BIDIRECTIONAL SWITCHED BOOST CONVERTER DESIGN FOR AC-DC HYBRID MICROGRID

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The Degree of Master of Technology

Department of Electrical Engineering

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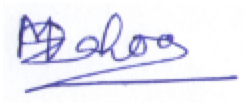

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This thesis entitled Bidirectional Switched Boost Converter Design for AC-DC hybrid Microgrid by Manoranjan Sahoo is approved for the degree of Master of Technology from IIT Hyderabad.

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Dedicated to

My father Late Anadi Charan Sahoo, My Uncle Late Muralidhara Sahoo and
My Supervisor Dr. Siva Kumar K

Abstract

The objective of this project is to design a bidirectional switched boost converter. In conventional bidirectional Z-source converter (BZSC) the intermediate network comprises of two equal inductors and two equal capacitors along with one two quadrant active switch for buck or boost the voltage in a single stage. But, it is difficult to realize two equal inductors and two equal capacitors in practice which in turn raises the stability issues of the BZSC. Switched boost converter (SBC) is the improved derivative of Z-source converter (ZSC), where the intermediate network comprises of one inductor and one capacitor along with one diode and one single quadrant active switch for controlling the voltage gain. In SBC power flow is limited to one direction that is from DC side to AC side. But in AC-DC hybrid micro grid, energy storage and many other applications power flow is needed to be bidirectional. The proposed bidirectional switched boost converter (BSBC) preserves all the advantages of SBC and provides additional advantage of bidirectional power flow which makes it suitable for AC-DC hybrid microgrid. The unaltered voltage gain is achieved in both the direction of power flow. To verify the operation and theoretical analysis the proposed converter is simulated using MATLAB Simulink and the results are shown.

Nomenclature

DG : Distributed Generation

VSC : Voltage source converter

SBI : Switched Boost Inverter

BSBC : Bidirectional Switched Boost Converter

L_1, L_2 : Inductors in the impedance network of Z-Source Inverter

C_1, C_2 : Capacitors in the impedance network of Z-Source Inverter

V_{L1} : Voltage across inductor L_1 of Z-Source Inverter

V_{L2} : Voltage across inductor L_2 of Z-Source Inverter

V_{C1} : Voltage across capacitor C_1 of Z-Source Inverter

V_{C2} : Voltage across capacitor C_2 of Z-Source Inverter

I_{L1} : Current through the inductor L_1 of Z-Source Inverter

I_{L2} : Current through the inductor L_2 of Z-Source Inverter

I_l : Current fed to the inverter leg from DC side

R_l : Load at the AC bus of the inverter

D : shoot through duty ratio of the inverters

V_0 : Input DC voltage fed to the Z-Source Inverter

V_g : Input DC voltage fed to the Switched Boost Inverter and Bidirectional Switched Boost Converter

v_d : DC voltage fed to the impedance network of Z-Source Inverter

v_i : DC voltage fed to the inverter legs from DC source of Z-Source Inverter

v_i' : Peak DC voltage fed to the inverter legs from DC source of Z-Source Inverter

v_{ac}' : Peak AC output phase voltage of Z-Source Inverter

T_s : Switching time period of the switches used in the inverters

i_i : equivalent load current represented by current source in Z-Source inverter and Switched Boost inverter

i_L : Current through the inductor ‘L’ of Switched Boost Inverter

i_C : Current through the capacitor ‘C’ of Switched Boost Inverter

V_i : DC voltage fed to the Switched Boost Inverter leg

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Chapter 1

Introduction

1.1 Motivation

In recent years to meet the power crisis, research are focused towards distributed power generation. These distributed generation (DG) systems consist of different renewable energy sources such as solar, wind, fuel cell etc. It has been observed that the global installation of solar power is increasing significantly as shown in Figure-1 [1-2].

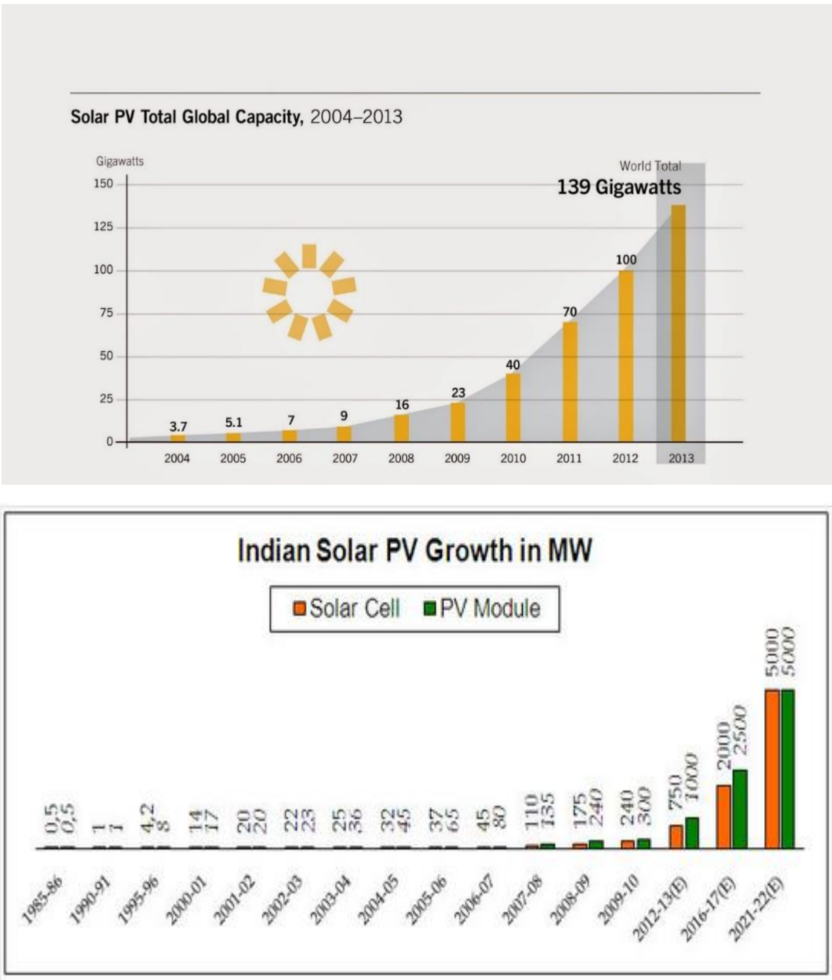


Figure.1: – Solar Power Installation growth statistics

For interaction among loads, renewable source and utility grid along with their optimal control micro grids are formed. Micro grids are mainly classified into three types namely AC micro grid, DC micro grid and AC-DC hybrid micro grid [3-4]. Only AC micro grid or only DC micro grid suffers a limitation of multiple conversion stages (ac-dc-ac or dc-ac-dc) as shown in Figure: 2 and Figure: 3 respectively.

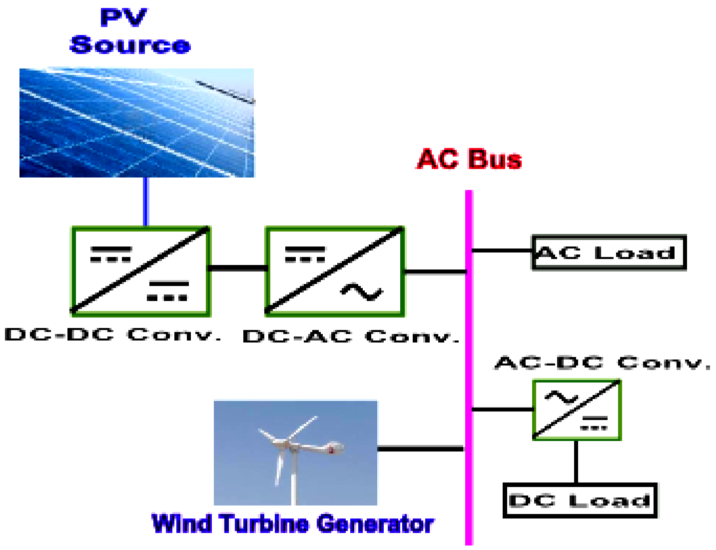


Figure: 2 - AC Microgrid

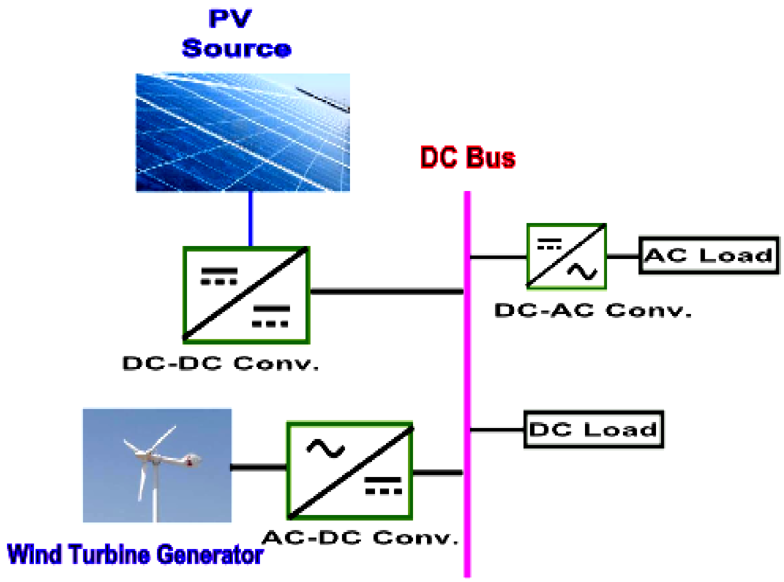


Figure: 3 – DC Microgrid

AC-DC hybrid micro grid is formed by tying AC micro grid and DC micro grid together with the help of bi-directional converters as shown in Figure: 4. This effectively reduces the number of conversion stages and power sharing is made possible in both the directions [5].

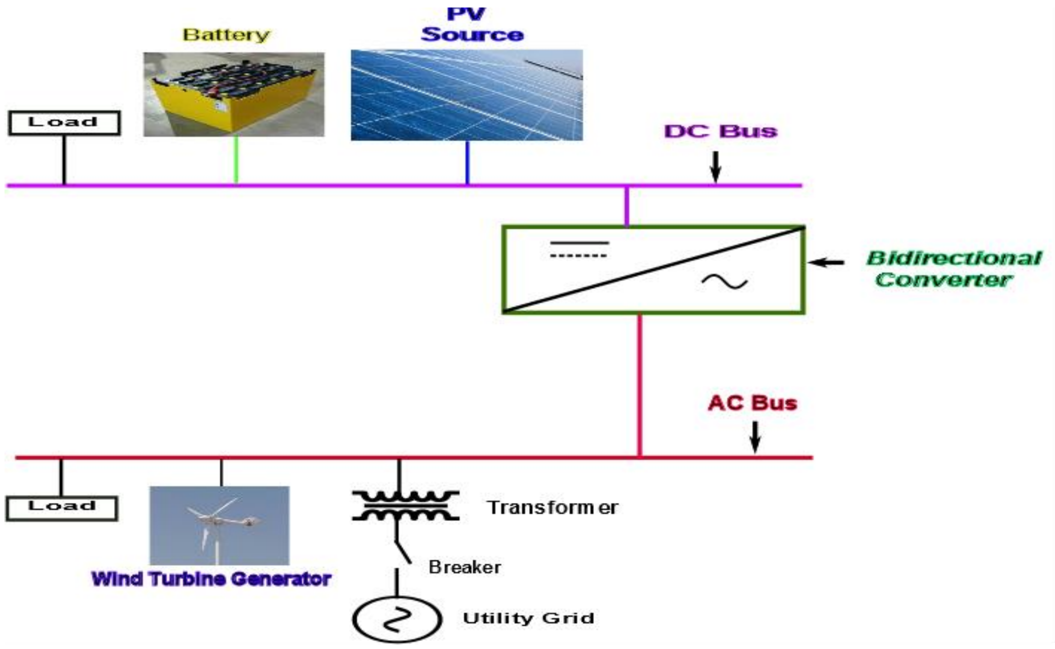


Figure: 4 – AC - DC Hybrid Microgrid

1.2 Need of Single Stage Inverter

To increase the reliability of PV system lower number of PV cells are connected in series which suffers from low single cell voltage [5-6]. But, Conventional Voltage source converter acts as buck converter when operated as inverter and behaves as boost converter when operated as rectifier [7-8]. Generally to overcome the above issues two methods are widely used. One method is to use DC-DC boost converter before the inversion as shown in figure: 5. But as number of power conversion stages increase, control becomes more complex, efficiency also decreases [9-10].

