

Mathematical Modeling of a Novel Z-Source Boost Hybrid Converter

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Abstract

The abundant availability of solar power and increasing demand for electrical power has attached more penetration of solar power in the power grid. The low DC output of solar photovoltaic (SPV) system is connected with the load through the power converter unit. This converter unit has more switching stages which leads to heavy power loss with reduce gain and create the shoot-through problem in the inverters. These are overcome by the Z-source network and boost derived hybrid converter. Boost derived hybrid converter (BDHC) is a single input dual output converter which can connect DC and AC load simultaneously. This paper proposes a Z-source network cascaded with the boost derived hybrid converter called z-source boost hybrid converter (ZSBHC) for SPV application. The proposed converter provide inherent shoot-through, increased gain, reduced switching count results in reduced switching losses, high power processing capability and more reliable. The modelling and the performance analysis of the Z-source boost hybrid converter (ZSBHC) is validated with the simulation results using Matlab/Simulink software.

Keywords: Z-Source network; Boost derived hybrid converter; State space modeling;

1 INTRODUCTION

Role of renewable energy sources in power electronic and power system applications are increased high in recent years. To reduce the environmental pollution, to manage decrease in availability of fossil fuels and to meet the demand of the electricity requirement, the local balancing of power production and consumption. The local balancing sources like solar photovoltaic, wind energy, fuel cell, hydro energy etc. penetration is increased in the power distribution system. Photo voltaic energy has major contribution among all sources for power generation, as it is eco-friendly, abundant availability, high reliability and less maintenance [1]. In spite of these advantages the output voltage of the photovoltaic cell is low and not suitable for practical applications, it needs to be boosted with high conversion ratio for effective utilization. Hence the high gain DC-DC converters are employed [2], [3], [4]. For AC load applications this boost output is inverted by the single phase or three phase inverter. Traditional DC to DC and DC to AC converter are cascaded for AC load from the unregulated supply which exhibits more switches in the circuit that causes increased size, weight and cost. More researches [5], [6] discussed about reducing number of switches by implementing hybrid power converters[7]. Boost derived hybrid converter (BDHC) is a reduced switch single converter which producing dual output of DC and AC voltage simultaneously from a single source [8]. This BDHCs DC and AC gain is improved when it is cascading with the Z-source network like a Z-source converter. The conventional Z-source inverter is shown in Fig. 1 which is proposed by F.Z.Peng [9] to solve the shoot-through problem in VSI and the output limitation of the VSI. Z-source DC-DC converter has been proposed [10], [11] as shown in Fig. 2 which explains the improvement of the conventional boost converter. Z-source inverters for SPV residential application is explained in [12], [13].

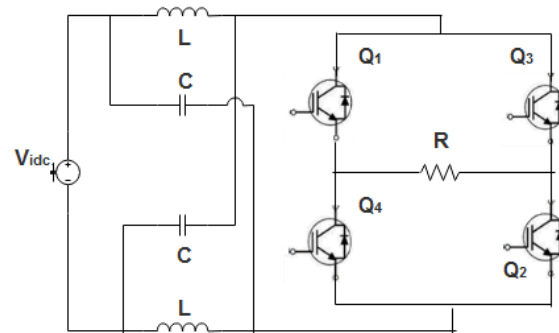


Fig. 1 Z-source inverter

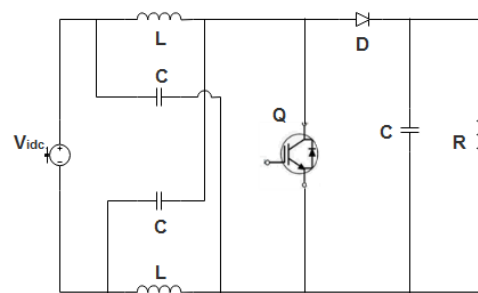


Fig. 2 .Z-source dc-dc converter

A novel ZSBHC is presented in this paper to activate the inherent shoot-through, high voltage gain of both AC and DC loads. This converter has further advantages of simple structure and low voltage stress on the switches and diode. The application of the proposed converter is promising for a step up stage of photovoltaic smart residential system.

