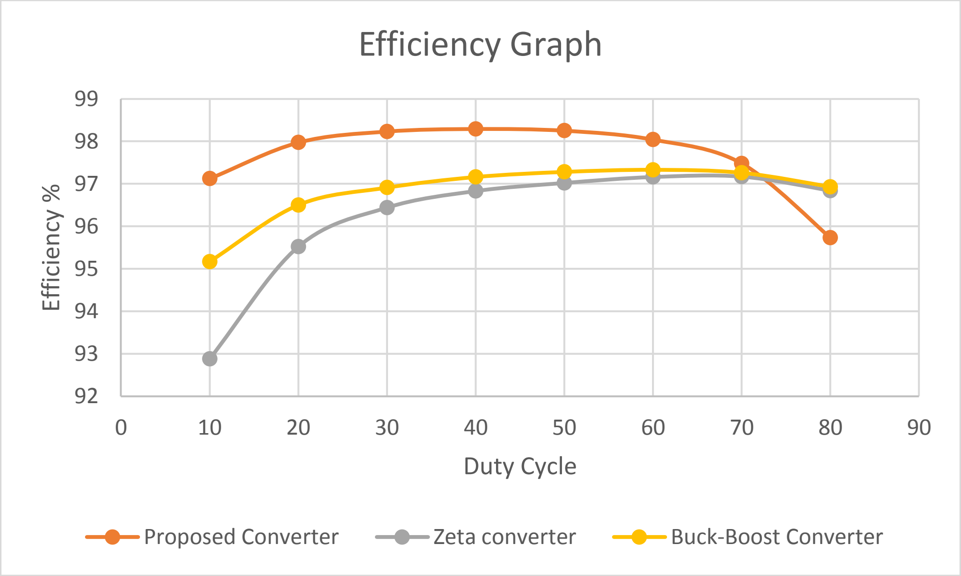
From Fig. 4.7(b), it can be observed that the efficiency of the proposed AC-DC converter is better when compared with conventional AC-DC Zeta and Buck-Boost converter. Efficiency of the proposed AC-DC converter increases up to 40% duty cycle. After that, efficiency decreases but still higher than conventional Zeta and Buck-Boost converter.

Table 4.5: Efficiency data for the AC-DC proposed and conventional converters

Duty Cycle (%)	Proposed converter (%)	Zeta converter (%)	Buck-Boost converter (%)
10	97.12	92.88	95.17
20	97.97	95.52	96.5
30	98.23	96.44	96.91
40	98.29	96.83	97.16
50	98.25	97.02	97.28
60	98.04	97.16	97.33
70	97.48	97.17	97.26
80	95.73	96.84	96.93



(a)



(b)

Fig. 4.7: AC-DC Efficiency comparison

4.4.3 Input Power Factor

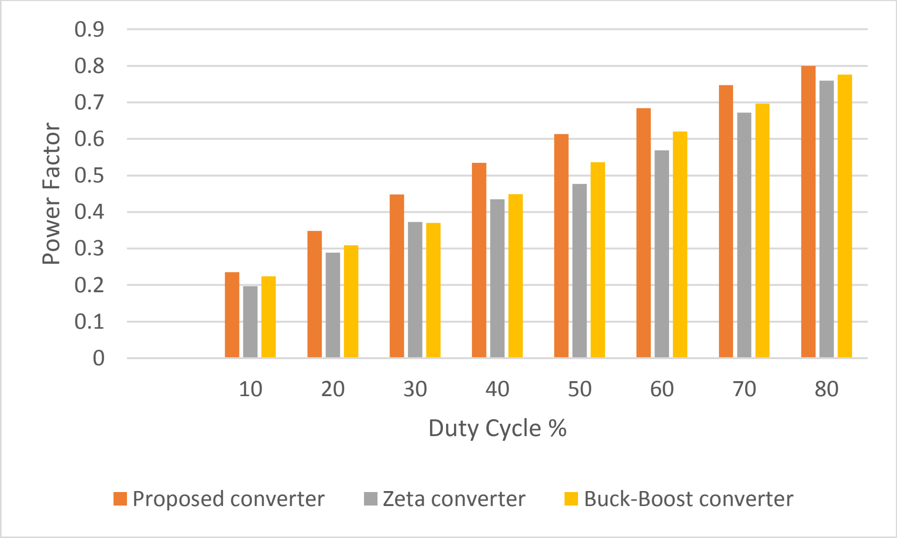
The proposed converter has higher input power factor, when compared with conventional Buck-Boost and Zeta converter. From Table 4.6, it can be observed that with increase in duty cycle power factor also increases and peaks at 0.7996 at 80% duty cycle. Conventional AC-DC Zeta and Buck-Boost converter also experience similar trend having maximum value at 0.7592 and 0.7757 respectively.

Fig. 4.8(a) shows the power factor bar diagram of the converters. From the bar diagram it can be observed that the power factor value of the proposed AC-DC converter is higher than the conventional AC-DC Zeta and Buck Boost converter.

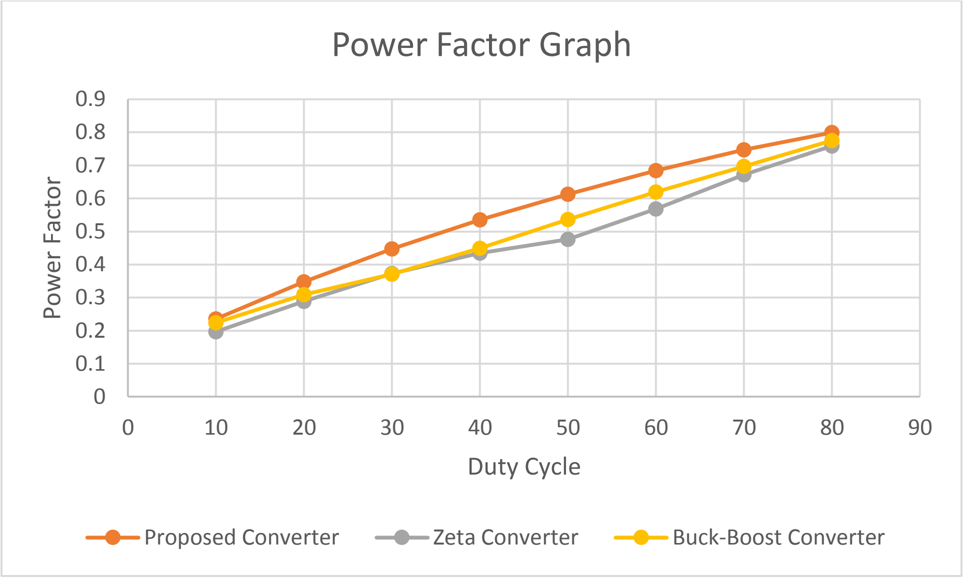
Fig 4.8(b) shows the power factor curve of the converters. From the graph a rising trend of the power factor is observed. Power factor of the proposed AC-DC converter is higher than conventional AC-DC Zeta and Buck-Boost converter.

Table 4.6: Power Factor data for the AC-DC proposed and conventional converters

Duty Cycle (%)	Proposed converter	Zeta converter	Buck-Boost converter
10	0.2355	0.1971	0.2239
20	0.3481	0.2886	0.309
30	0.4476	0.3728	0.3704
40	0.535	0.435	0.449
50	0.613	0.4768	0.5364
60	0.6844	0.5684	0.6199
70	0.7474	0.6718	0.6968
80	0.7996	0.7592	0.7757



(a)



(b)

Fig. 4.8: Power Factor Comparison

4.4.4 Output Voltage Comparison

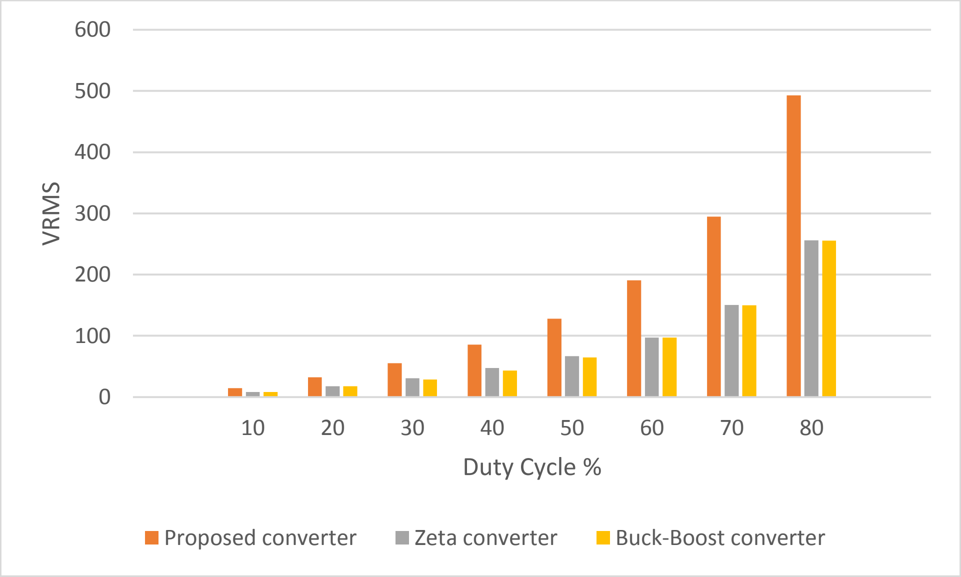
As shown in Table 4.7 the output voltage of the proposed converter increases as duty cycle increases. With increase duty cycle the output voltage of the proposed AC-DC converter increases and reaches a maximum value of 493V. Conventional AC-DC Zeta and Buck-Boost converter also follow similar pattern having maximum output voltage of 255.84V and 255.5V respectively at 80% duty cycle.