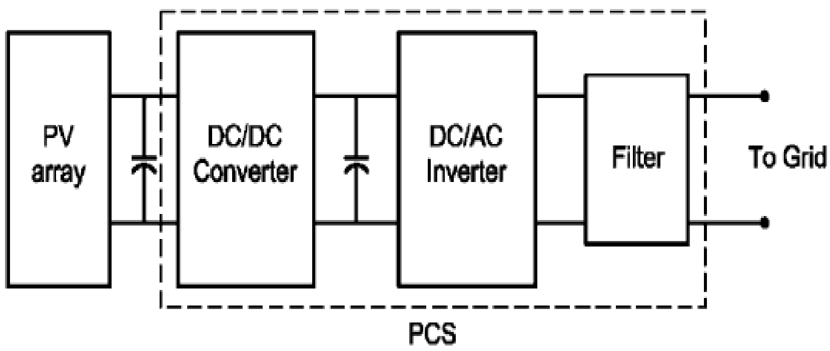


Figure: 5 – Using DC-DC Boost converter before inversion

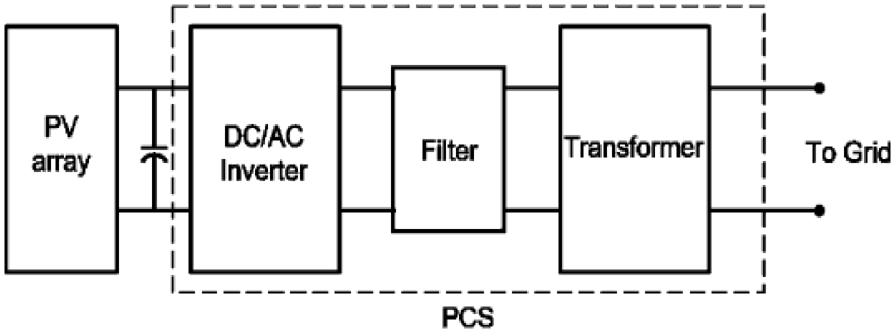


Figure: 6 – Using line frequency transformer after the inversion

Another important issue associated with conventional voltage source converter is, it suffers from shoot through fault as shown in figure: 7.

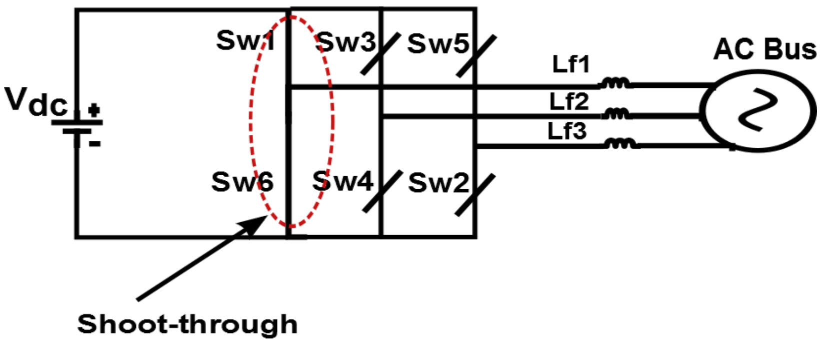


Figure: 7 – Voltage source converter

To avoid the shoot through fault in conventional voltage source inverter a dead band circuit is used. This dead band circuit introduces a time delay in between the switching pulses fed to the switches of one inverter leg.

Chapter 2

Z-Source Inverter

Z- Source converter overcomes the issues discussed in previous chapter and is able to buck or boost the input voltage along with its inversion in single stage [11-14]. As a result system efficiency becomes more as compared to two stage conversion. It uses two high frequency inductors, two capacitors along with one diode to achieve the above objective as shown in figure: 8. Here two equal inductors and two equal capacitors are used for stable operation of the converter. The two inductors (L1 and L2) and two capacitors (C1 and C2) are connected in 'X' shaped to provide input impedance between the input DC 'Vo' and inverter leg. This helps in boosting the input voltage 'Vo' as well as making the inverter shoot through fault tolerant. Here the input source can be both voltage source as well as current source. The switches in the inverter leg can be a combination of switching devices like controlled active switches (e.g. Mosfet, IGBT etc.) and diodes. The output AC voltage of the Z-source inverter can be varied between zero and infinity. Here diode is used to restrict reverse current from the Z-source network to input DC 'Vo' side.

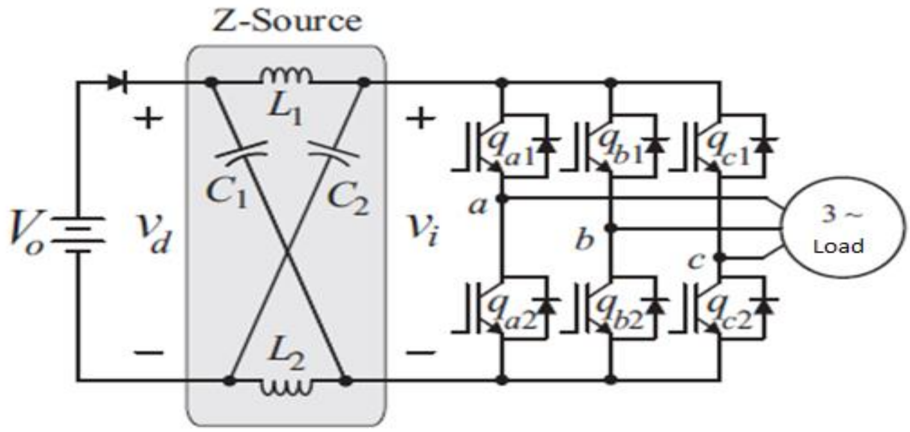


Figure: 8 – Z- Source inverter

2.1 Operation of Z-Source Inverter

The Z-source inverter can buck or boost the input DC voltage in a wide range, whereas conventional voltage source inverter (VSI) and current source inverter (CSI) cannot provide such feature. Traditional voltage source inverter is operated in eight states i.e. six active states and two zero states. In the active states power is transferred from DC source to AC load, where as in zero state voltage across the load are made zero by switching 'ON' either all the upper switches or lower switches. The Z-source inverter is operated in nine states. Like conventional voltage source inverter it operates in eight states along with this it operates in one more state i.e. shoot through state. In shoot through state all the switches in the one or more inverter legs are switched 'ON'. The AC output voltage of the inverter can be controlled (i.e. buck or boost the output voltage) widely by regulating this shoot through state. For rectifier mode of operation instead of diode two quadrant switches are used. Z- Source converter basically operates on two states i.e.-

(A) Non-Shoot through state
(B) Shoot through state

(A) Non- Shoot through state

Non-shoot through state is same as the power transfer state (active state) of conventional voltage source inverter. In this mode of operation the switches in the inverter legs are operated like conventional voltage source inverter. So, the inverter leg can be represented

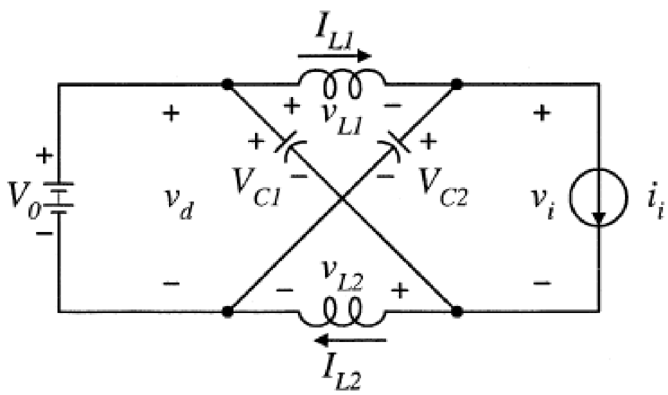


Figure: 9 - Non-Shoot through state of Z-Source inverter

by equivalent current source as shown figure:9. During this mode of operation input DC voltage source along with inductor supply power to load as well as boost the capacitor voltage as shown in figure: 9.

(B) Shoot through state

During this mode of operation both the switches on one or all of the inverter legs are switched 'ON'. As a result input diode is reverse biased and capacitors energize the inductors as shown in Figure: 10. It is same as the zero state of conventional voltage source converter where zero power is transferred to the load during this state.

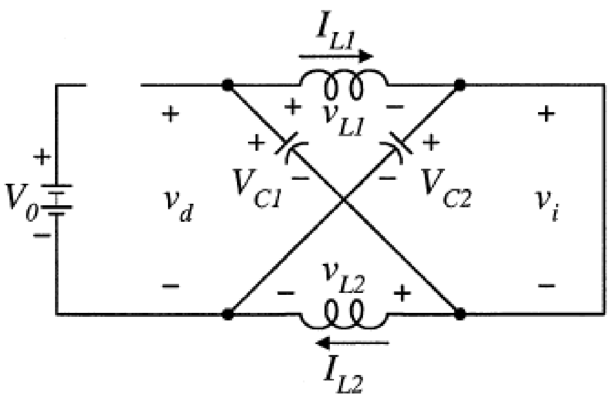


Figure: 10 – Shoot through state of Z- source inverter

2.2 Mathematical Formulation of Voltage Gain for Z-Source Inverter

Let the inductors (L_1 and L_2) used in the Z-source network are of having equal inductance 'L' .Similarly, capacitors (C_1 and C_2) used in the Z-source network are of having equal capacitance 'C'. As a result, the Z-source network behaves as a symmetrical network. Now from the circuit,

$$V_{C1}=V_{C2}=V_C \tag{2.1}$$

$$V_{L1}=V_{L2}=V_L \tag{2.2}$$

Now during shoot through period, DT_s from figure: 10,

$$V_L = V_C \tag{2.3}$$

$$v_d = 2V_C \tag{2.4}$$

$$v_i = 0 \tag{2.5}$$

Now during Non-shoot through period, $(1\text{-}D)T_s$ from figure: 9,

$$V_L = V_o - V_C \tag{2.6}$$

$$v_d = V_o \tag{2.7}$$

$$v_i = 2V_C - V_o \tag{2.8}$$

Using volt-second balance across the inductors,

$$\frac{V_C DT_s + (V_o - V_C)(1\text{-}D)T_s}{T_s} = 0 \tag{2.9}$$

$$V_C = V_o \frac{(1\text{-}D)}{(1\text{-}2D)} \tag{2.10}$$

Similarly, average DC voltage fed to the inverter leg can be found to be,

$$V_i = \frac{DT_s \times 0 + (1\text{-}D)T_s(2V_C - V_o)}{T_s} = \frac{1\text{-}D}{(1\text{-}2D)} V_o = V_C \tag{2.11}$$

The peak DC voltage fed to the inverter leg can be found to be,

$$v_i' = V_C - V_L = 2V_C - V_o = \frac{1}{1\text{-}2D} V_o \tag{2.12}$$

The peak ac output phase voltage can expressed as,

$$v_{ac}' = \frac{MV_o}{1\text{-}2D} \tag{2.13}$$

From the equation (2.13), it can be observed that, the peak ac output phase voltage cab be varied , by varying modulation index ‘M’ and shoot through duty ratio ‘D’. For ensuring active state not interfering the shoot through state, the sum of the shoot through period and non-shoot through period are made less than or equal to unity i.e.

$$M+D \leq 1 \quad (2.14)$$

2.3 PWM Control of Z-Source Inverter

The PWM technique adapted for Z-Source inverter is more or less similar to the PWM technique used for conventional voltage source inverter as shown in figure. 11. This can be done by both sine-triangle PWM technique and state vector PWM technique. Here it can be noted that, each phase leg switches ‘ON’ and ‘OFF’ once per switching cycle. The shoot through zero state intervals are allocated uniformly without changing the total zero state interval in each phase so that the active state intervals are unchanged.