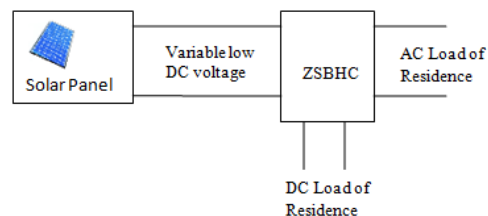


Fig. 3 Smart residential system using ZSBHC block

Fig. 3 depicts the ZSBHC for the residential power system application. A single ZSBHC can produce dual output of AC and DC simultaneously from a single source. In this paper, the ZSBHC circuit modeling is developed by state-space averaging techniques [14] and is validated with simulated results using MATLAB/Simulink software and experimental result.

2 OPERATION OF THE PROPOSED CONVERTER

A. Circuit Description

The proposed ZSBHC consists of the Z-source network cascaded with boost derived hybrid converter (BDHC) as shown in Fig. 4. Z-source network has two identical inductors and two identical capacitors connected in X-shape. The boost derived hybrid converter is a single DC input and dual AC and DC output converter. It has four IGBT switches to achieve the AC and DC output simultaneously. The Z-source network connected in front of the BDHC make the circuit gain as high as conventional BDHC. In Fig. 4, the capacitor C_d is a filter capacitor for the DC load and C_1 is the filter capacitor for AC load. R_d and R_1 are the DC and AC load resistors respectively. L , L_d and $L_1 - L_2$ are the Z-source, DC filter and AC filter inductors respectively.

B. Modes of operation

The IGBT switches Q_1 to Q_4 are responsible for both DC and AC outputs. Diode D, inductor L_d , capacitor C_d , resistor R_d are responsible for achieving boost output and inductors L_1 , L_2 , capacitor C_1 , resistor R_1 are responsible for inverter operation. The converter operates in two modes namely shoot-through interval mode and power interval mode.

Assuming the continuous conduction for the converter during shoot-through interval mode the switches Q_1 and Q_4 or switches Q_2 and Q_3 conduct as shown in Fig. 5. Diode D gets reverse biased, since the capacitor voltage is greater than the source voltage. The current through the inductor, i_L increases and its from the capacitor C. The filter capacitors C_1 and C_d discharges through the load resistors R_1 and R_d respectively to maintain the continuous conduction of the circuit. During the power interval mode the IGBT

switches Q_1 and Q_2 or Q_3 and Q_4 conduct. Diode D now switched ON and the source communicates with both the loads R_1 and R_d .

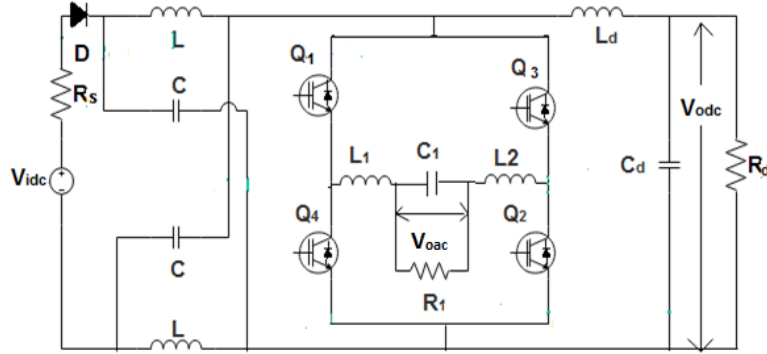


Fig. 4 Z-source boost hybrid converter

The equivalent circuits of the shoot-through interval and power interval modes are represented in Fig. 5 and Fig. 6 respectively. The switching pulses are same as in [8].