The bar diagram in Fig. 4.9(a) shows the voltage comparison between the converters. From the bar diagram it can be observed that the output voltage of the proposed converter is significantly higher than conventional AC-DC Zeta and Buck-Boost converter. With increase in duty cycle the difference in output voltage also increases.

Fig. 4.9(b) shows the output voltage graph of the compared converters. From the graph it can be observed that the output voltage follows an exponential relation with duty cycle. With increase in duty cycle, the output voltage value also increases. Output voltage of the proposed AC-DC converter is higher than conventional Zeta and Buck-Boost converter.

Table 4.7: Output voltage data for the AC-DC proposed and conventional converters

Duty Cycle (%)	Proposed converter (V)	Zeta converter (V)	Buck-Boost converter (V)
10	14.48	8.03	8.12
20	32.16	17.82	17.5
30	55.03	30.93	28.46
40	85.42	47.18	43.26
50	127.8	66.64	64.7
60	190.9	97.2	96.85
70	294.6	150.58	150.1
80	493	255.84	255.5



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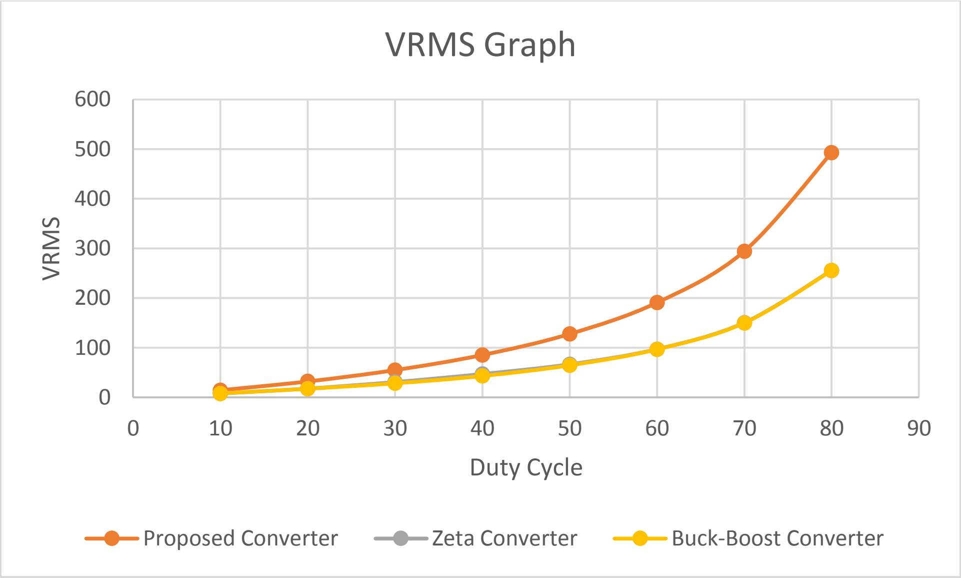


(b)

Fig. 4.9: AC-DC Voltage Comparison

4.5 Closed Loop Feedback

4.5.1 Output Analysis

Fig. 4.10 illustrates the output voltage for the closed loop feedback topology of the proposed DC-DC converter.

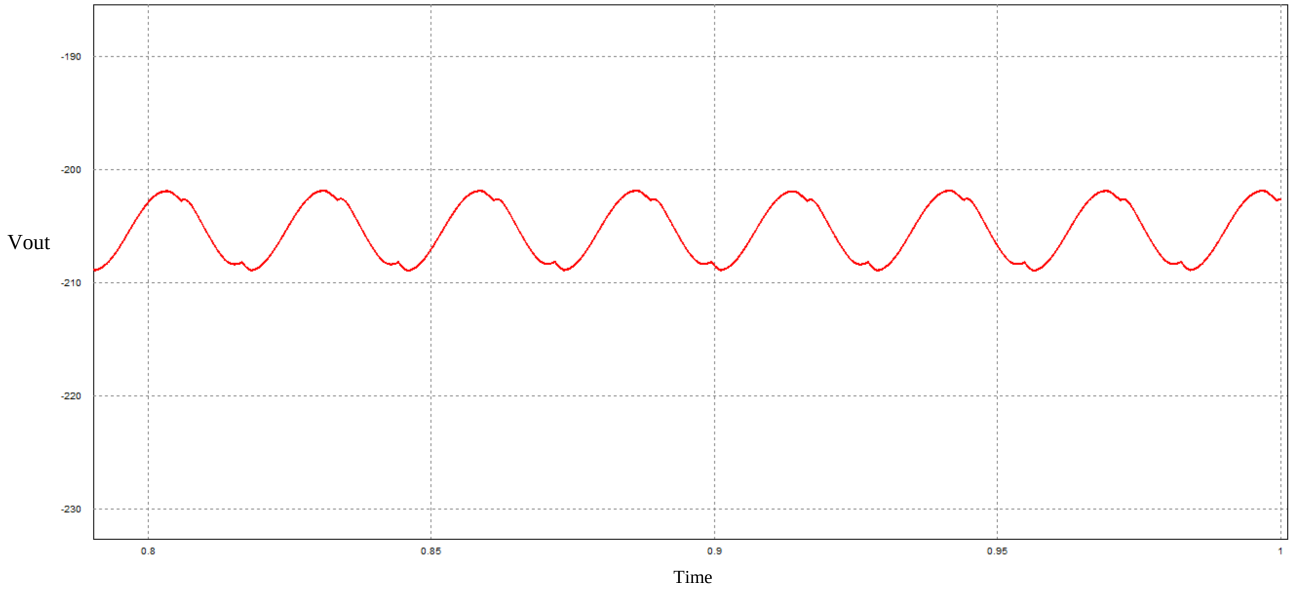


Fig. 4.10: Output Voltage of Closed loop topology from 0.8s to 1s

4.5.2 Comparison between Open and Closed loop

Efficiency of the converter can be increased significantly by using a Closed Loop Feedback. The efficiency of the converter increases to 99.67%. The following table shows a comparison between the two topology. The comparison is made by taking the best result from open loop converter.

Table 4.8: Comparison between closed and open loop

Parameters	Proposed DC-DC converter without feedback	Proposed DC-DC converter with feedback
Efficiency (%)	98.38	99.67

4.6 Comparison between Integrated Boost-CUK and Cascaded SEPIC Boost converter

4.6.1 Integrated Boost CUK converter

Integrated Boost Cuk converter [26] is a combination of two conventional converter. Boost converter and Cuk converter. The circuit diagram of the converter is shown in Fig. 4.11. The circuit consists of two inductors, three capacitors, two diodes and one switch. Components L_1, SW, D_1, and C_2 forms Boost part of the converter. Cuk part of the converter is formed by L_1, SW, C_1, D_2, L_2 and C_3.

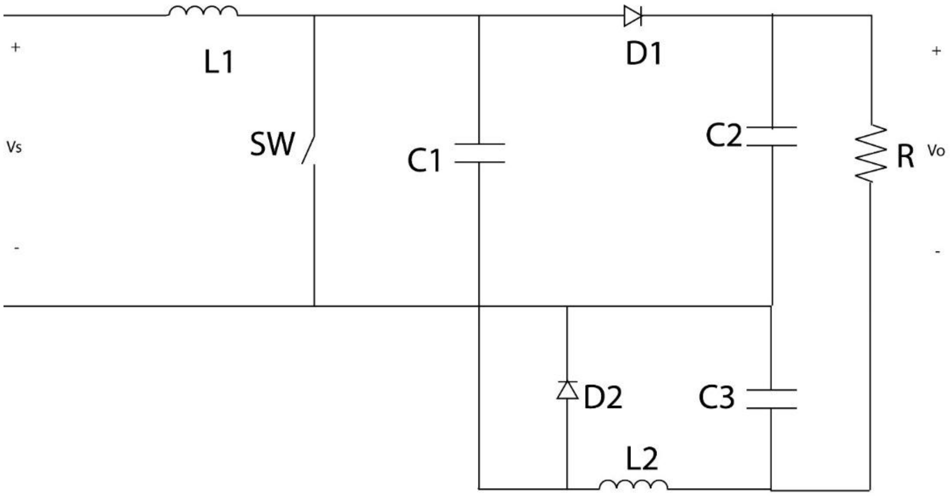


Fig. 4.11: Integrated Boost Cuk converter

4.6.2 Cascaded SEPIC Boost converter

Fig. 4.12 shows the cascaded SEPIC Boost converter [27]. As the name suggests, the said converter is a combination of SEPIC and Boost converter. The circuit consists of two inductors, three capacitors, two diodes and one switch. Components L_1, SW, D_1, and C_2 forms Boost part of the converter. SEPIC part of the converter is formed by L_1, SW, C_1, D_2, L_2 and C_3.