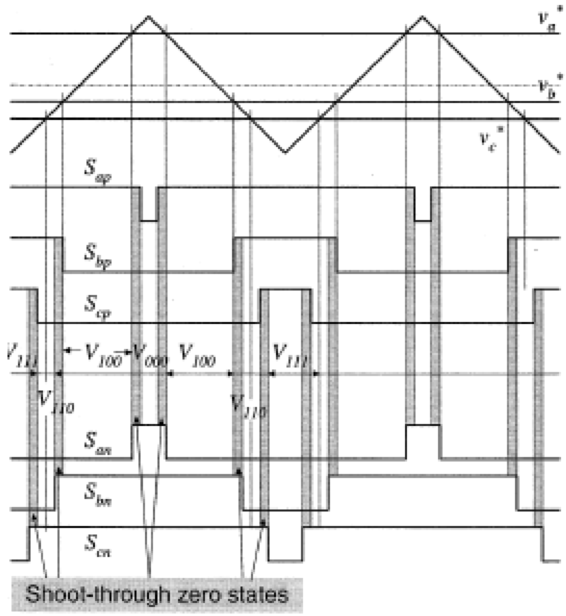


Figure: 11- PWM control of Z-Source Inverter

2.4 Disadvantages of Z-Source Inverter

Z- Source converter follows 5th order dynamics in which two zeroes and two poles are on imaginary axis of s-plane [16]. So for stable operation of the converter inductance of both the inductors and capacitance of both the capacitors are made equal to facilitates pole zero cancellation. The control to output transfer function of Z-source converter is given as below:

$$\frac{v_{c1}}{d} = \frac{b_4 s^4 + b_3 s^3 + b_2 s^2 + b_1 s + b_0}{a_5 s^5 + a_4 s^4 + a_3 s^3 + a_2 s^2 + a_1 s + a_0} \tag{2.1}$$

The coefficients of the above equation are given by,

$$b_0 = -R_l (2D-1)(V_{C1} + V_{C2} - V_g) \tag{2.2}$$

$$b_1 = (I_{L1} + I_{L2} - I_l)(L_2 R_l (D-1) - L_1 D R_l) - (V_{C1} + V_{C2} - V_g)(L_1 (D-1) + L_l (2D-1)) \tag{2.3}$$

$$b_2 = -L_l (L_2 + DL_1 - DL_2)(I_{L1} + I_{L2} - I_l) - C_2 R_l (V_{C1} + V_{C2} - V_g)(DL_1 - L_1 + DL_2) \tag{2.4}$$

$$b_3 = -C_2 [L_1 L_2 R_l (I_{L1} + I_{L2} - I_l) + (V_{C1} + V_{C2} - V_g)(L_1 (L_2 + L_1)(D-1) + DL_2 L_l)] \tag{2.5}$$

$$b_4 = -C_2 L_1 L_2 L_l (I_{L1} + I_{L2} - I_l) \tag{2.6}$$

$$a_0 = R_l (2D-1)^2 \tag{2.7}$$

$$a_1 = L_l (2D-1)^2 + (L_1 + L_2)(D-1)^2 \tag{2.8}$$

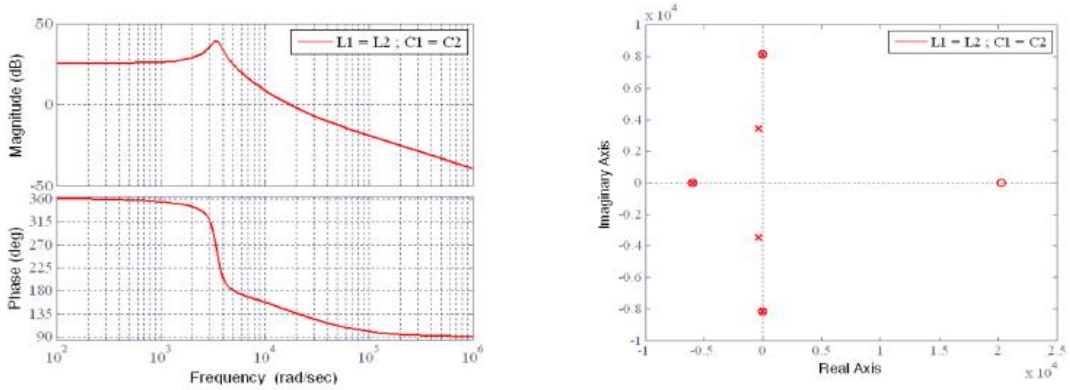
$$a_2 = L_1 R_l (C_2 (1-D)^2 + C_1 D^2) + L_2 R_l (C_1 (1-D)^2 + C_2 D^2) \tag{2.9}$$

$$a_3 = L_1 L_2 [(C_1 + C_2)(1-D)^2] + L_2 L_l [C_1 (1-D)^2 + C_2 D^2] + L_1 L_l [C_2 (1-D)^2 + C_1 D^2] \tag{2.10}$$

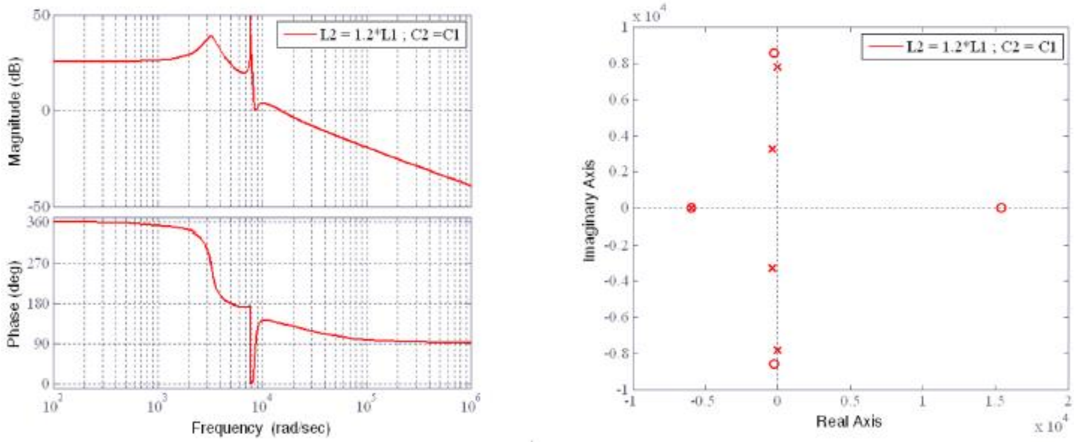
$$a_4 = C_1 C_2 L_1 L_2 R_l \tag{2.11}$$

$$a_5 = C_1 C_2 L_1 L_2 L_l \tag{2.12}$$

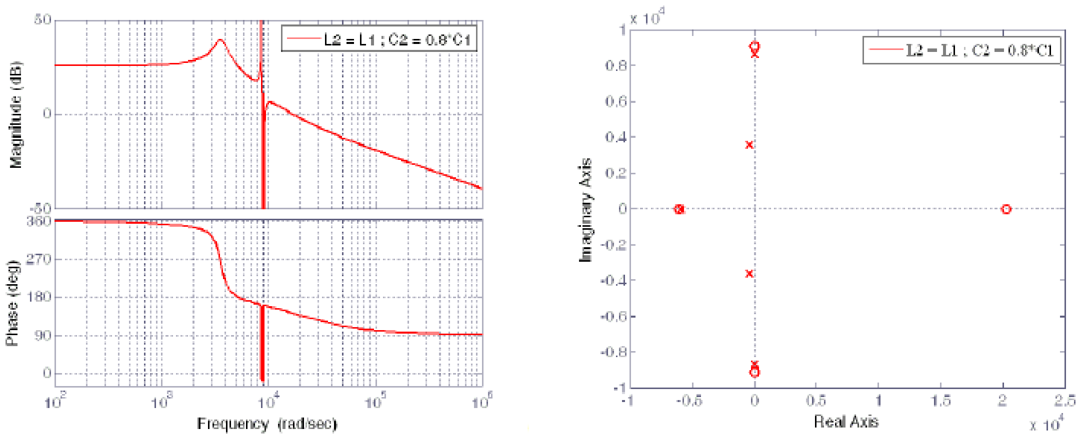
But it is difficult to realize equal inductors and equal capacitors in real time always which may lead to unstable operation of the converter. Also using more number



(a)



(b)



(c)

Figure: 12 - Bode Plot and pole zero plot of Z – source converter

of magnetics in the circuit increases the system weight and size. Similarly, using more number of high voltage capacitors increases the system cost and size.

Chapter 3

Switched Boost Inverter

Switched boost converter is an improved derivative of Z- source converter which preserves all the advantages of Z- source converter along with it uses reduced number of reactive elements [17-18]. It uses a single quadrant active switch 'S', two diodes (D_1, D_2), one capacitor 'C', one inductor 'L' between the input DC voltage source 'V_g' and inverter bridge as shown in figure. 13.

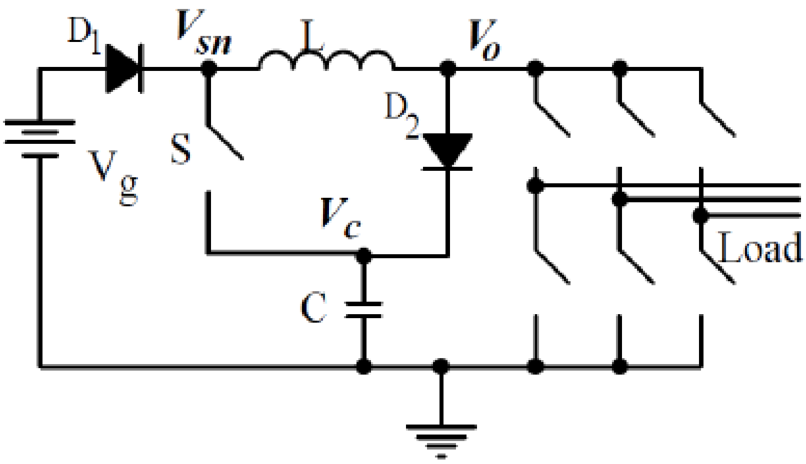


Figure: 13- Switched boost inverter

3.1 Operation of Switched Boost Inverter

The switched boost inverter is also operated in two state like Z-Source inverter i.e.

(A) Non- shoot through state

(B) Shoot through state

(A) Non- Shoot through state

During this mode of operation single quadrant switch 'S' is turned 'OFF', which in turn forward bias both the diode D_a and D_b. As a result input DC voltage source Vg and inductor supply power to load and charge the capacitor 'C' as shown in figure: 14. In this interval the inverter bridge can be represented by a current source as shown in figure. 14. The inductor current 'i_L' is sum of the capacitor current 'i_C' and inverter bridge input current 'i_i'.

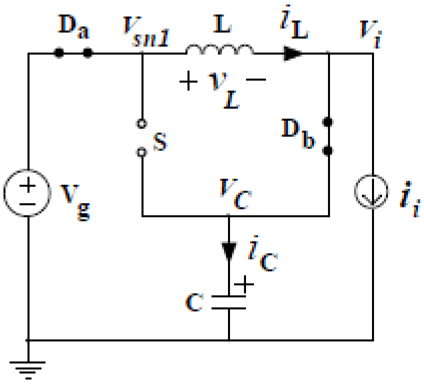


Figure: 14 – Non-shoot through state of SBI

(B) Shoot through state

During this mode of operation single quadrant switch 'S' as well as both the switches on the one more inverter legs are turned 'ON', which in turn reverse bias both the diodes Da, Db.