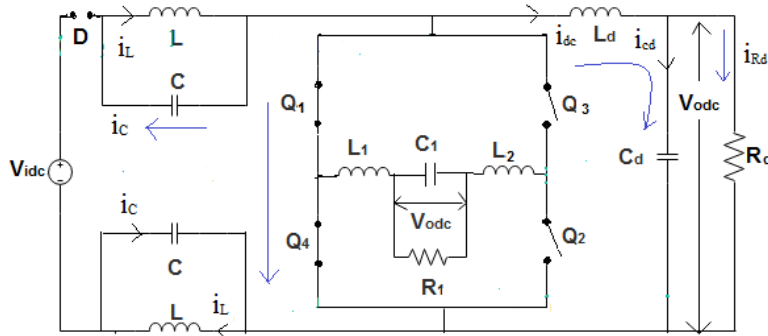


Fig. 5. Shoot-through interval mode of ZSBHC

3 SWITCHING STRATEGY OF ZS-BHC

The switching technique is as same as that of the conventional boost derived hybrid converter. Fig. 7 shows the modified unipolar sine-PWM. In this scheme, the shoot-through is realized by gating ON

the switches Q_1 and Q_4 at the same leg and the power interval is realized by gating ON the alternate leg switches Q_1 and Q_2 . At power interval the current from the input inductor is shared by the DC and AC load. Depend upon that the control strategy is developed.

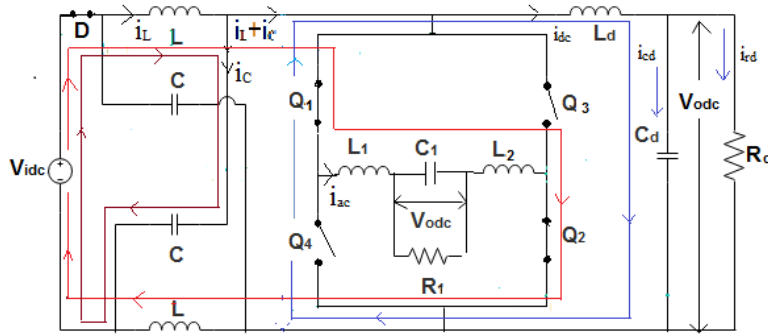


Fig. 6. Power interval mode

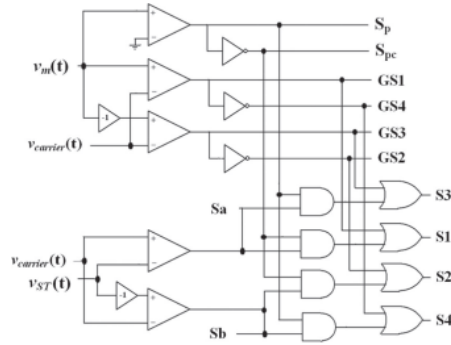


Fig. 7 Control Scheme of ZSBHC

In the Fig. 7 signals S_1 to S_4 are given to the gate terminal of the control switches Q_1 to Q_4 respectively. $V_{carrier(t)}$ is the high frequency carrier signal. The two reference signal $V_{m(t)}$ and $V_{ST(t)}$ are the sinusoidal and DC signals respectively. $V_m(t)$ controls the shoot through interval thus duty ratio of the DC output and $V_{ST}(t)$ controls the AC peak value of sine pulse thus modulation index of the AC output.

4 ZSBHC CIRCUIT ANALYSIS

A. Steady-state Analysis of ZSBHC

During shoot-through interval mode, the inductor current raises gradually and at the same time the capacitor current flows opposite direction to that of the inductor current. At power interval mode the input current flows through the AC and DC loads. The current through the input inductor and voltage across the inductor are i_L and V_L respectively and the voltage across the DC capacitor is V_{dc} . In the DC pulse width digital modulation as in [8], the inductor current ripple is twice that of the fundamental frequency. So the ON period is represented by 2δ and OFF period is represented by the $1-2\delta$, where δ is a duty ratio. The inductor voltage second balance equation is given in the equation (1)

$$\frac{1}{T}[V_c(2\delta)T + (V_{dc} - V_c)(1 - 2\delta)T] = 0 \quad (1)$$

From the equation (1) the voltage across the DC capacitor or output DC voltage is solved and is given in (2)

$$V_c = \frac{1 - 2\delta}{1 - 4\delta} V_{dc} \quad (2)$$

From the equation (2), it is understood that the duty ratio is ranges from 0 to 0.25, the duty ratio limitation for the ZSBHC is given in the equation (3). For the low value of delta the ZSBHC achieves high output compare to the BDHC. The design value of each passive elements of ZSBHC is the same in conventional Z-source and BDHC.

$$0 \leq \delta \leq 0.25 \quad (3)$$

The conventional BDHC has the limitation for modulation index m_a and duty ratio δ , which is given in the equation (4)

$$\delta + m_a \leq 1 \quad (4)$$

The AC gain increases with the increase of modulation index (m_a) for any fixed value of duty cycle δ .