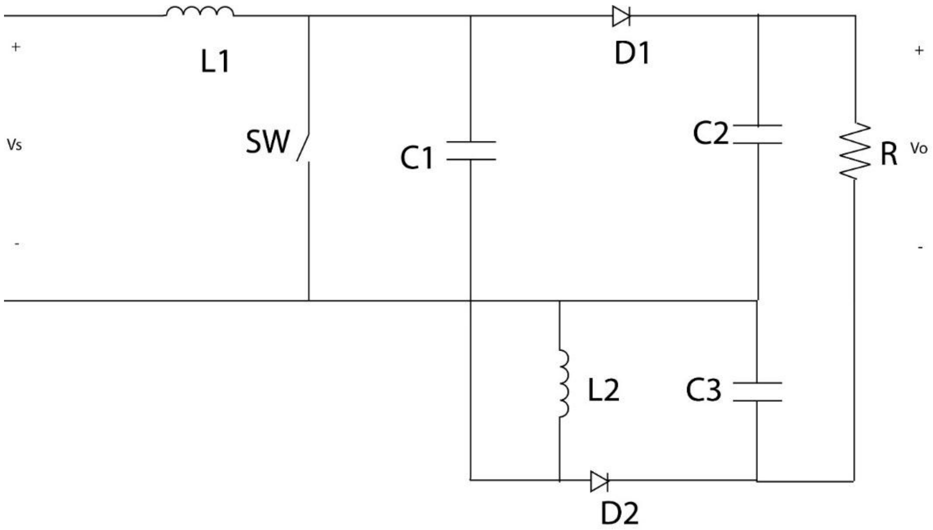


Fig. 4.12: Cascaded SEPIC Boost converter

4.6.3 Efficiency Comparison between Cascaded DC-DC Buck-Boost Zeta and Boost CUK

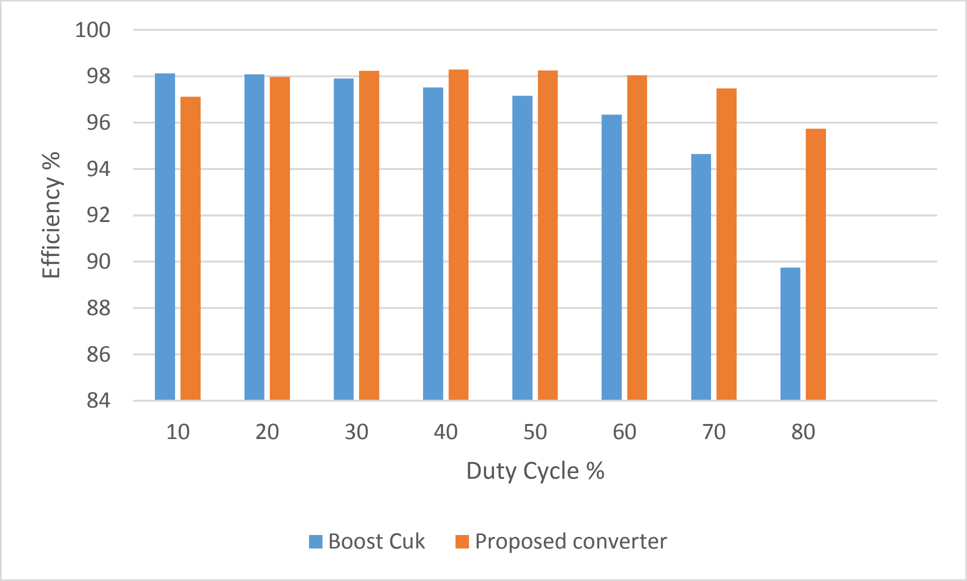
The following table show the efficiency comparison between cascaded Buck-Boost Zeta and Boost Cuk. From the table it can be observed that with increase in duty cycle efficiency of the proposed DC-DC converter increases and has its maximum efficiency of 98.38% at 40% duty cycle. After that the efficiency decreases and have minimum efficiency at 95.7%. For Boost Cuk converter the maximum efficiency is at 10% duty cycle with 98.121%. With increases in duty cycle the efficiency of the Boost Cuk converter decreases to 89.74% at 80% duty cycle.

From 4.13(a), it can be observed from the bar diagram that initially the efficiency of both the cascaded converters were similar. But with increase in duty cycle, the difference in efficiency of the proposed converter and Boost Cuk converter increases.

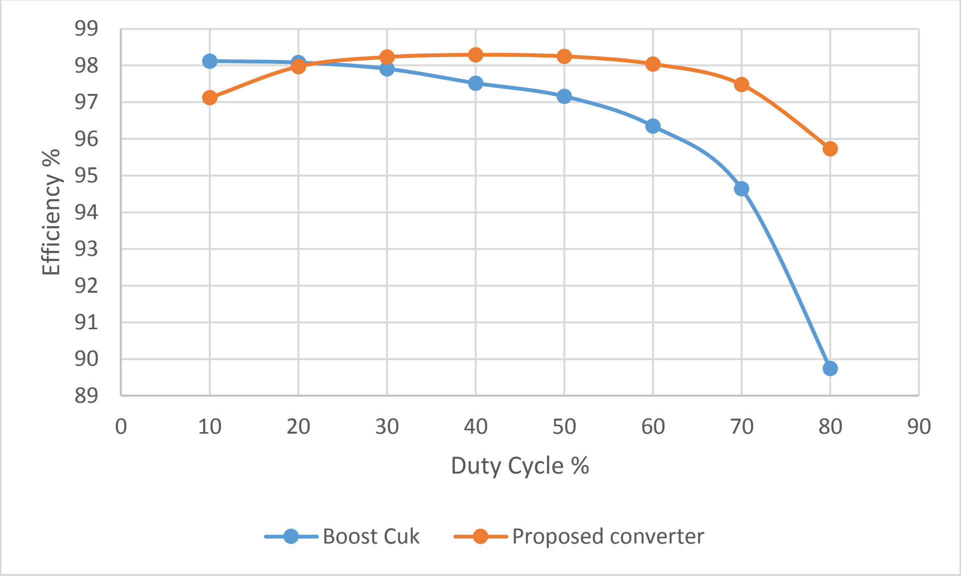
From Fig. 4.13(b), it can be illustrated that initially the efficiency of Boost Cuk converter is higher than the proposed converter. However after at 20% duty cycle it can be observed that the proposed DC-DC Buck-Boost Zeta converter has higher efficiency than Boost Cuk converter.

Table 4.9: Efficiency data for the DC-DC proposed and Boost CUK converter

Duty Cycle (%)	Proposed converter (%)	Boost CUK (%) [26]
10	97.53	98.121
20	98.19	98.08
30	98.36	97.91
40	98.38	97.52
50	98.3	97.16
60	98.09	96.35
70	97.45	94.64
80	95.7	89.74



(a)



(b)

Fig. 4.13: Efficiency comparison between Cascaded Buck-Boost Zeta and CUK Boost

4.6.4 Efficiency Comparison between Cascaded DC-DC Buck-Boost Zeta and SEPIC Boost

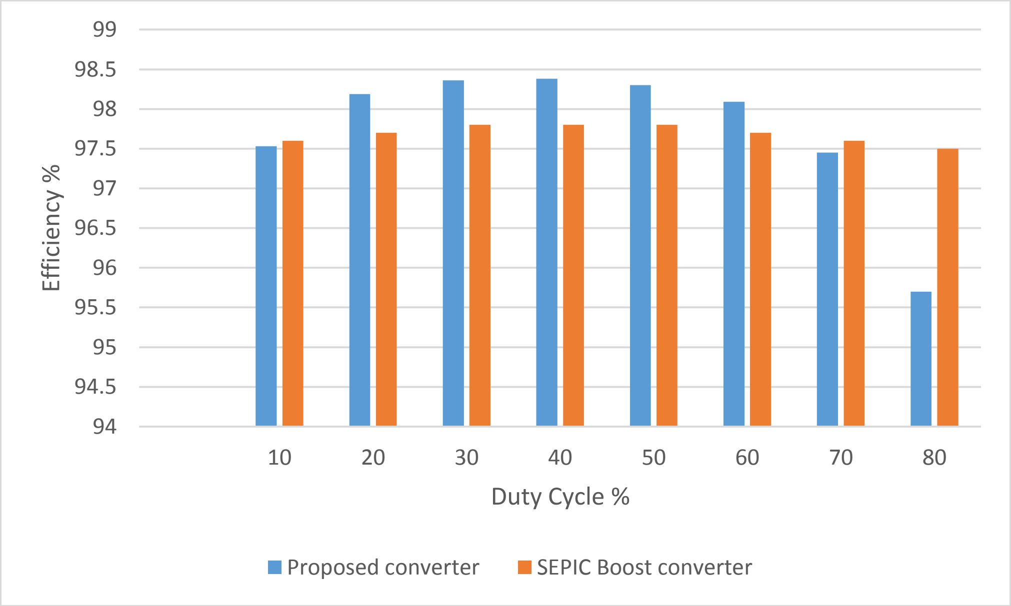
Table 4.10 shows the efficiency comparison between cascaded Buck-Boost Zeta and SEPIC Boost. Efficiency of cascaded Buck-Boost Zeta increases with increase in duty cycle, having maximum efficiency at 98.38%. For the cascaded SEPIC Boost converter, the efficiency is remains stable at 97.7%.

Fig. 4.14(a) illustrates the efficiency bar diagram of the converters. From the bar diagram it can be observed that efficiency of the SEPIC Boost converter is constant. For the proposed converter, the efficiency initially increases than decreases with duty cycle.