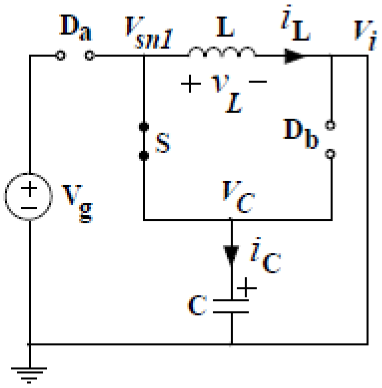


Figure: 15 – Shoot-through state of SBI

Here the inverter legs are represented by short circuit. As a result capacitor 'C' energize the inductor 'L' as shown in figure: 15. So, the capacitor current is same as the inductor current. During this period power transfer to the load is zero.

3.2 Mathematical Formulation of Voltage Gain for Switched Boost Inverter

The steady state waveform for voltage fed to the inverter leg and inductor current of Switched Boost Inverter is as shown in figure. 16(a).

During non-shoot through state (1-D)T_s from figure. 14:

The voltage across inductor 'L' can be represented by,

$$v_L = V_g - V_C \quad (3.1)$$

The DC voltage fed to the inverter bridge can be found to be,

$$v_i = V_C \quad (3.2)$$

Similarly, current through the capacitor can be found to be,

$$i_C = I_L - I_i \quad (3.3)$$

During shoot through state DT_s from figure. 15:

The voltage across inductor 'L' can be represented by,

$$v_L = V_C \quad (3.4)$$

The DC voltage fed to the inverter bridge can be found to be,

$$v_i = 0 \quad (3.5)$$

Current through the capacitor can be found to be,

$$i_C = -I_L \tag{3.6}$$

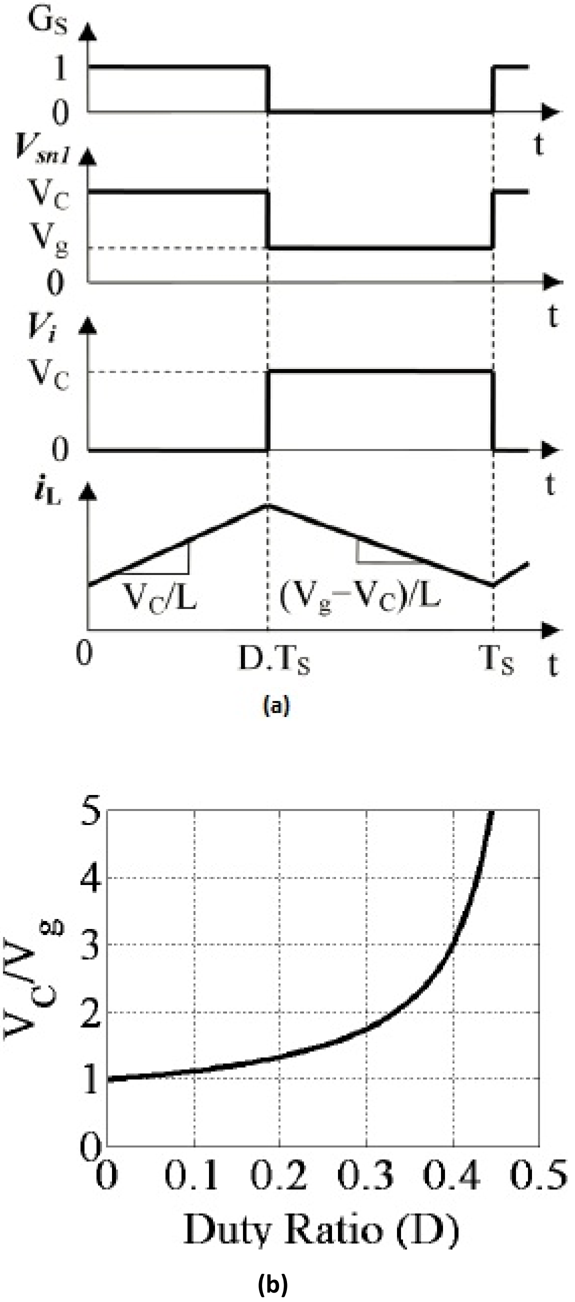


Figure: 16- (a) Steady state wave form of Switched Boost Inverter (b) Voltage gain versus duty cycle plot of Switched Boost Inverter

Applying volt-second balance across the inductor 'L' for the whole switching period,

$$V_C D + (V_g - V_C)(1-D)=0 \tag{3.7}$$

$$V_C = V_g \frac{1-D}{1-2D} \tag{3.8}$$

Similarly, using current-second balance through the capacitor 'C' for the whole switching period,

$$-I_L D + (I_L - I_i)(1-D)=0 \tag{3.9}$$

$$I_L = I_i \frac{1-D}{1-2D} \tag{3.10}$$

From, equation (3.8) it can be realized that the capacitor voltage can be boosted with a suitable value of shoot through duty ratio 'D'. The duty cycle 'D' can be varied between zero and 0.5. Here also sum of the shoot through duty ratio 'D' and modulation index 'M' cannot exceed unity. The voltage gain at capacitor 'C' versus duty cycle is plotted as shown in figure 16(b).

The control to output transfer function of switched boost converter is as given below:

$$\frac{V_C}{d} = \frac{b_2 s^2 + b_1 s + b_0}{a_3 s^3 + a_2 s^2 + a_1 s + a_0} \tag{3.1}$$

$$a_0 = R_l (2D-1)^2 \tag{3.2}$$

$$a_1 = L_1 (2D-1)^2 + L(D-1)^2 \tag{3.3}$$

$$a_2 = CLR_l \tag{3.4}$$

$$a_3 = CLL_l \tag{3.5}$$

$$b_0 = -R_l (2D-1)(2V_C - V_g) \tag{3.6}$$

$$b_1 = -L_l(2D-1)(2V_C - V_g) + L[V_C(1-D) + R_l(I_l - 2I_L)] \quad (3.7)$$

$$b_2 = (I_l - 2I_L)LL_l \quad (3.8)$$

3.3 PWM Control of Switched Boost Inverter

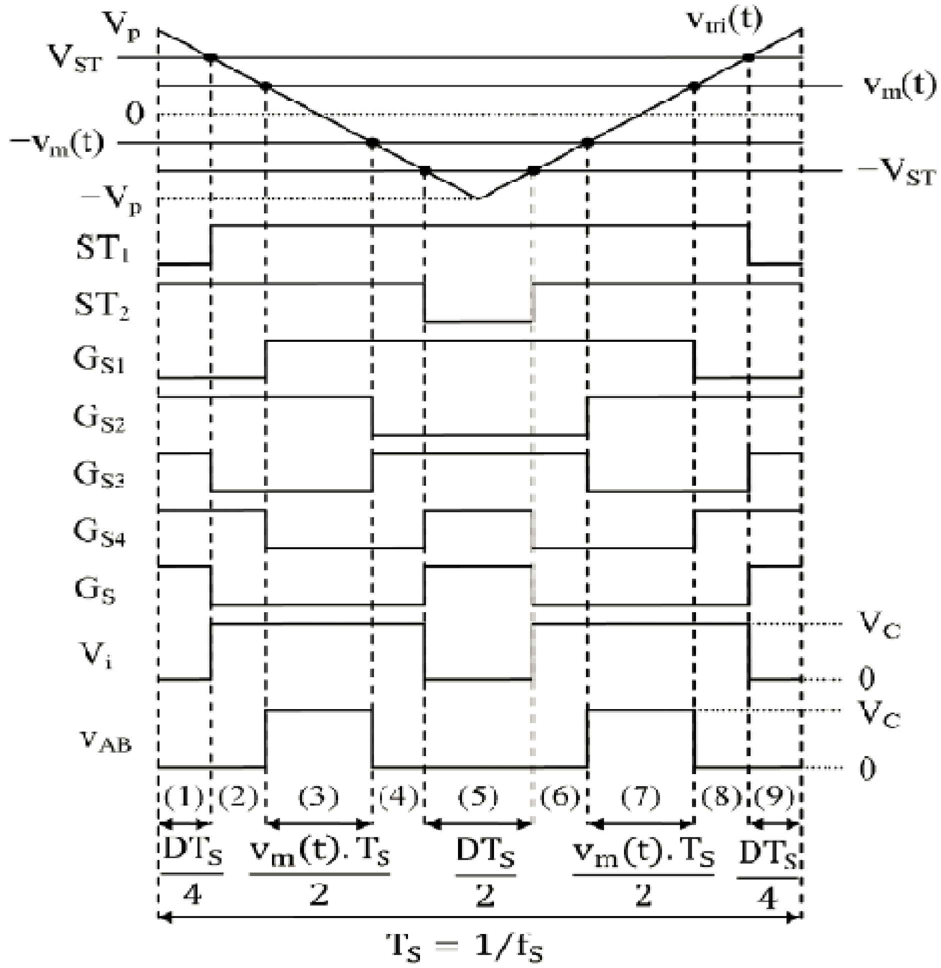


Figure: 17- PWM Control of Switched Boost Inverter

For controlling the switches of the Switched Boost Inverter a modified PWM strategy is used as shown in figure. 17. The switching signal for inverter legs can be generated by comparing modulating sinusoidal signal $V_m(t)$ and $-V_m(t)$ with triangular carrier signal $V_{tri}(t)$. The frequency of carrier signal is very high as compared to modulating signal. The shoot though signal is generated by comparing signal V_{ST} and $-V_{ST}$ with carrier signal which introduces shoot through period uniformly throughout the whole switching period.

Chapter 4

Problem Definition

Switched boost inverter is an improved derivative of Z- source inverter as discussed in the previous section but power flow is unidirectional because of the diodes D_a and D_b. So, this converter can be operated only as inverter. But in applications like AC-DC hybrid microgrid and some energy storage application converter needed to be bidirectional. So, in order achieve this objective a bidirectional switched boost converter has been proposed in the next chapter. It allows power flow in both the direction i.e. from DC bus side to AC bus side as well as AC bus side to DC bus, based on the power status of the buses. As a result, it is able to maintain two DC bus voltages and one AC bus voltage, which makes it more suitable for AC-DC hybrid microgrid as shown in figure. 18.

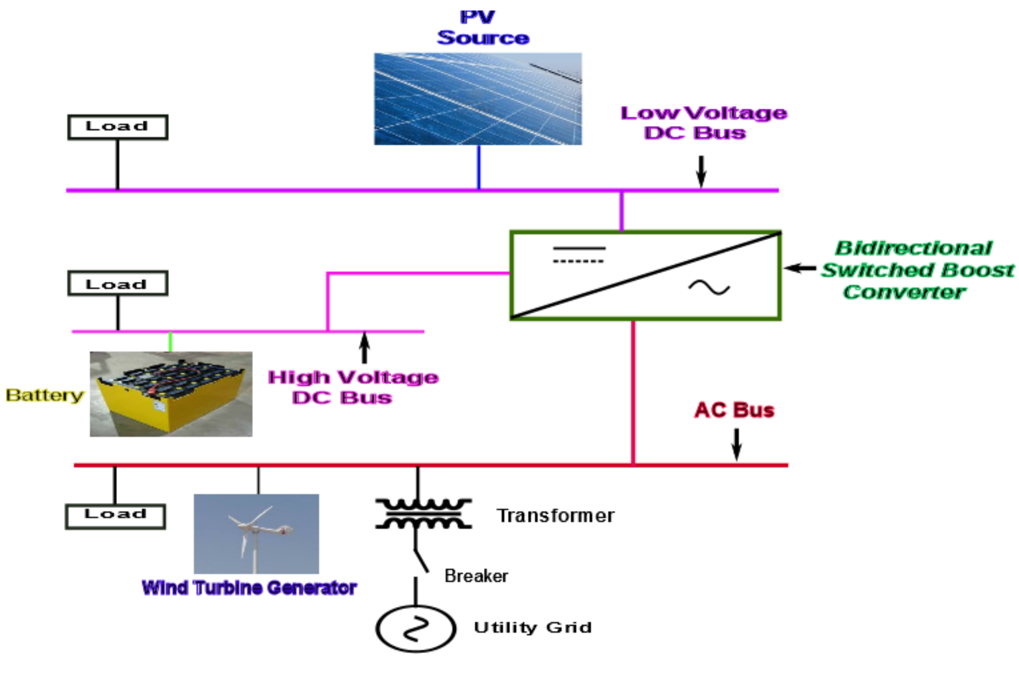


Figure. 18: Schematic of AC-DC hybrid Microgrid using Bidirectional Switched Boost Inverter