B. Dynamic Analysis of ZSBHC

The dynamic modeling of the ZSBHC is obtained by KVL and KCL for both the shoot-through interval mode and power interval

mode. In the circuit, V_{idc} is input source voltage, V_c , V_{odc} and V_{oac} are the voltage across the Z-source capacitor, DC filter capacitor and AC filter capacitor respectively. i_L , i_{dc} and i_{ac} are current through the input inductor, DC output inductor and AC output inductor. For shoot-through interval mode shown in the Fig. 5 the set of state differential equations are given in (5) to (10).

$$L \frac{di_L}{dt} = V_c \quad (5)$$

$$C \frac{dV_c}{dt} = -i_L \quad (6)$$

$$\frac{di_{ac}}{dt} = 0 \quad (7)$$

$$C_1 \frac{dV_{oac}}{dt} = -\frac{V_{oac}}{R_1} \quad (8)$$

$$L_d \frac{di_{dc}}{dt} = -V_{odc} \quad (9)$$

$$C_d \frac{dV_{odc}}{dt} = i_{dc} - \frac{V_{odc}}{R_d} \quad (10)$$

For the power interval mode shown in the Fig. 6 the set of differential state equations are given in (11) to (16)

$$L \frac{di_L}{dt} = V_{idc} - V_c \quad (11)$$

$$C \frac{dV_c}{dt} = -i_L - i_{ac} - i_{dc} \quad (12)$$

$$(L_1 + L_2) \frac{di_{ac}}{dt} = V_{idc} - V_{oac} \quad (13)$$

$$C_1 \frac{dV_{oac}}{dt} = i_{ac} - \frac{V_{oac}}{R_1} \quad (14)$$

$$L_d \frac{di_{dc}}{dt} = V_{idc} - V_{odc} \quad (15)$$

$$C_d \frac{dV_{odc}}{dt} = i_{dc} - \frac{V_{odc}}{R_d} \quad (16)$$

5 STATE-SPACE MODELING OF ZS-BHC

The steady state currents i_L , i_{ac} , i_{dc} and steady state voltages V_c , V_{odc} and V_{oac} are accurately computed using the solution of the

averaged state-space differential equation. The state-space general equation is represented as $X^{\&}(t)=Ax(t) +Bu(t)$ and $Y(t)=Cx(t)+Du(t)$ where A, B are the averaged state matrices for ON and OFF period of the switches respectively, and C and D are the input matrices. The averaged state space matrices are given as $A = \delta A_1 + (1\delta)A_2$ and $B = \delta B_1 + (1\delta)B_2$. From the state equations (5) to (10) the ON state matrix are developed in the form of and is given in the equation (17) for the ON period of $2\delta t$

$$\begin{bmatrix} I_L^{\&} \\ V_C^{\&} \\ i_{ac}^{\&} \\ V_{oac}^{\&} \\ i_{dc}^{\&} \\ V_{odc}^{\&} 1 \end{bmatrix} = \begin{bmatrix} 0 & \frac{1}{L} & 0 & 0 & 0 & 0 \\ -\frac{1}{C} & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & -\frac{1}{R_1 C_1} & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & \frac{1}{L_d} \\ 0 & 0 & 0 & 0 & \frac{1}{C_d} & -\frac{1}{C_d R_d} \end{bmatrix} \begin{bmatrix} I_L \\ V_C \\ i_{ac} \\ V_{oac} \\ i_{dc} \\ V_{odc} \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \end{bmatrix} [V_{idc}] \quad (17)$$