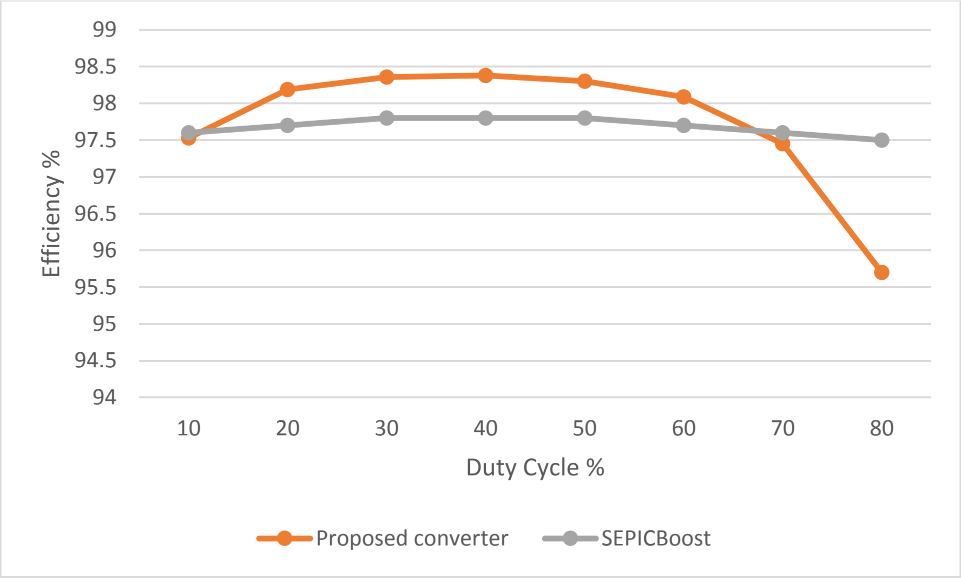
From Fig. 4.14(b), it can be observed that up to 68% duty cycle, efficiency of the proposed DC-DC converter is higher than cascaded SEPIC Boost converter, which has a steady efficiency.

Table 4.10: Efficiency data for the DC-DC proposed and SEPIC Boost converter

Duty Cycle (%)	Proposed converter (%)	SEPIC Boost converter (%) [27]
10	97.53	97.6
20	98.19	97.7
30	98.36	97.8
40	98.38	97.8
50	98.3	97.8
60	98.09	97.7
70	97.45	97.6
80	95.7	97.5



(a)



(b)

Fig. 4.14: Efficiency comparison between Cascaded Buck-Boost Zeta and SEPIC Boost

4.6.5 Efficiency Comparison between Cascaded AC-DC Buck-Boost Zeta and Boost Cuk

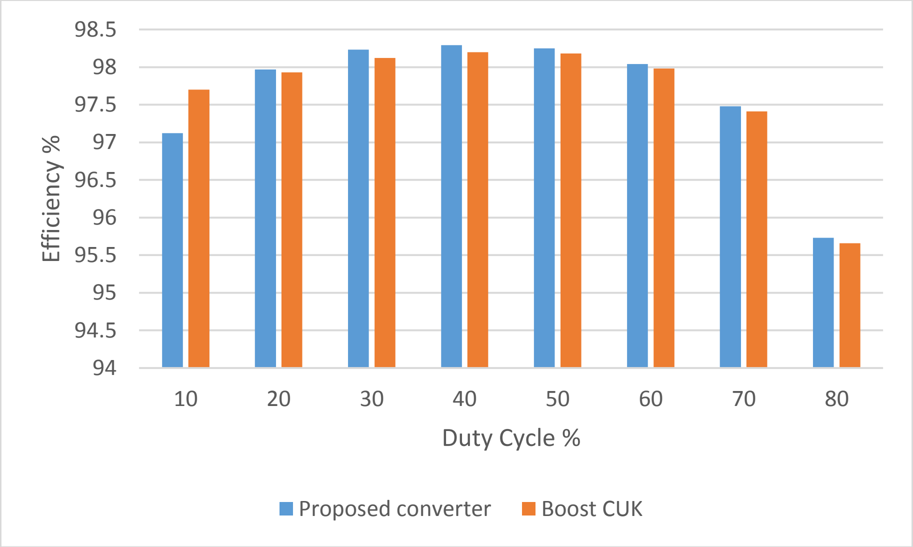
The following table shows the efficiency comparison between cascaded AC-DC Buck-Boost Zeta and Boost Cuk. From the table it be observed that the efficiency of the proposed converter increases to its maximum value of 98.29%. For Boost Cuk converter, the efficiency increases to 98.2% at 40% duty cycle.

From Fig. 4.15(a), it can be observed that the efficiency difference between the two converters is very little. Initially both the converters have efficiency around 97%, which later increases to 98%.

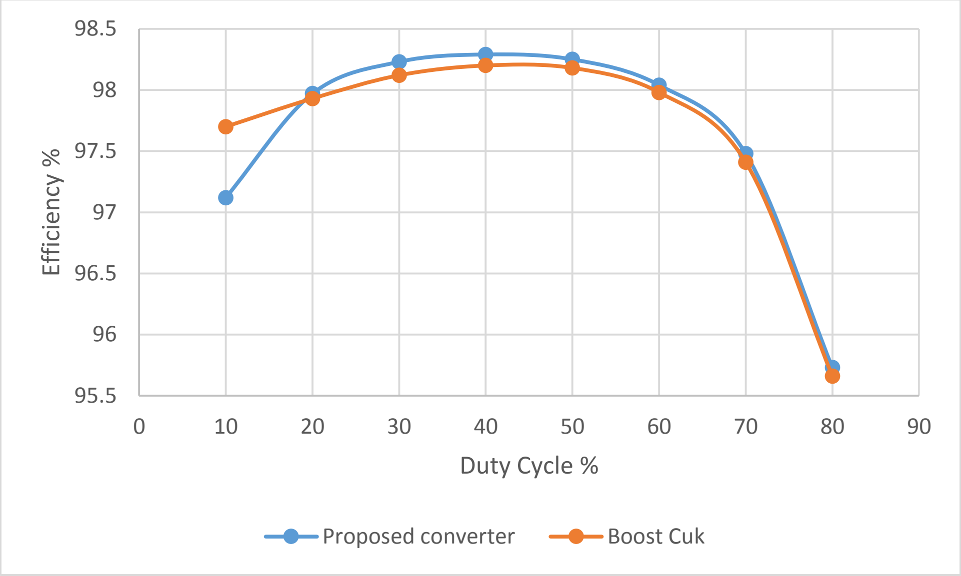
Fig. 4.15(b), illustrates the efficiency comparison graph of the converters. From the graph it can be observed that both the converters experience similar effects in efficiency when duty cycle is increased.

Table 4.11: Efficiency data for the AC-DC proposed and Boost Cuk converter

Duty Cycle (%)	Proposed converter (%)	Boost Cuk converter (%) [26]
10	97.12	97.7
20	97.97	97.93
30	98.23	98.12
40	98.29	98.2
50	98.25	98.18
60	98.04	97.98
70	97.48	97.41
80	95.73	95.66



(a)



(b)

Fig. 4.15: Efficiency comparison between Cascaded AC-DC Buck-Boost Zeta and CUK Boost

4.6.6 Efficiency Comparison between Cascaded AC-DC Buck-Boost Zeta and SEPIC Boost

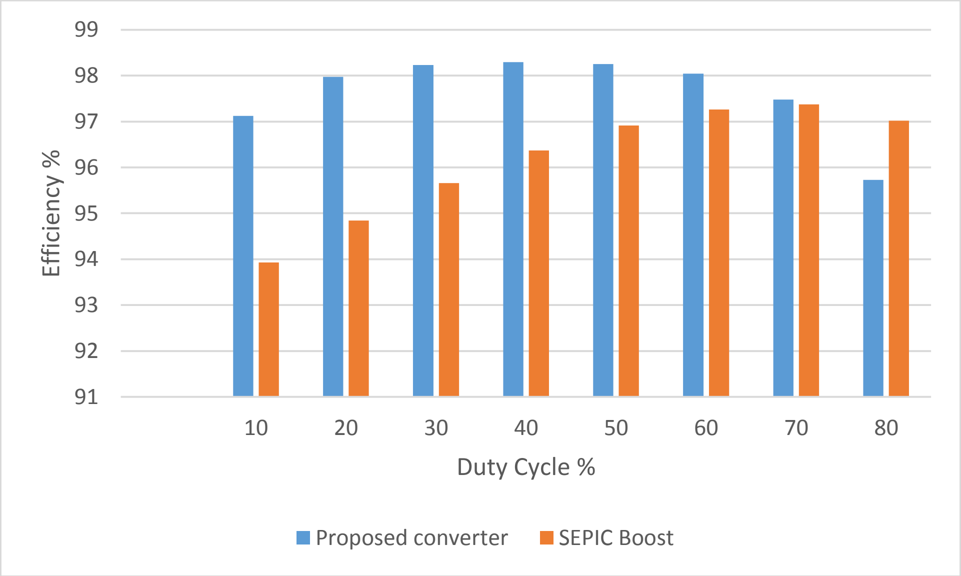
Table 4.12 shows the efficiency comparison between cascaded AC-DC Buck-Boost Zeta and SEPIC Boost. From the table it can be observed that efficiency of the proposed AC-DC converter increases with increase in duty cycle. The peak value is achieved at 40% duty cycle with efficiency of 98.29%. The minimum efficiency is at 80% duty cycle. The AC-DC SEPIC Boost converter has maximum efficiency value of 97.37% at 70% duty cycle.

From Fig. 4.16(a), it can be observed that initially the efficiency difference between the two converters is significant. With increase in duty cycle this difference decreases.

Fig. 4.16(b) illustrates the efficiency graph of the converters. From the graph it can be observed that for up to 70% duty cycle, the efficiency of the proposed AC-DC converter is better than cascaded SEPIC Boost converter.