Chapter 5

Proposed Bidirectional Switched Boost Converter (BSBC)

The proposed Bidirectional Switched Boost Converter for three phase system, exhibits buck-boost characteristic in both the direction of power flow by which it helps in power sharing between the DC buses and AC bus[19-20]. The intermediate network of BSBC is comprised of three single quadrant active switches (S, S1, and S2), two relays (S3, S4), one capacitor C,

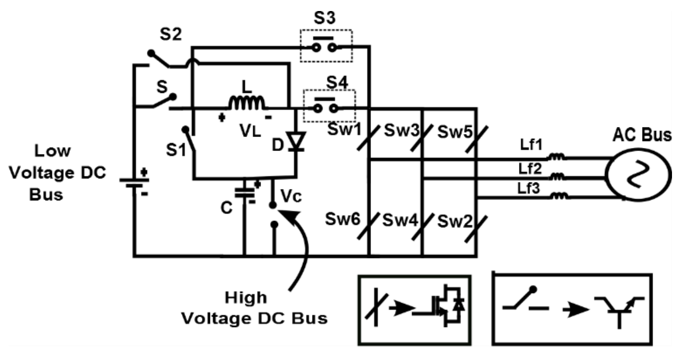


Figure: 19 - Schematic of BSBC

one inductor L and a diode D as shown in Figure. 19.The energy status at AC bus and DC buses determines the direction of power flow and based on the direction of power flow relays S3 and S4 are operated. Generally the frequency of variation in energy status at AC bus and DC bus are used to be less, so the switches S3 and S4 are taken as relays. Switches S, S1, S2 are taken as high frequency single quadrant controlled switches which are operated based on shoot through duty ratio to get required voltage gain in both the direction of power flow. In conventional bidirectional Z-source converter when operating mode is shifted from inverting mode to rectifying mode or vice versa current through the inductor is reversed whereas, in proposed BSBC current through the inductor is always unidirectional.

5.1 Operating Modes and Mathematical Validation

A. **INVERTING MODE OF OPERATION**

In inverting mode of operation power is transferred from low voltage DC bus to high voltage DC bus and AC bus. In this mode the voltage Vg at low voltage DC bus is boosted to high voltage DC across capacitor C based on shoot through duty ratio which is fed to high voltage DC bus. At the same time average voltage fed to the converter from DC side is also boosted which is inverted based on modulation index and fed to the AC bus. The controlled switch

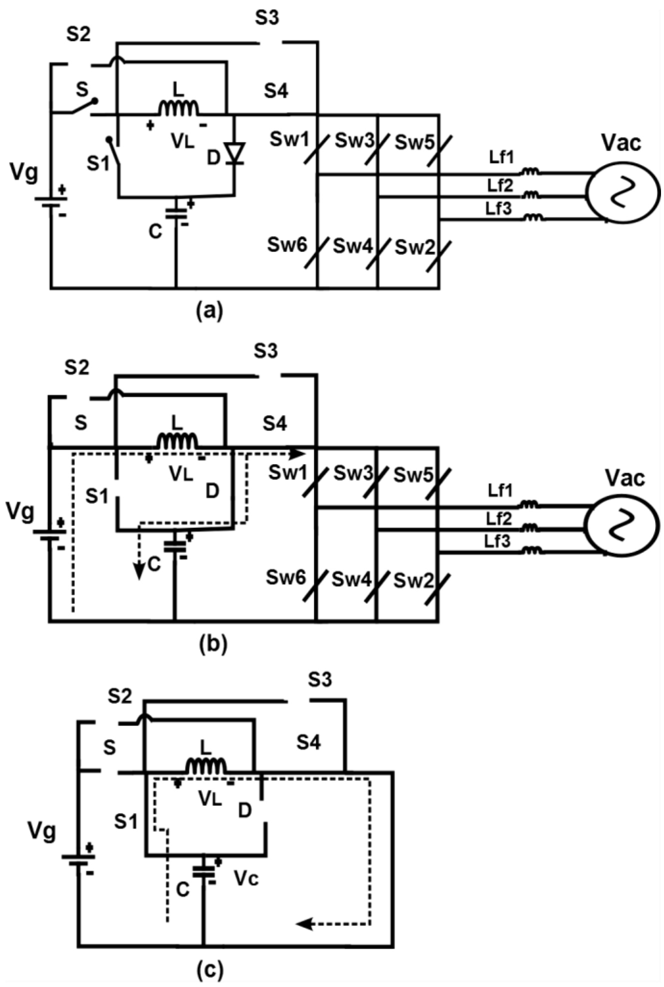


Figure 20: (a) Schematic of BSBC in inverting mode (b) Equivalent circuit during non-shoot state of BSBC in inverting mode (c) Equivalent circuit during shoot state of BSBC in inverting mode

‘S2’, relay ‘S3’ are turned OFF whereas relay ‘S4’ is turned ON for the entire inverting mode as shown in Figure. 20(a). In inverting mode the BSBC is mainly operated in two states i.e. non-shoot through state and shoot through state. In non-shoot through state the switch ‘S’ is turned ON and switch ‘S1’ is turned OFF which in turn forward biases the diode D at the same time the switches (Sw1, Sw2, Sw3, Sw4, Sw5, Sw6) in the converter legs are operated based on the PWM control signal like conventional VSC. As a result both low voltage DC bus and inductor L supply power to AC bus and capacitor C as shown in Figure. 20(b). In shoot through state switch ‘S1’ is turned ON, switch ‘S’ is turned OFF and the switches in one or more converter legs are turned ON which in turn reverse biases the diode D. Because of this capacitor boost the energy of inductor which helps in boosting the average DC voltage fed to converter from DC side as shown in Figure. 20(c).

The relationship between low voltage DC input and high voltage AC/DC output are derived as follows

Let,

T_{ON} = shoot through period

T_S = switching time period

D = shoot through duty ratio (ratio of T_{ON} to T_S)

V_L = Voltage across the inductor L

V_I = average DC voltage fed to the converter leg

V_m = peak value of AC bus phase voltage Vac

M = modulation index

V_C = Voltage across capacitor C

In non-shoot through period (1-D) T_S from Figure.20 (b)

$$V_L = Vg - V_C \tag{5.1}$$

$$V_I = V_C \tag{5.2}$$

In shoot through period DT_S from Figure.20(c)

$$V_L = V_C \tag{5.3}$$

$$V_I = 0 \tag{5.4}$$

Applying volt-sec balance across inductor for the entire switching period Ts , using equation (5.1) and equation (5.3) as,

$$\frac{V_C}{V_g} = \frac{1\text{-}D}{1\text{-}2D} \tag{5.5}$$

Average DC voltage fed to the converter leg from DC side is found out from equation (5.2) and equation (5.4) as,

$$V_I = V_C\left(1\text{-}D\right) \tag{5.6}$$

The peak output AC line voltage is given by

$$V_m = V_g M \frac{1\text{-}D}{(1\text{-}2D)} \tag{5.7}$$

It can be observed from equation (5.5) and equation (5.7) that V_C can be boosted and V_m can be bucked or boosted based on the shoot through duty ratio ‘D’ and modulation index ‘M’.

B. **RECTIFYING MODE OF OPERATION**

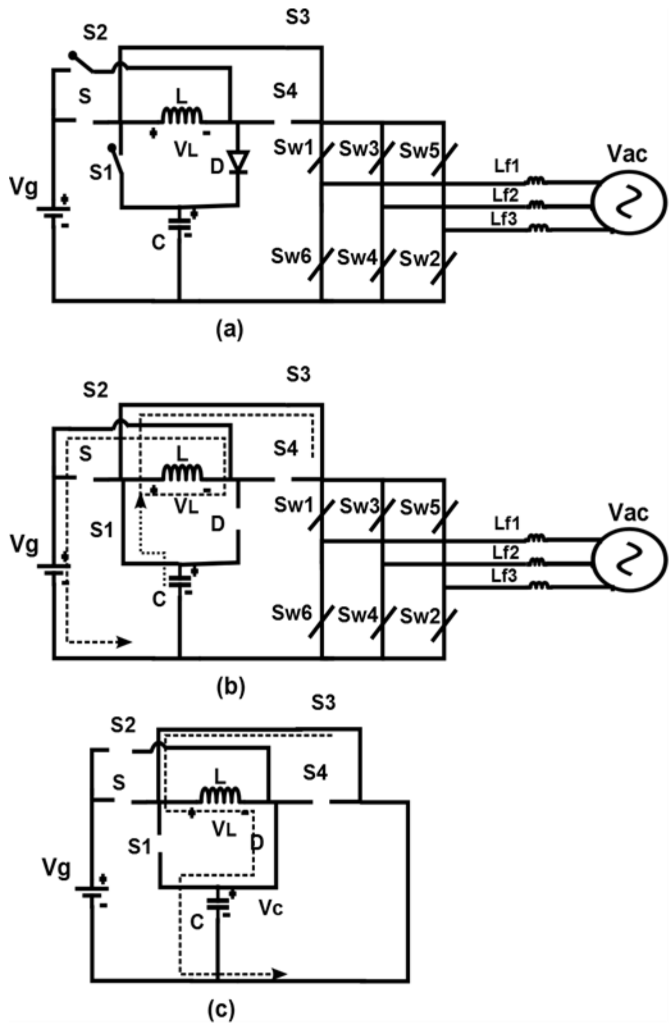


Figure. 21: (a) Schematic of BSBC in rectifying mode (b) Equivalent circuit during non-shoot state of BSBC in rectifying mode (c) Equivalent circuit during shoot state of BSBC in rectifying mode

In rectifying mode of operation power is transferred from AC bus to DC buses. During this mode of operation the peak AC line voltage Vm of the AC bus is converted to high voltage DC across capacitor C and low voltage DC at low voltage DC bus based on the modulation index and shoot through duty ratio. The switch 'S' and relay 'S4' are turned OFF whereas relay 'S3' is turned ON for the entire rectifying mode of operation as shown in Figure. 21 (a).In this mode of operation the power converter operates mainly in two states i.e. non-shoot through state and shoot through state. During non-shoot through state switches 'S1' and 'S2' are turned ON which in turn reverse biases the diode D. As result both AC bus and capacitor

C supplies energy to the low voltage DC bus and energize the inductor L as shown in Figure.21 (b). In shoot through state switches ‘S1’ and ‘S2’ are turned OFF which in turn forward biases the diode D. Because of this inductor transfer energy to capacitor C which helps to buck the average DC voltage at low voltage DC bus as shown in Figure. 21 (b).

The relationship between AC input and high/low voltage DC output are derived as follows,
In non-shoot through period (1-D)Ts from Figure.21 (b) ,

$$V_L = V_C - Vg \tag{5.8}$$

$$V_I = V_C \tag{5.9}$$

In shoot through period DTs from Figure.21(c),

$$V_L = -V_C \tag{5.10}$$

$$V_I = 0 \tag{5.11}$$

Applying volt-sec balance across inductor L for the entire switching period Ts, using equation (5.8) and equation (5.10) as,

$$\frac{V_g}{V_C} = \frac{1\text{-}2D}{1\text{-}D} \tag{5.12}$$

Similarly using equation (5.9) and equation (5.11) average DC voltage just after the rectifier leg fed to the intermediate network from AC side is found to be as,

$$V_I = V_C\left(1 - D\right) \tag{5.13}$$

From traditional voltage source rectifier, peak value of converter output in rectifying mode,

$$v = \frac{V_m}{M\cos\varphi} \tag{5.14}$$

Where, Φ is the equivalent lag angle

Using equation (5.12) and equation (5.14),

$$V_g = \frac{V_m(1\text{-}2D)}{M(1\text{-}D)\cos\varphi} \tag{5.15}$$

From equation (5.14) and equation (5.15) it is observed that the voltage across capacitor can be boosted based on modulation index M and voltage at low voltage DC bus Vg can be bucked based on modulation index M and shoot through duty ratio ‘D’.