and using state equations (11) to (16) the following OFF state matrix are developed in the form of for power interval mode and is given in the equation (18) with the duration of $(1-2\delta)t$

$$\begin{bmatrix} I_L^{\&} \\ V_C^{\&} \\ i_{ac}^{\&} \\ V_{oac}^{\&} \\ i_{dc}^{\&} \\ V_{odc}^{\&} 1 \end{bmatrix} = \begin{bmatrix} 0 & -\frac{1}{L} & 0 & 0 & 0 & 0 \\ \frac{1}{C} & 0 & -\frac{1}{C} & 0 & -\frac{1}{C} & 0 \\ 0 & 0 & 0 & -\frac{1}{L_1+L_2} & 0 & 0 \\ 0 & 0 & \frac{1}{C_1} & -\frac{1}{R_1 C_1} & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & -\frac{1}{L_d} \\ 0 & 0 & 0 & 0 & \frac{1}{C_d} & -\frac{1}{C_d R_d} \end{bmatrix} \begin{bmatrix} I_L \\ V_C \\ i_{ac} \\ V_{oac} \\ i_{dc} \\ V_{odc} \end{bmatrix} + \begin{bmatrix} \frac{1}{L} \\ 0 \\ \frac{1}{L_1+L_2} \\ 0 \\ \frac{1}{L_d} \\ 0 \end{bmatrix} [V_{idc}] \quad (18)$$

Using the equations (17) and (18), the averaged state-space model is developed and is shown in the equation (19)

The Table I show the typical values as in [8] for the ZSBHC circuit.

$$\begin{bmatrix} I_L \\ V_C \\ i_{ac} \\ V_{oac} \\ i_{dc} \\ V_{odc} \end{bmatrix} = \begin{bmatrix} 0 & \frac{4D-1}{L} & 0 & 0 & 0 & 0 \\ \frac{1-4D}{C} & 0 & -\frac{1-2D}{C} & 0 & -\frac{1-2D}{C} & 0 \\ 0 & 0 & 0 & \frac{1-2D}{m_a(L_1+L_2)} & 0 & 0 \\ 0 & 0 & \frac{1-2D}{m_a C_1} & -\frac{1}{m_a R_1 C_1} & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & -\frac{1-4D}{L_d} \\ 0 & 0 & 0 & 0 & \frac{1}{C_d} & -\frac{1}{C_d R_d} \end{bmatrix} \begin{bmatrix} I_L \\ V_C \\ i_{ac} \\ V_{oac} \\ i_{dc} \\ V_{odc} \end{bmatrix} + \begin{bmatrix} \frac{1-2D}{L} \\ 0 \\ \frac{1-4D}{L_1+L_2} \\ 0 \\ \frac{1-2D}{L_d} \\ 0 \end{bmatrix} [V_{idc}] \quad (19)$$

TABLE 1: ZSBHC SYSTEM PARAMETERS

Parameters	Values
V_{idc}	40V
L	160 μ H
C	33 μ F
L_1, L_2	250 μ H
C_1	10 μ F
L_d	250 μ H
C_d	1Mf
R_1	5 Ω
R_d	10 Ω

These numerical values are substituted in the equation (19) and the state matrices are given as

$$A = \begin{bmatrix} 0 & -3750 & 0 & 0 & 0 & 0 \\ 18181.8 & 0 & -24242.4 & 0 & -24242.2 & 0 \\ 0 & 0 & 0 & -5333 & 0 & 0 \\ 0 & 0 & 266666.7 & -66666.7 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & -2400 \\ 0 & 0 & 0 & 0 & 1000 & -100 \end{bmatrix}$$

$$B = [5000 \quad 0 \quad 1600 \quad 0 \quad -3200 \quad 0]^T$$

$$C = [0 \quad 1 \quad 0 \quad 1 \quad 0 \quad 1]^T$$

$$D=[0]$$

After solving the numerical state matrix using m-file coding, the state variables, current through the inductors and voltage across the capacitors are shown in the equation (20)

$$x = [i_L \quad V_c \quad i_{ac} \quad V_{oac} \quad i_{dc} \quad V_{odc}]^T$$

$$= [11.11A \quad 53.33V \quad 3.0A \quad 12V \quad 5.3A \quad 53.33]^T \quad (20)$$