Table 4.12: Efficiency data for the AC-DC proposed and SEPIC Boost converter

Duty Cycle (%)	Proposed converter (%)	SEPIC Boost converter (%) [27]
10	97.12	93.93
20	97.97	94.84
30	98.23	95.66
40	98.29	96.37
50	98.25	96.91
60	98.04	97.26
70	97.48	97.37
80	95.73	97.02



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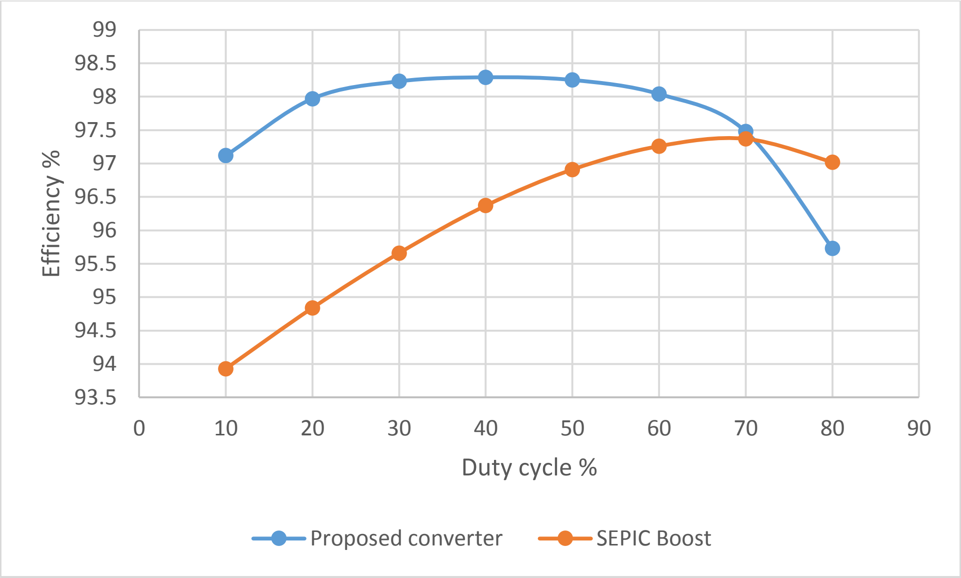


(b)

Fig. 4.16: Efficiency comparison between Cascaded AC-DC Buck-Boost Zeta and SEPIC Boost

4.7 Frequency Analysis of DC-DC Cascaded Buck-Boost Zeta Converter

In this section, the switching frequency analysis of the proposed converter is shown. The analysis is done for 30%, 50% and 70% duty cycle. The frequency range is from 10 KHz to 22 KHz, with an increment of 2 KHz.

4.7.1 30% Duty Cycle

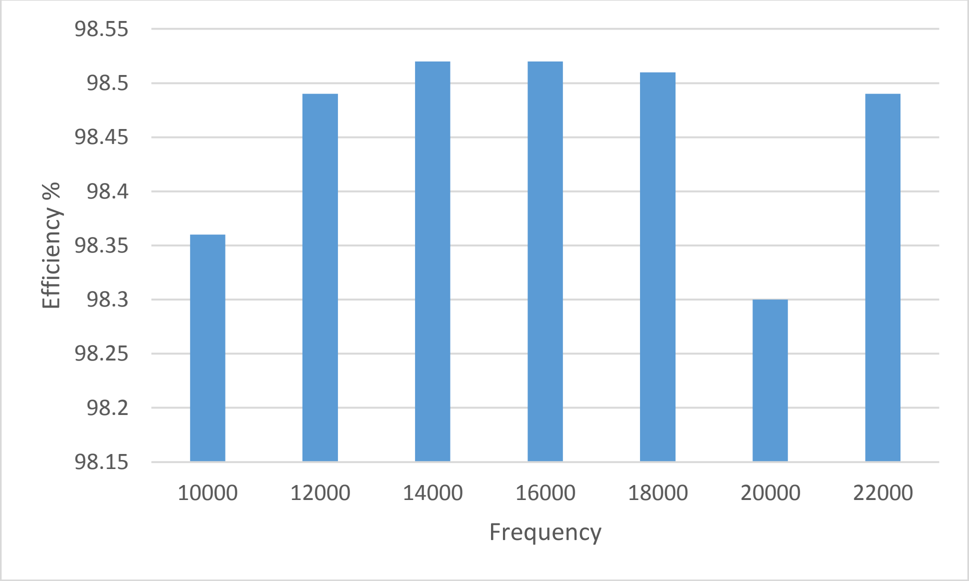
From the following table, it can be observed that efficiency increases with increases in switching frequency and peaks at 98.52%, at 16 KHz.

From the bar diagram in Fig. 4.17(a), it can be observed that the efficiency of the proposed DC-DC converter is similar for different frequencies for 30% duty cycle. The efficiency of the converter is around 98%.

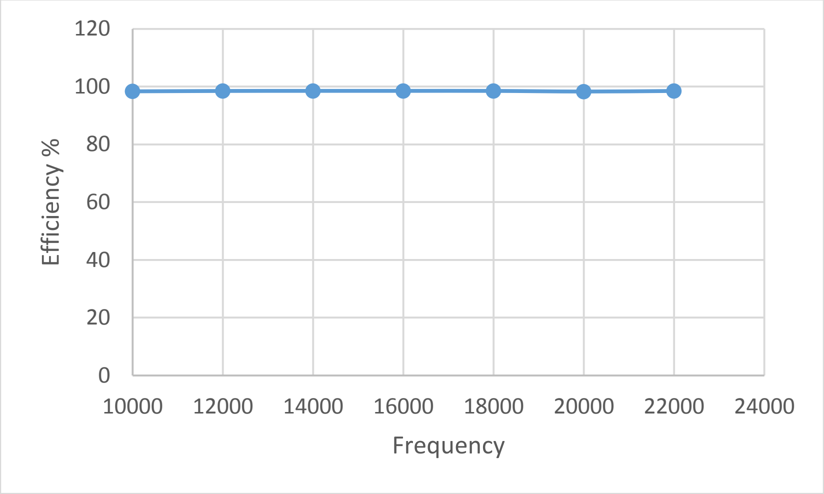
Fig. 4.17(b) illustrates that efficiency of the proposed DC-DC converter is stable with little change in it, at 30% duty cycle.

Table 4.13: Efficiency with different switching frequency at 30% duty cycle

Frequency	Efficiency (%)
10 KHz	98.36
12 KHz	98.49
14 KHz	98.52
16 KHz	98.52
18 KHz	98.51
20 KHz	98.3
22 KHz	98.49



(a)



(b)

Fig. 4.17: Efficiency of the DC-DC cascaded Buck-Boost Zeta converter at different frequency (Duty cycle= 30%)

4.7.2 50% Duty Cycle

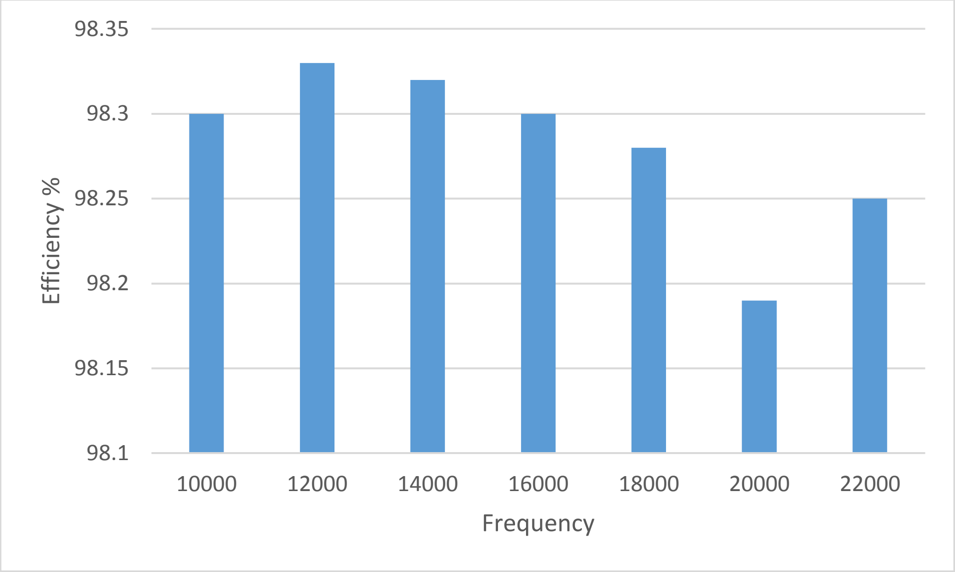
Table 4.14 illustrates the efficiency of the DC-DC proposed converter for different frequency level at 50% duty cycle. From the table it can be observed that with increase in duty cycle, efficiency of the converter decreases slightly and has a minimum efficiency of 98.19% at 20 KHz.

From the bar diagram in Fig. 4.18(a), it can be observed that the efficiency of the converter is similar having efficiency at around 98%.

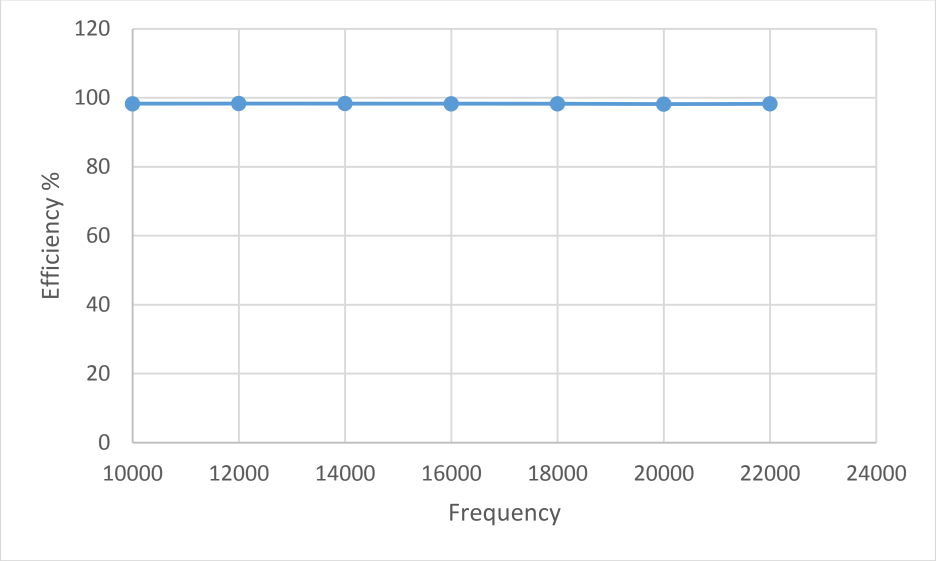
Fig. 4.18(b), illustrates the efficiency graph of the proposed converter at different frequencies. From the graph it can be observed that the efficiency of the converter is stable at different frequencies for 50% duty cycle.