5.2 Controlling Of Bidirectional Switched Boost Converter

The shoot through control signal ‘Sw’ is generated by comparing two constant signals Vst and –Vst with triangular carrier signal Vtri(t) as shown in Figure 22 [19-20]. The control signal for the switches of converter legs are generated by comparing modulating signals (Va(t), Vb(t), Vc(t)) , Vst, -Vst with the triangular signal Vtri(t) . During inverting mode of operation the shoot through control signal ‘Sw’ is given to switch ‘S1’ and non-shoot through control signal ‘Sw0’ is given to switch ‘S’. At the time of rectifying mode of operation the non-shoot through signal ‘Sw0’ is given to both the switches S1 and S2.

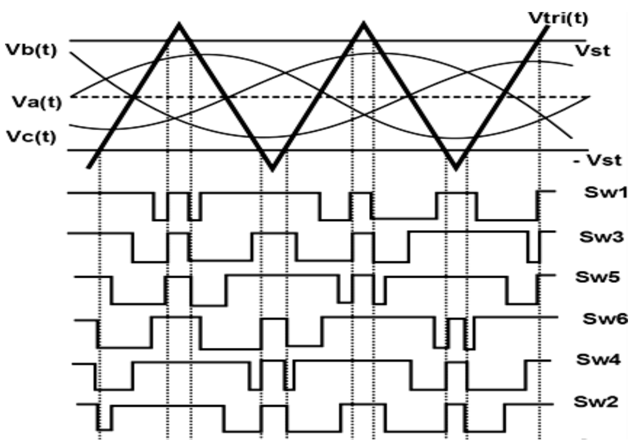


Figure. 22: Generation of control signal for Bidirectional Switched boost converter switches

Chapter 6

Simulation Results

Three phase Bidirectional Switched Boost Converter:

The circuit has been designed and implemented using MATLAB Simulink. For simulation the parameters have been taken as shown in Table 6.1. In inverting mode parameters have

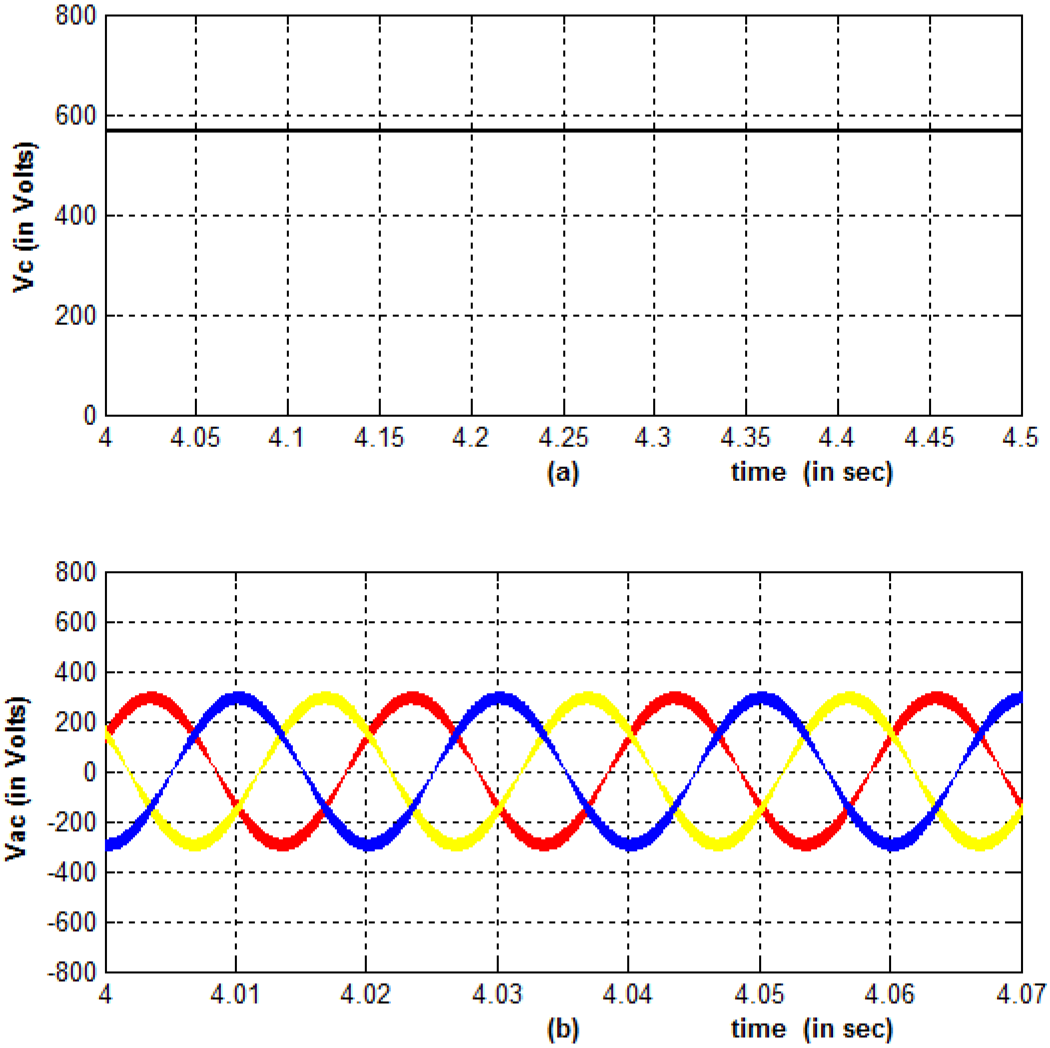


Figure.23: (a) Voltage across capacitor C (in Volts) versus time (in sec) (b) Three phase AC output voltage (in Volts) versus time (in sec) of BSBC during inverting mode of operation

Table: 6.1 Parameter Table for 3-Phase BSBC

Parameter	Values
Input Voltage at low Voltage DC bus (V_g)	188 Volts
Inductor 'L'	12 mH
Capacitor 'C'	1500 µF
Switching frequency (f_s)	10 kHz
fundamental frequency (f)	50 Hz
shoot through duty ratio (d)	0.4
modulation index (M)	0.6
Inductor 'L_f'	0.1 mH
loads at three phase AC bus	100 Ω/phase

been taken as, input DC voltage source at low voltage DC bus, Vg = 188 Volts, inductor L = 12 mH, capacitor C = 1500 µF, switching frequency fs = 10 kHz, fundamental frequency f=50 Hz, shoot through duty ratio D = 0.4, modulation index M = 0.6, inductor Lf = 0.1 mH per phase, loads at three AC bus R = 100 Ω per phase. Using equation (5.5) and equation (5.7) the boosted capacitor voltage V_C and peak AC output phase voltage Vm has been found to be, V_C = 565 Volts, V_m = 339 Volts.

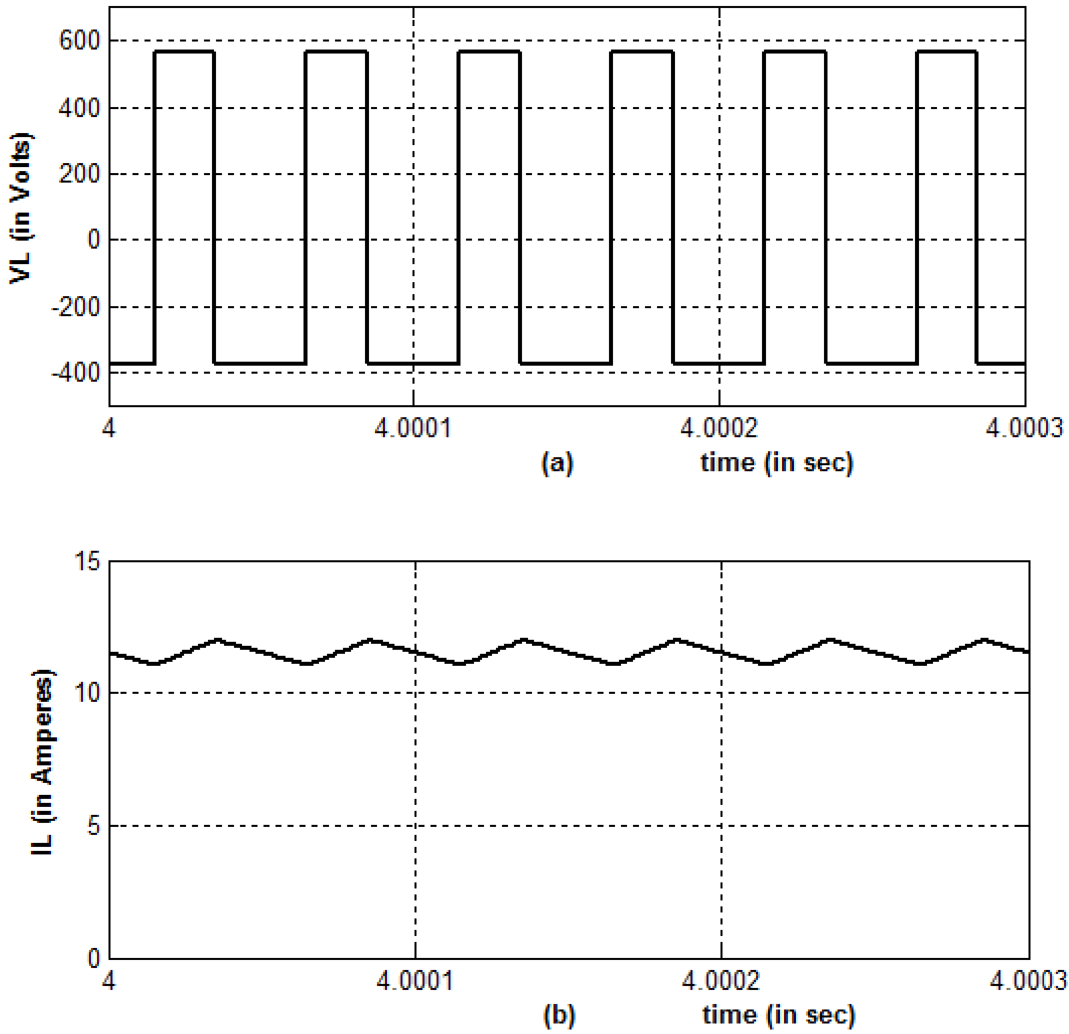


Figure.24: (a) Voltage across inductor L (in Volts) versus time (in sec) (b) Current through inductor L (in Amperes) versus time (in sec) during inverting mode of operation

After simulation average voltage across capacitor(V_C) has been boosted to 565 Volts with significantly low ripple and peak output AC phase voltage has been found to be V_m = 330 Volts with THD 5 % as shown in Figure.23 (a) and Figure.23 (b) respectively. Here it has been observed that voltage across inductor L during shoot through equal to voltage across capacitor C, so inductor current have rising current slope.