These steady state values are validated through the simulation results. MATLAB/Simulink is used for simulation and the simulated numerical output values are given in equation (21)

$$Outputx = [10.8A \quad 53V \quad 2.83A \quad 14.1V \quad 5.224A \quad 52.4]^T \quad (21)$$

The input and output voltages and currents for ac and dc load are noted and shown in the Fig. 8 and Fig 9. The steady state parameters theoretical values and simulated values are noted in Table II.

TABLE 2: SYSTEM PARAMETERS VALIDATION

Sl.No.	Parameters	Value	
		Theoretical	Practical
1.	i_L	11.11A	10.8A
2.	V_c	53.33V	53V
3.	i_α	3.0A	2.83A
4.	V_{oc}	12V	14.1V
5.	i_{dc}	5.3A	5.24A
6.	V_{dc}	53.33V	52.4V

From the Table 2, it is inferred that the simulated and theoretical values are similar and the simulation results validate the model of ZSBHC.

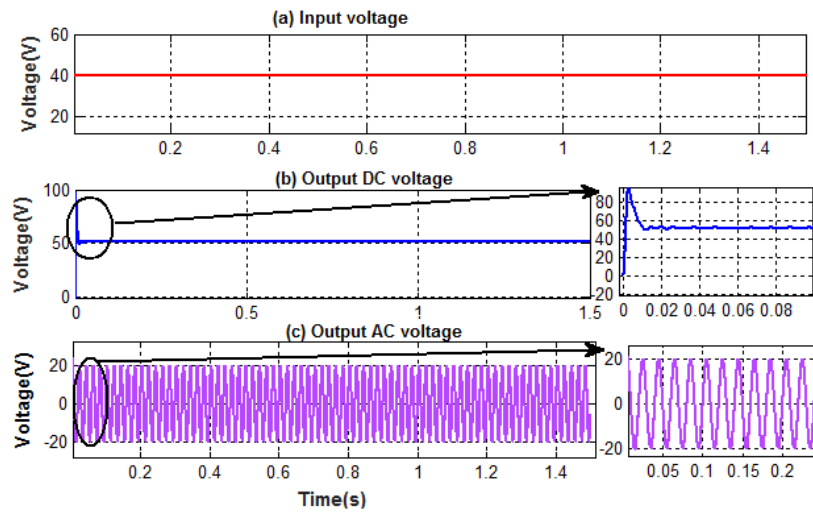


Fig. 8. Input and output ac and dc voltage waveforms of ZSBHC

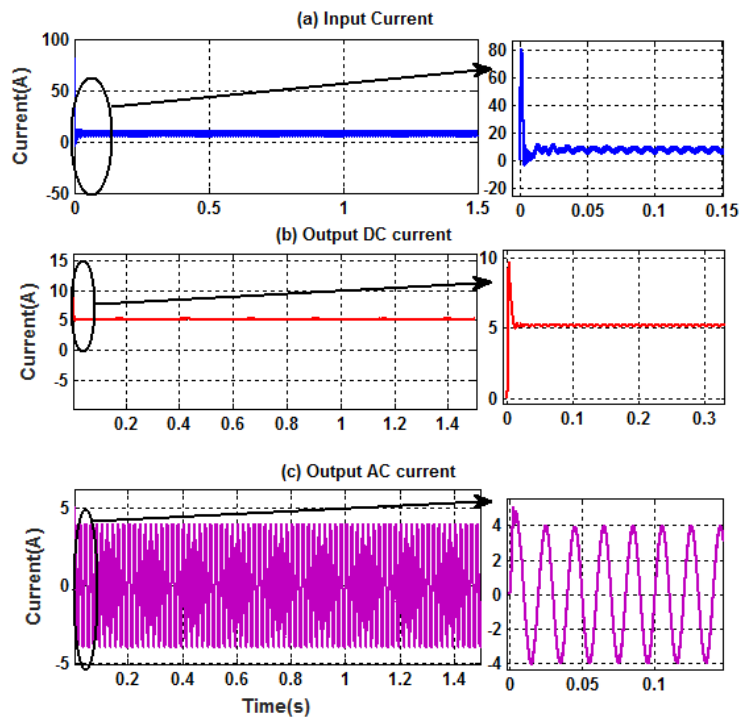


Fig. 9. Input and output ac and dc current waveforms of ZSBHC

6 EXPERIMENTAL VERIFICATION

The characteristics of ZSBHC has been validated with the laboratory prototype. A 320W IGBT based circuit setup is demonstrated for verification. Based on the Table I the components are chosen. The other important components specifications are in the Table 3. The voltage and current sensors are used for the measuring of both the voltage and current. Fig. 10(a) and (b) shows the steady-state open-loop behavior of the BDHC voltage and current waveforms. Considering the input