Table 4.15: Efficiency with different switching frequency at 50% duty cycle

Frequency	Efficiency (%)
10 KHz	98.3
12 KHz	98.33
14 KHz	98.32
16 KHz	98.3
18 KHz	98.28
20 KHz	98.19
22 KHz	98.25



(a)



(b)

Fig. 4.18: Efficiency of the DC-DC cascaded Buck-Boost Zeta converter at different frequency (Duty cycle= 50%)

4.7.3 70% Duty Cycle

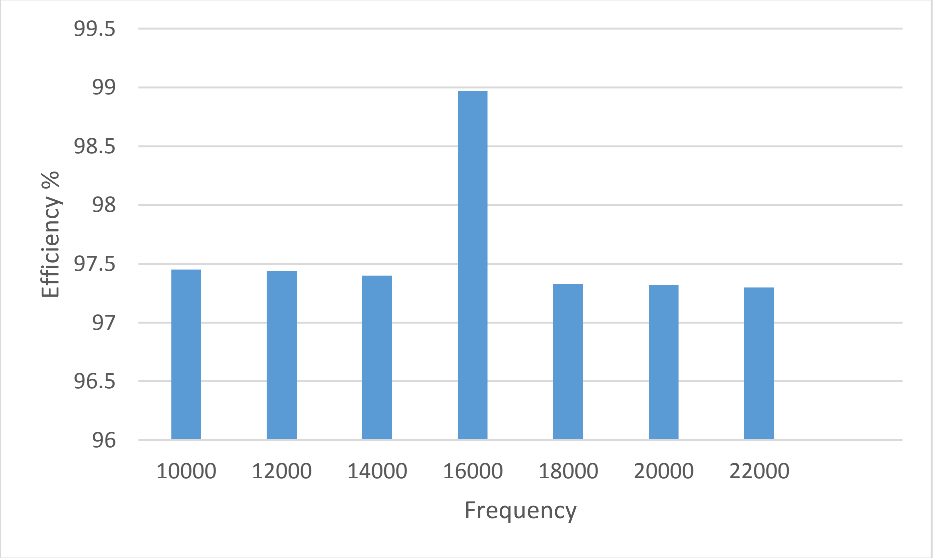
As illustrated in Table 4.16 the value of the efficiency is almost constant for up to 14 KHz. Then efficiency peaks to 98.97% at 16 KHz. After this the value decreases and maintains a constant value around 97%

From Fig. 4.19(a), it can be observed that the efficiency of the proposed DC-DC converter is constant around 97%. However the value peaks to 98.97% at 16 KHz.

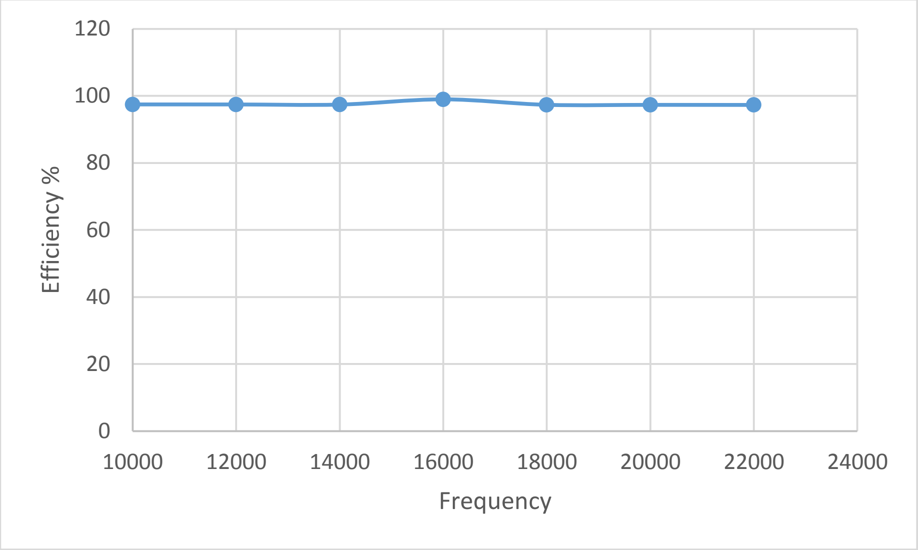
Fig. 4.19(b) illustrates the efficiency graph of the converter at 70% duty cycle for different frequencies. It can be observed from the graph that the efficiency of the graph is constant but at 16 KHz, the value spikes to 98.97%.

Table 4.16: Efficiency with different switching frequency at 70% duty cycle

Frequency	Efficiency (%)
10 KHz	97.45
12 KHz	97.44
14 KHz	97.4
16 KHz	98.97
18 KHz	97.33
20 KHz	97.32
22 KHz	97.3



(a)



(b)

Fig. 4.19: Efficiency of the DC-DC cascaded Buck-Boost Zeta converter at different frequency (Duty cycle= 70%)

4.8 Load Analysis of DC-DC Cascaded Buck-Boost Zeta Converter

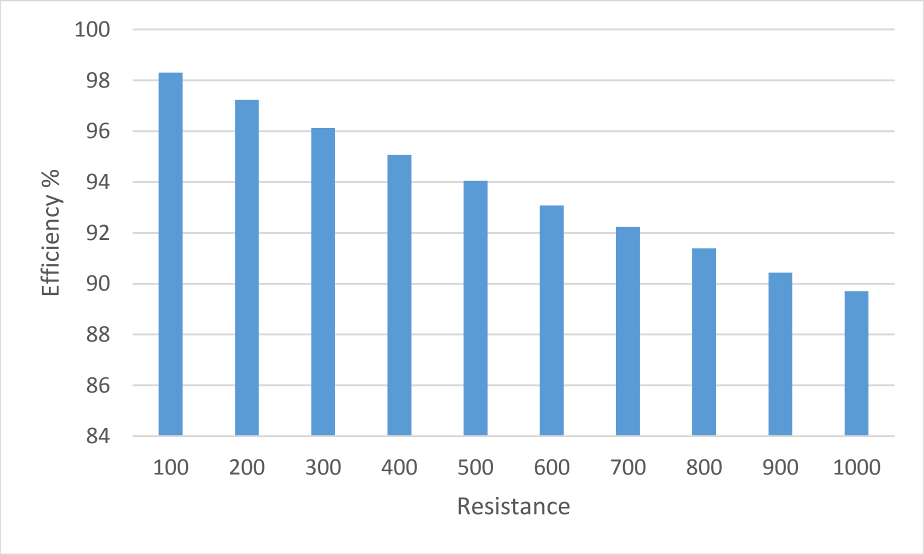
Table 4.17 shows load analysis of the proposed converter at 50% duty cycle. From the data below, it can be observed that the value of efficiency decreases with the increase in load. The load analysis is done up to 1000 ohm, having a minimum efficiency at 1000 ohm. The lowest value of the converter is 89.71%.

The bar diagram in Fig. 4.20(a) illustrates the load analysis of the cascaded Buck Boost Zeta converter. From the diagram, it can be observed that the efficiency experiences a downward trend with increase in load value.

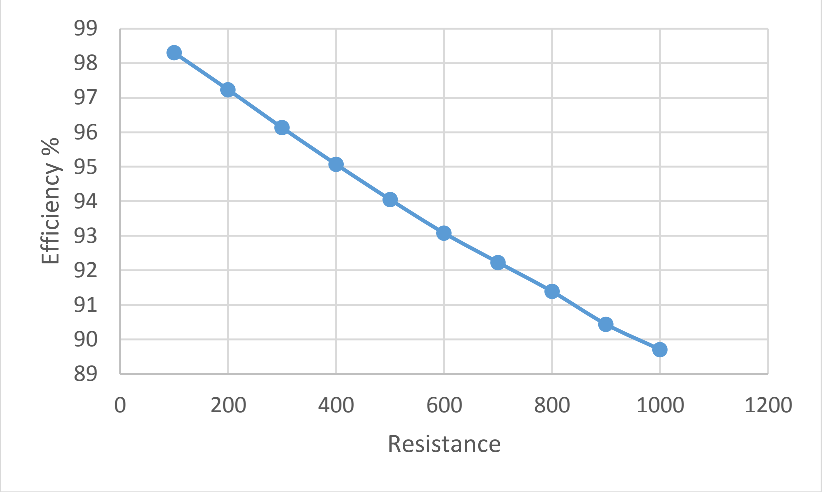
The load graph in Fig. 4.20(b) shows that the relation between resistance and efficiency is almost linear in nature. With increases in resistance the efficiency value decreases.