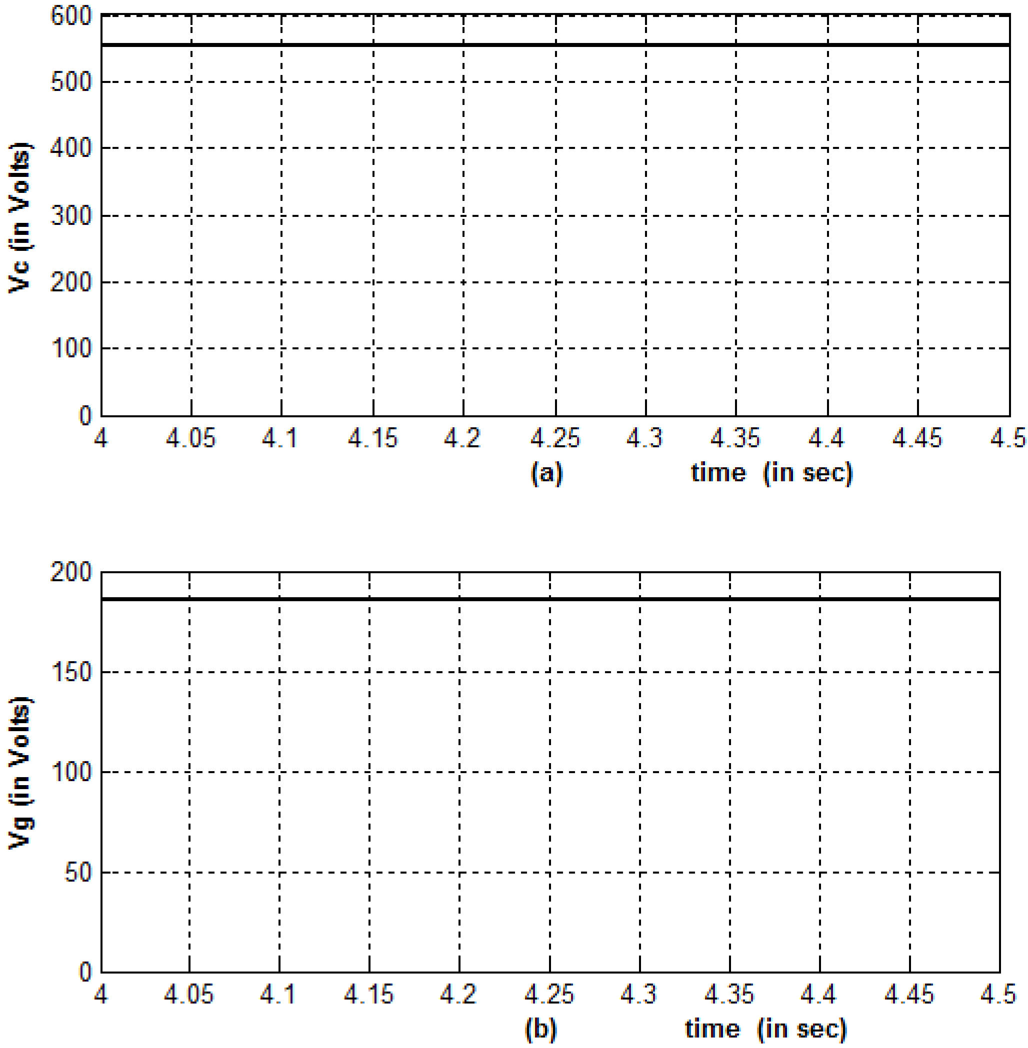


Figure.25: (a) Voltage across capacitor C (in Volts) versus time (in sec) (b) Output voltage at low voltage DC bus (in Volts) versus time (in sec) of the BSBC in rectifier mode

During non-shoot through state inductor used to release energy to the load, as a result it has falling current slope characteristics as shown in Figure. 24 (a) and Figure 24 (b).

In rectifier mode of operation three phase input AC peak phase voltage (Vm) has taken 339 Volts and load at low voltage DC bus R1=100 Ω while all remaining parameter has taken same as inverting mode. Using equation (14) and equation (15), the voltage across capacitor C and at low voltage DC bus has been found to be V_C = 565 Volts, Vg =188 Volts. The average voltage across capacitor C after simulation has been found to be, Vc = 553.3 Volts with 0.13 % ripple and average voltage at low voltage DC bus (Vg) has been found to be 185.72 Volts with 0.04 % ripple as shown in Figure 25(a) and Figure 25(b) respectively.

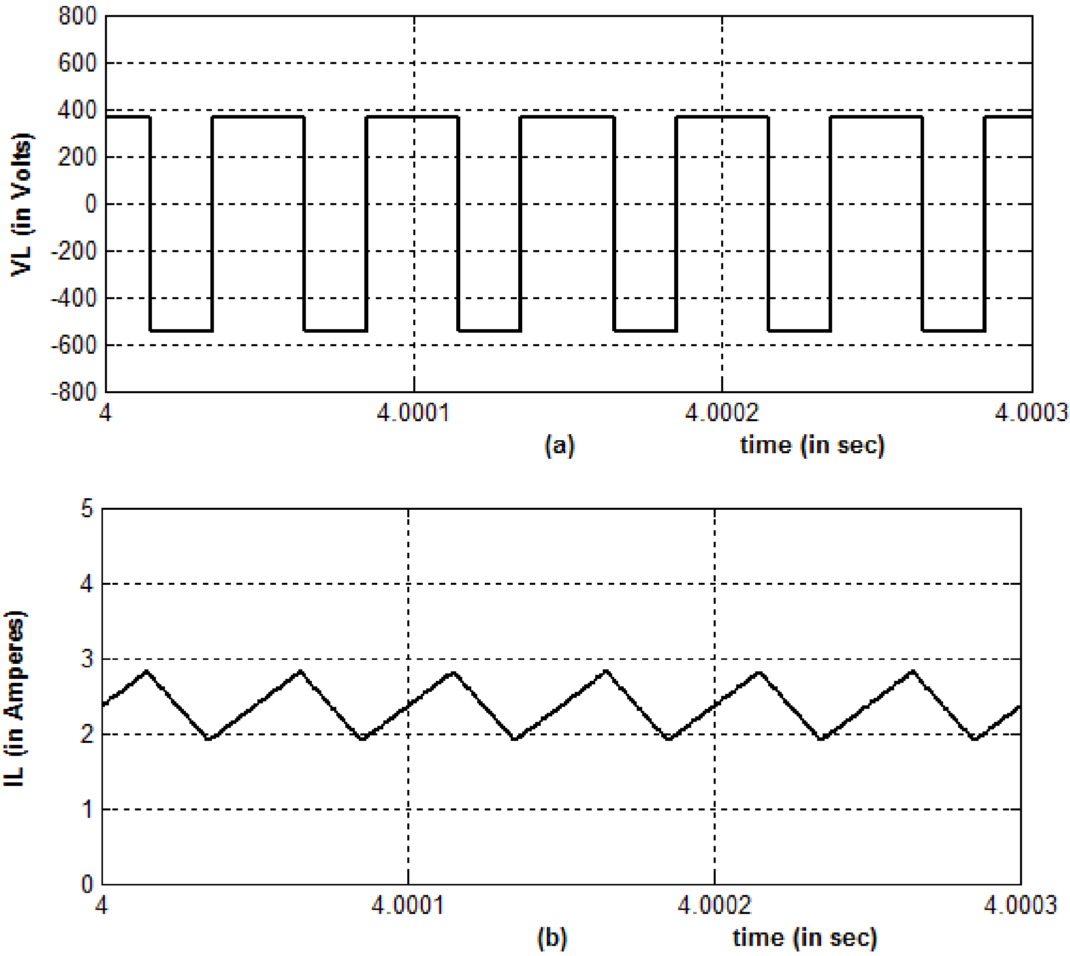


Figure.26: (a) Voltage across inductor L (in Volts) versus time (in sec) (b) Current through inductor L (in Amperes) versus time (in sec) of the BSBC in rectifier mode of operation

In non-shoot through state, voltage across inductor is positive so it has rising current slope whereas in shoot through state voltage across inductor is negative of capacitor voltage, so it has falling current slope as shown in Figure 26(a) and Figure 26(b).

Single phase Bidirectional Switched Boost Converter:

Table: 6.2 Parameter Table Single Phase BSBC

Parameter	Values
Input Voltage at low Voltage DC bus (V_g)	60 Volts
Inductor 'L'	12 mH
Capacitor 'C'	1500 µF
Switching frequency (f_s)	10 kHz
fundamental frequency (f)	50 Hz
shoot through duty ratio (D)	0.4
modulation index (M)	0.6
Inductor 'L_f'	0.1 mH
loads at AC bus	100 Ω/phase

The circuit has been designed and implemented using MATLAB Simulink. For simulation the parameter has been taken as shown in Table.6.2. In inverting mode parameter has been taken as, input DC voltage source V_g = 60 Volts, inductor L = 12 mH, capacitor C = 1500 µF, switching frequency f_s = 10 kHz, fundamental frequency f=50 Hz, shoot through duty ratio D = 0.4, modulation index M = 0.6, inductor L_f = 2 mH, load at AC bus R = 100 Ω. Using equation (3) and equation (4) the boosted capacitor voltage V_C and peak AC output voltage V_m has been found to be, V_C = 180 Volts, V_m = 108 Volts.

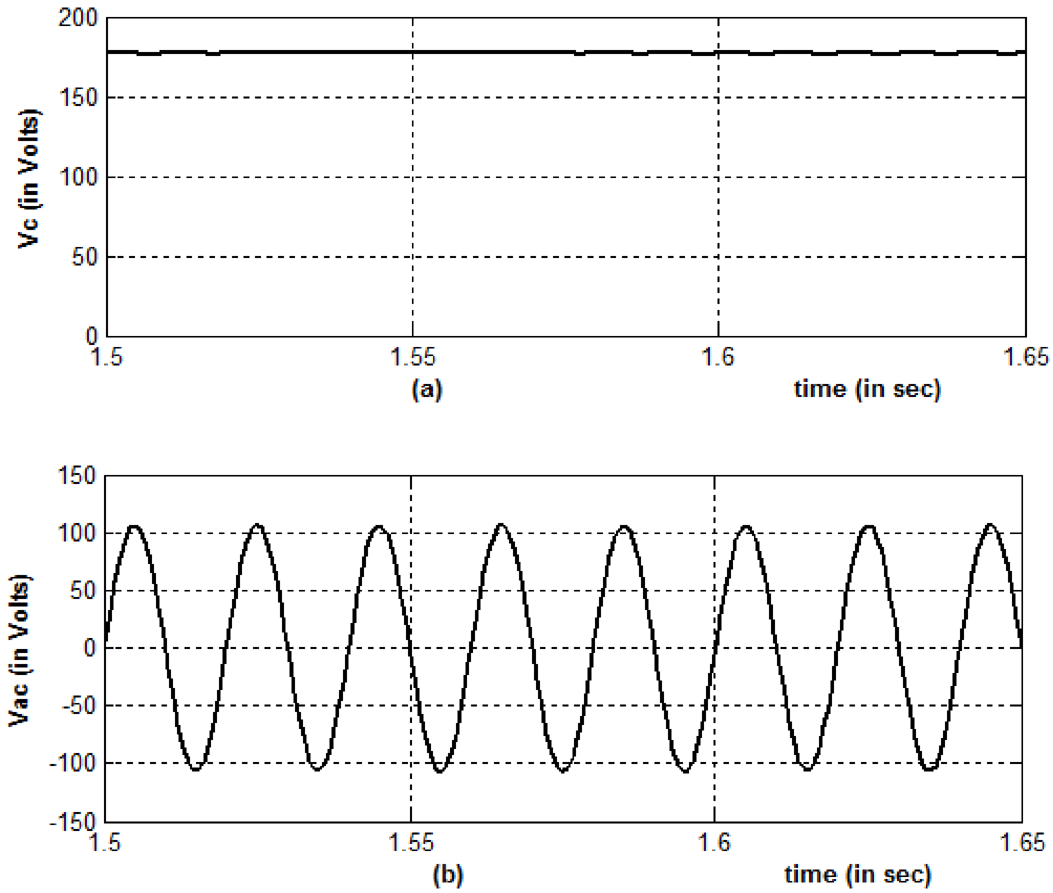


Figure.27: (a) Voltage across capacitor C (in Volts) versus time (in sec) (b) Output AC voltage (in Volts) versus time (in sec) in rectifying mode of operation

After simulation average voltage across capacitor (V_C) has been boosted to 178.5 Volts with 0.5 percent ripple and peak output AC line voltage has been found to be, $V_m = 108$ Volts as shown in Figure.25 (a) and Figure.25 (b) respectively. After simulation average voltage across capacitor(V_C) has been boosted to 178.5 Volts with 0.5 percent ripple and peak output AC line voltage has been found to be $V_m = 108$ Volts as shown in Figure.27 (a) and Figure.27 (b) respectively.