voltage as 40V DC, the output dc voltage of 53V is obtained from the setup for the duty cycle of 0.1. The ac output is 15 V (rms) for modulation index of 0.3. The DC and AC loads are 10 and 5 , respectively. Hence, the prototype serves 265 W DC and 35 W AC loads approximately. Thus, the theoretically calculated voltage and current relationship closely matches the experimentally observed values.

TABLE 3: COMPONENT DESCRIPTION

Components	Manufacturer/No.
IGBT Switches	SKM100GB176d (Semikron)
Diode	30EPH 06 (Vishay)
Driver Circuit	TLP 320 IC
FPGA Board	Spartan 6 (Xilinx)
Voltage Sensor	LV20-P
Current Sensor	LA25-P

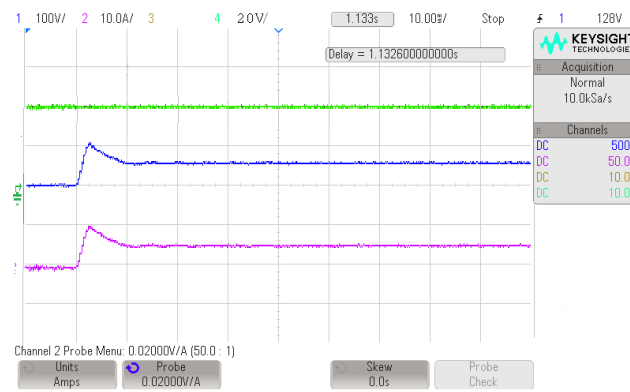


Fig. 10 a. Input and Output DC, AC voltages for 0.1 duty ratio and 0.3 modulation index

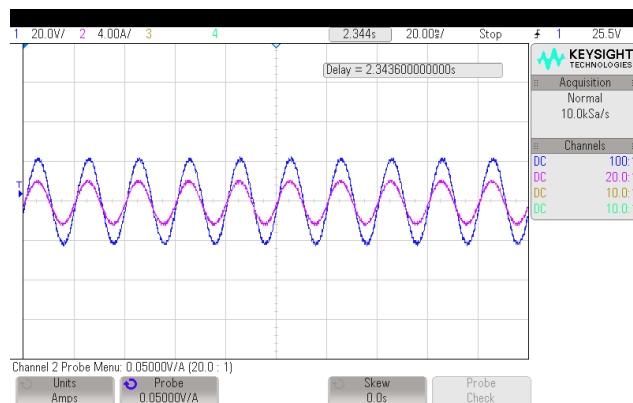


Fig. 10 b. Output AC voltage and current for duty ratio 0.1 and 0.3 modulation index of ZSBHC

7 CONCLUSION

The novel Z-source boost hybrid converter is constructed and the state-space modeling of the circuit is developed. The theoretical value of the model is validated with the simulated results and experimental results. The resulting models are accurate enough and can predict the dynamic behavior of the converter. The ZSBHC performance is better and upgrading the output and is very suitable for the solar PV residential applications. This state-space modeling will be implemented for further analysis and development of the closed loop control of the ZSBHC for the solar PV system.

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