Table 4.17: Efficiency with different load at 70% duty cycle

Resistance (ohm)	Efficiency (%)
100	98.3
200	97.23
300	96.13
400	95.07
500	94.05
600	93.08
700	92.23
800	91.39
900	90.44
1000	89.71



(a)



(b)

Fig. 4.20: Load analysis of the proposed converter (Duty cycle = 50%)

4.9 Comparison between Formula and Simulation Results

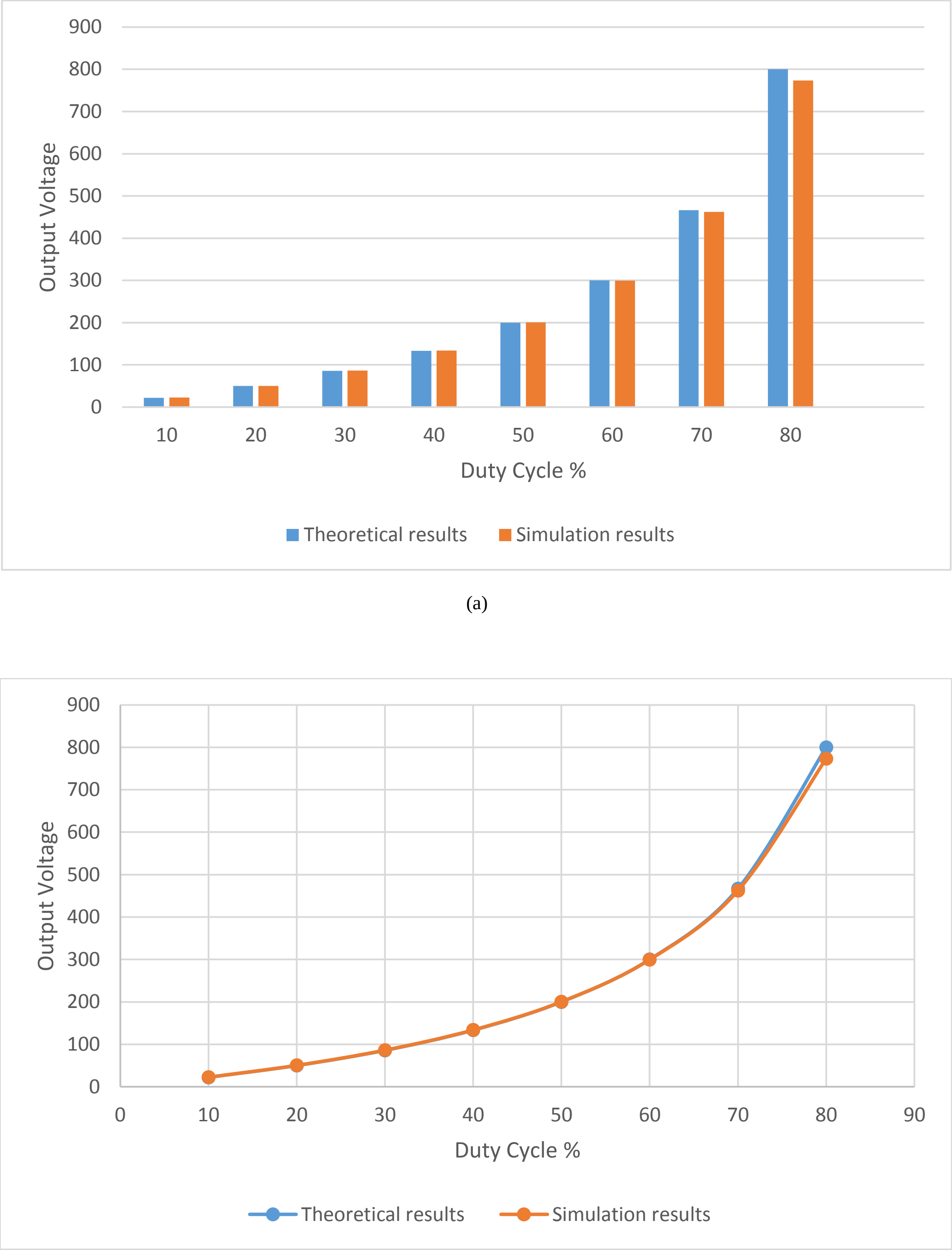
Table 4.18 illustrates the comparison between the voltage collected from formula and simulation results. From the following table, it can be observed that the data achieved from the formula is very close with the simulation results, thus solidifying the accuracy of the formula.

The bar diagram in Fig. 4.21(a) shows that the difference in voltage between the formula derived and simulation derived is almost insignificant, thus solidifying the accuracy of the formula.

The graph in Fig. 4.21(b) shows that the formulated voltage and simulated voltage is almost similar and there is almost no difference between the derived values.

Table 4.18: Voltage Comparison between formula and simulation

Duty Cycle (%)	Formulated voltage (V)	Simulated voltage (V)
10	22.22	22.38
20	50	50.22
30	85.71	86.21
40	133.33	133.8
50	200	200.35
60	300	299.5
70	466.67	461.97
80	800	773.36



(a)

(b)

Fig. 4.21: Voltage Comparison between formula and simulation

From the previous simulation results, it can be stated that the DC-DC topology achieves a maximum efficiency of 98.38% with maximum output voltage of 773.36V. DC-DC closed loop topology on the other hand achieves an improved efficiency of 99.67%. AC-DC topology of the converter attains maximum efficiency of 98.29%, with maximum voltage of 493V.

Table 4.19: Optimum data from DC-DC topology

	Optimum Efficiency (%)	Optimum Voltage (V)
DC-DC topology	98.38	773.36

Table 4.20: Optimum data from AC-DC topology

	Optimum Efficiency (%)	Optimum Power Factor	Optimum Voltage (V)
AC-DC topology	98.29	0.7996	493

Table 4.21: Optimum data from DC-DC Closed loop topology

	Efficiency (%)
DC-DC Closed loop topology	99.67

Chapter 5

Conclusion

In this section, the outcomes of the proposed converter are shown, as well as future works and modifications are discussed.

5.1 Conclusion of this work

Various types of power electronic converters are now frequently used in electric power system applications such as power converter, communication systems, grid-connected systems, DC power supply and so on. A DC-DC converter that provides different levels of output voltage is really essential and have a wide variety of applications. However, the traditional DC-DC converters are unable to make proper conversion without compromising performance. There is always a trade-off between efficiency and performance. For example- high voltage gain will deteriorate the signal and introduce total harmonic distortion shape. Trade-off is also visible among all the performance parameters of the DC-DC converters. However with the help of cascaded topologies such drawbacks can be overcame.

Even in cascaded DC-DC converter, the efficiency decreases as the duty cycle of the DC-DC converter increases. This decrease in efficiency is caused by conduction loss and circuit algorithm. To overcome such limitations, in this research, a new cascaded converter has been developed and analyzed. The proposed converter is developed based on conventional Buck-Boost and Zeta converter. The cascaded topology provides higher efficiency with maximum efficiency of 98.38% along with higher output voltage. The proposed converter is also analyzed with AC-DC and closed-loop feedback topology, showing a significant improvement over conventional converters. The AC-DC topology provides maximum efficiency of 98.29%, having maximum power factor of 0.7996. Maximum output voltage is at 493V. The closed loop topology improves the efficiency to 99.67%. The proposed converter can be used efficiently instead of a conventional Buck-boost and Zeta converter in applications requiring high voltage. The optimal results of the DC-DC, AC-DC and closed-loop topology of the proposed converter are given below.

5.2 Recommendation for future work

The proposed converter has shown better performance when compared with conventional converters. However majority of the analysis was done on open loop topology, particularly for

AC-DC topology. Without the utilization of an effective controller, the AC-DC topology suffer from THD. With the help of a controller, the THD can be managed. Power Factor can also be further improved with the help of a controller.

Reference:

[1] Wang, Hao. "Microgrid generation planning considering renewable energy target." 2016 IEEE International Conference on Power and Energy (PECon). IEEE, 2016.

[2] Elavarasan, Rajvikram Madurai, et al. "A comprehensive review on renewable energy development, Challenges, and policies of leading Indian states with an international perspective." IEEE Access 8 (2020): 74432-74457.

[3] Eseye, Abinet Tesfaye, et al. "Optimal energy trading for renewable energy integrated building microgrids containing electric vehicles and energy storage batteries." IEEE Access 7 (2019): 106092-106101.

[4] Yi, Wenfei, et al. "Multiobjective robust scheduling for smart distribution grids: Considering renewable energy and demand response uncertainty." IEEE Access 6 (2018): 45715-45724.

[5] Nikoobakht, Ahmad, et al. "Assessing increased flexibility of energy storage and demand response to accommodate a high penetration of renewable energy sources." IEEE Transactions on Sustainable Energy 10.2 (2018): 659-669.

[6] Tomaszuk, A., and A. Krupa. "High efficiency high step-up DC/DC converters-a review." Bulletin of the Polish Academy of Sciences: Technical Sciences (2011): 475-483.

[7] Forouzesh, Mojtaba, et al. "Step-up DC–DC converters: a comprehensive review of voltage-boosting techniques, topologies, and applications." IEEE transactions on power electronics 32.12 (2017): 9143-9178.

[8] Usova, Maria A., and Vladimir I. Velkin. "Possibility to use renewable energy sources for increasing the reliability of the responsible energy consumers on the enterprise." 2018 17th International Ural Conference on AC Electric Drives (ACED). IEEE, 2018.

[9] M. H. Rashid, "Power Electronics: Circuits, Devices and Applications", Prentice-Hall, Inc., Englewood Cliffs, Second Edition, 1993.

[10] Kolluri, Sandeep, and N. Lakshmi Narasamma. "A new isolated auxiliary current pump module for load transient mitigation of isolated/nonisolated step-up/step-down dc–dc converter." IEEE Transactions on Power Electronics 30.10 (2015): 5991-6000.