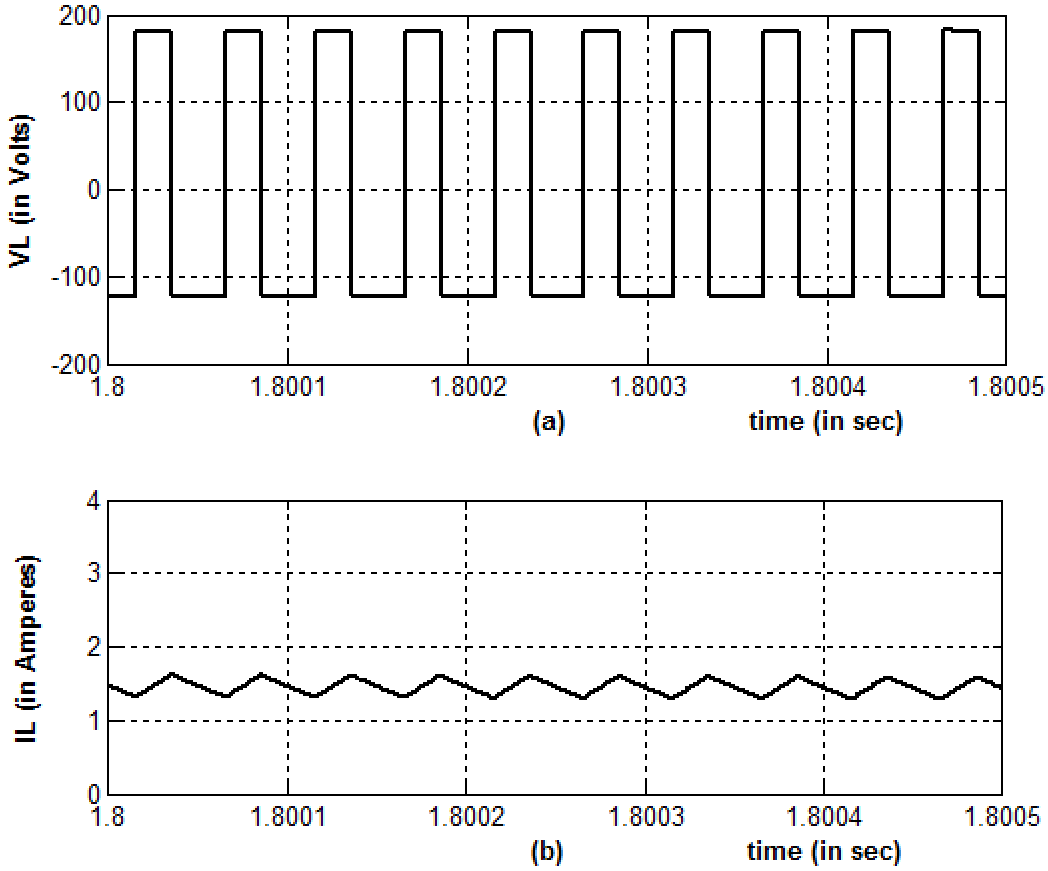


Figure.28: (a) Voltage across inductor L (in Volts) versus time (in sec) (b) Current through inductor L (in Amperes) versus time (in sec) in rectifying mode of operation

Here it has been observed that voltage across inductor L during shoot through equal to voltage across capacitor C, so inductor current have rising current slope while during non-shoot through state inductor used to release energy to the load ,as a result it has falling current slope characteristics as shown in Figure. 28 (a) and Figure.28 (b) .

In rectifier mode of operation input AC peak line voltage (V_m) has taken 108 Volts and load at low voltage DC bus R1=100 Ω while all remaining parameter has taken same as inverting mode. Using equation (13) and equation (15), the voltage across capacitor C and at low voltage DC bus has been found to be V_C = 180 Volts, Vg =60 Volts. The average voltage across capacitor C after simulation has been found to be, Vc = 163 Volts with 10 percent ripple and average voltage at low voltage DC bus (V_g) has been found to be 60 Volts with 1.85 percent ripple as shown in Figure. 29(a) and Figure. 29(b) respectively.

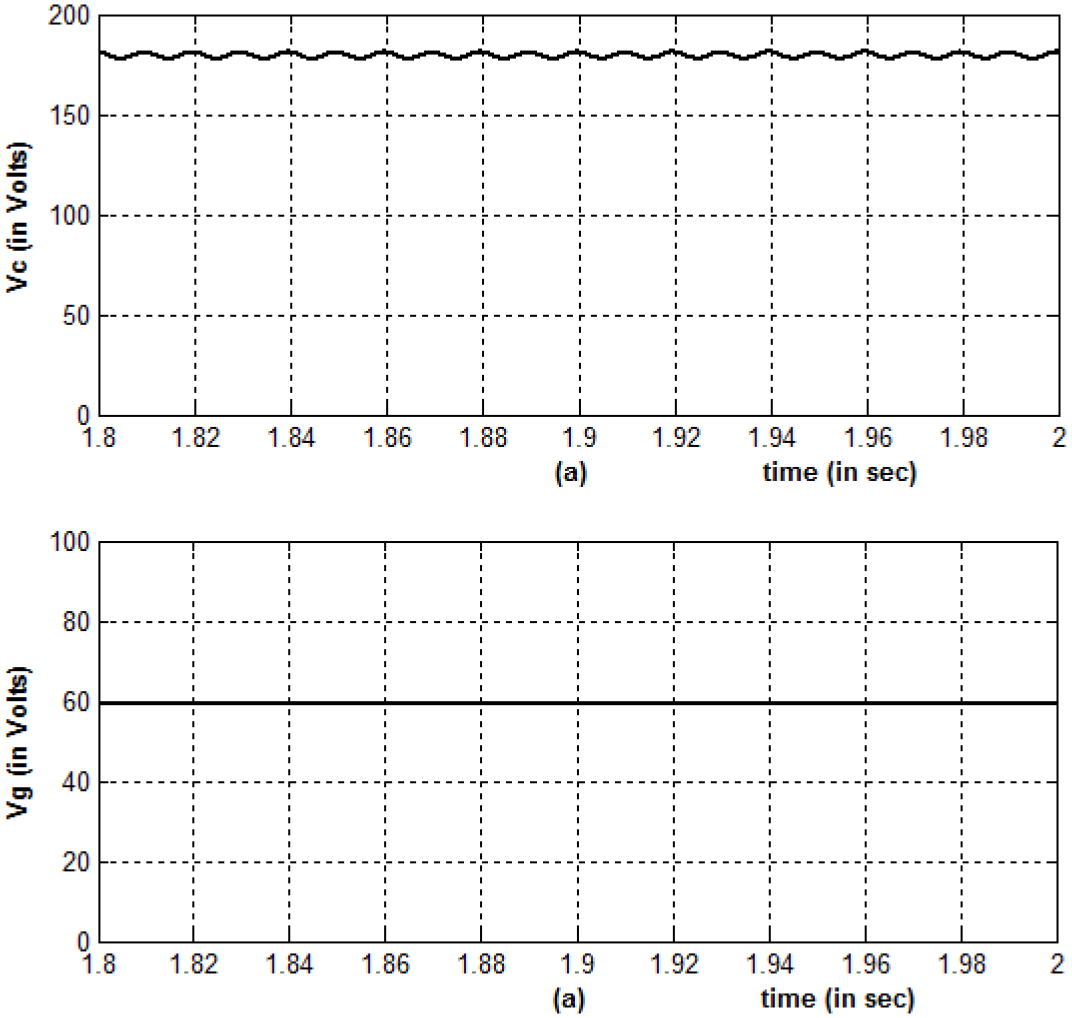


Figure. 29: (a) Voltage across capacitor C (in Volts) versus time (in sec) (b) Output voltage at low voltage DC bus (in volts) versus time (in sec)

In non-shoot through state voltage across inductor is positive so it has rising current slope whereas in shoot through state voltage across inductor is negative of capacitor voltage so it has falling current slope as shown in Figure. 30(a) and Figure. 30(b) respectively .Two DC voltage levels at two DC buses and one AC voltage level at AC bus has been maintained in both the direction of power flow.

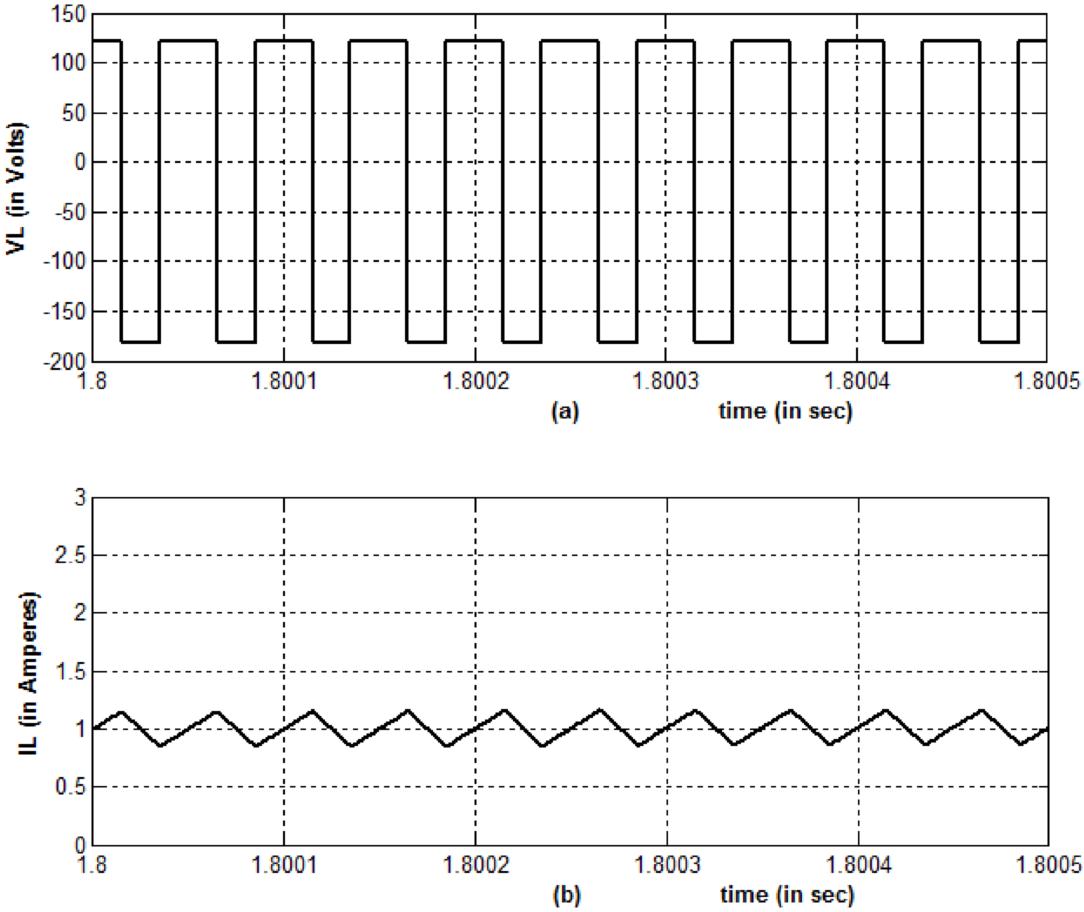


Figure. 30: (a) Voltage across inductor L (in Volts) versus time (in sec) (b) Current through inductor L (in Amperes) versus time (in sec) of the BSBC in rectifier mode

From the voltage and current waveforms of the inductor 'L' it can be observed that volt-second balance is maintained. The voltage ripple at high voltage DC bus can be minimized by using suitable value of capacitor 'C'. Similarly current ripple at inductor can be minimized further with suitable value of inductor 'L'

Chapter 7

Conclusion

A Bidirectional Switched Boost Converter for three phase system as well as single phase is designed for this project which retains all the advantages of conventional Bidirectional Z-source converter like, it is capable of buck or boost the input voltage and its conversion (AC to DC or DC to AC) simultaneously in single stage. In addition to above advantages BSBC requires, less reactive elements and shows better dynamic performance as compared to BZSC. With the help of BSBC two different DC level (DC buses) voltages and AC level (AC bus) voltage can be maintained which makes it more suitable for AC-DC hybrid micro grid. PWM control strategy adapted for switches are discussed for both inverting and rectifying modes of operation. The converter operation is analyzed and verified by simulation using Matlab/Simulink.

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