[11] Kolluri, Sandeep, and N. Lakshmi Narasamma. "A new isolated auxiliary current pump module for load transient mitigation of isolated/nonisolated step-up/step-down dc–dc converter." IEEE Transactions on Power Electronics 30.10 (2015): 5991-6000.

[12] Ashique, Ratil H., and Zainal Salam. "A family of true zero voltage zero current switching (ZVZCS) nonisolated bidirectional DC–DC converter with wide soft switching range." IEEE Transactions on industrial electronics 64.7 (2017): 5416-5427.

[13] Mishima, Tomokazu, Yujiro Takeuchi, and Mutsuo Nakaoka. "Analysis, design, and performance evaluations of an edge-resonant switched capacitor cell-assisted soft-switching PWM boost dc–dc converter and its interleaved topology." IEEE transactions on power electronics 28.7 (2012): 3363-3378.

[14] Onar, Omer C., et al. "A bidirectional high-power-quality grid interface with a novel bidirectional noninverted buck–boost converter for PHEVs." IEEE Transactions on Vehicular Technology 61.5 (2012): 2018-2032.

[15] Khosroshahi, Alireza E., et al. "A Two-Stage Coupled-Inductor-Based Cascaded DC-DC Converter with a High Voltage Gain." 2019 IEEE Canadian Conference of Electrical and Computer Engineering (CCECE). IEEE, 2019.

[16] Fu, Jian, et al. "A novel single-switch cascaded DC-DC converter of boost and buck-boost converters." 2014 16th European Conference on Power Electronics and Applications. IEEE, 2014.

[17] Modeer, Tomas, Staffan Norrga, and Hans-Peter Nee. "High-voltage tapped-inductor buck converter utilizing an autonomous high-side switch." IEEE Transactions on Industrial Electronics 62.5 (2014): 2868-2878.

[18] Veerachary, Mummadi, and Punit Kumar. "Analysis and Design of Quasi-Z-Source Equivalent DC–DC Boost Converters." IEEE Transactions on Industry Applications 56.6 (2020): 6642-6656.

[19] Hwu, K. I., and T. J. Peng. "A novel buck–boost converter combining KY and buck converters." IEEE Transactions on power electronics 27.5 (2011): 2236-2241.

[20] Wu, Yung-Chun, and Yu-Kai Chen. "A three-in-one converter for regular and emergency lighting applications." IEEE Transactions on Industry Applications 45.1 (2009): 108-115.

[21] Madhusoodhanan, Sachin, et al. "Solid-state transformer and MV grid tie applications enabled by 15 kV SiC IGBTs and 10 kV SiC MOSFETs based multilevel converters." IEEE Transactions on Industry Applications 51.4 (2015): 3343-3360.

[22] Xiong, Song, et al. "A family of exponential step-down switched-capacitor converters and their applications in two-stage converters." IEEE Transactions on Power Electronics 29.4 (2013): 1870-1880.

[23] Ma, K-W., and Y-S. Lee. "A novel uninterruptible dc-dc converter for UPS applications." IEEE Transactions on Industry Applications 28.4 (1992): 808-815.

[24] Franceschini, Giovanni, et al. "3boost: A high-power three-phase step-up full-bridge converter for automotive applications." IEEE Transactions on Industrial Electronics 55.1 (2008): 173-183.

[25] Zhang, Di, et al. "Modular embedded multilevel converter for MV/HVDC applications." IEEE Transactions on Industry Applications 54.6 (2018): 6320-6331.

[26] Pires, V. Fernão, et al. "A photovoltaic generator system with a DC/DC converter based on an integrated Boost-Ćuk topology." Solar Energy 136 (2016): 1-9.

[27] Rahman, Mohammad Dehan, et al. "Single Phase AC-DC Cascaded Boost-SEPIC (CBS) Converter for Improved Power Quality at High Duty Cycle." 2020 Fourth International Conference on Computing Methodologies and Communication (ICCMC). IEEE, 2020.

[28] D. M. R. W. Erickson, Fundamentals of Power Electronics, Kluwer Academic Publishers, 2001.

[29] F. T. F. C. L. P. X. J. W. Q. Zhao, "A simple and effective to alleviate the rectifier reverse-recovery problem in continuous-current-mode boost converter," *IEEE Trans. Power Electron,* vol. 16, no. 5, pp. 649-658, Sep. 2001.

[30] C. M. L. M. C. C. L. T. H. C. T. Pan, "A low switch voltage stress interleaved boost converter for power factor correction," IEEE Int. Conf. Power Electronics and Drive Systems, pp. 49-54, 2009.

[31] A. A. A. Freitas, F. L. Tofoli, E. M. Sa, S. Daher and F. L. M. Antunes, "High-voltage gain DC-DC boost converter with coupled inductors for photovoltaic systems," *IET Power Electronics*, vol. 8, no. 10, April 2015.

[32] J. P. d. Souza, R. G. DE Oliveira, E. F. R. Romaneli and A. A. Badin, "A high static gain CUK DC-DC converter," in *IEEE 13th Brazilian Power Electronics Conference and 1st Southern Power Electronics Conference*, 2015.

[33] M. M. J. L. Huber, "A design approach for server power supplies for networking applications," Proc. 15th Annu. IEEE Appl. Power Electron. Conf. Exp., pp. 1163-1169, 2000.

[34] Y. Liang, "A New Type of Statcom Based on Cascading Voltage Source Inverters with Phase-shitted Unipolar SPWM," in IAS'98.

[35] F. C. L. D.-H. Lee, "New Cascade Switch Multilevel PWM Converters," APEC'99, pp. 329-324.

[36] Zumbahlen, Hank, ed. Linear circuit design handbook. Newnes, 2011.

[37] J. W. K. L. Muller, "High gain DC-DC converter based on the cockcroft-walton multiplier," IEEE Transactions on Power Electronics, vol. 31, no. 9, September 2016.

[38] M. H. Rashid, Power Electronics: Circuits, Devices and Applications, Englewood Cliffs: Prentice-Hall, Inc, Book, Second Edition, 1993.

[39] U. T. M. a. R. W. P. Mohan Ned, Power Electronics ,Converters Applications and Design, John Wiley & Sons, Inc., 1995.

[40] B. W. Williams, Power Electronics; Devices, Drivers, Applications and Passive Components, Book, Second Edition, Educational Low-Priced Books Scheme; ELBS, 1992.

[41] T. J. L. L. S. Y. J. F. C. S. M. Chen, "A cascaded high step-up DC–DC converter with single switch for microsource applications," IEEE Trans. Power Electron., vol. 26, no. 4, pp. 1146-1153, Apr. 2011.

[42] S. P. L. M. B. F. J. M. A. M. E. Durán, "A Zeta-buck-boost converter combination for single-input multiple-output applications," in IECON 2016 - 42nd Annual Conference of the IEEE Industrial Electronics Society, Florence, Italy, 23-26 Oct. 2016.

[43] X. Yue, D. Boroyevich, F. C. Lee, F. Chen, R. Burgos and F. Zhuo, "Beat Frequency Oscillation Analysis for Power Electronic Converters in DC Nanogrid Based on Crossed Frequency Output Impedance Matrix Model," in IEEE Transactions on Power Electronics, vol. 33, no. 4, pp. 3052-3064, April 2018, doi: 10.1109/TPEL.2017.2710101.

[44] S. P. Engel, M. Stieneker, N. Soltau, S. Rabiee, H. Stagge and R. W. De Doncker, "Comparison of the Modular Multilevel DC Converter and the Dual-Active Bridge Converter for Power Conversion in HVDC and MVDC Grids," in IEEE Transactions on Power Electronics, vol. 30, no. 1, pp. 124-137, Jan. 2015, doi: 10.1109/TPEL.2014.2310656.

[45] J. Hong, J. Yin, Y. Liu, J. Peng and H. Jiang, "Energy Management and Control Strategy of Photovoltaic/Battery Hybrid Distributed Power Generation Systems With an Integrated Three-Port Power Converter," in IEEE Access, vol. 7, pp. 82838-82847, 2019, doi: 10.1109/ACCESS.2019.2923458.

[46] J. R. R. Zientarski, M. L. da Silva Martins, J. R. Pinheiro and H. L. Hey, "Evaluation of Power Processing in Series-Connected Partial-Power Converters," in IEEE Journal of Emerging and Selected Topics in Power Electronics, vol. 7, no. 1, pp. 343-352, March 2019, doi: 10.1109/JESTPE.2018.2869370.

[47] Y. Lu, K. Sun, H. Wu, X. Dong and Y. Xing, "A Three-Port Converter Based Distributed DC Grid Connected PV System With Autonomous Output Voltage Sharing Control," in IEEE Transactions on Power Electronics, vol. 34, no. 1, pp. 325-339, Jan. 2019, doi: 10.1109/TPEL.2018.2822726.

[48] R. Majumder, A. Ghosh, G. Ledwich and F. Zare, "Power Management and Power Flow Control With Back-to-Back Converters in a Utility Connected Microgrid," in IEEE Transactions on Power Systems, vol. 25, no. 2, pp. 821-834, May 2010, doi: 10.1109/TPWRS.2009.2034666.

[49] I. Anand, S. Senthilkumar, D. Biswas and M. Kaliamoorthy, "Dynamic Power Management System Employing a Single-Stage Power Converter for Standalone Solar PV Applications," in IEEE Transactions on Power Electronics, vol. 33, no. 12, pp. 10352-10362, Dec. 2018, doi: 10.1109/TPEL.2018.2804658.