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PV Powered Switched-Inductor Embedded DC-link Impedance-source Inverter System

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ABSTRACT

Background: The traditional embedded impedance-source inverter topology exhibits the disadvantages of low boost factor and higher cost due to additional PV sources. **Objective:** This research paper deals with the performance improvisation of embedded impedance-source inverter topology called Switched-Inductor DC-link Embedded Z-source Inverter (SL-DC-link EZSI). Switched inductor concept is employed to the reduced source DC-link EZSI to achieve the strong boosting ability in terms of short shoot-through period. **Results:** Simulation of PV powered SL-DC-EZSI fed induction motor drive is performed. The operating principle and the topological analysis are given. Boost factor performance, capacitor voltage and DC-link voltages as a function of shoot-through ratio of the SL-EZSI system is compared with the proposed SL-DC-link EZSI system and the results are presented. **Conclusion:** PV powered Switched inductor DC-link EZSI topology is proposed and the results are presented. The propounded topology has the characteristics of high boost ratio, minimum shoot-through period, reduced voltage stress and low cost.

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INTRODUCTION

There has been an unpredictable hiatus between the demand and the production of electrical energy. To meet the requirement is a Himalayan task. The probable solution is to use the non-conventional energy which is available in plenty particularly solar energy. Power Electronic inverters in renewable energy application require both buck-boost capabilities to ride through the load current and supply voltage variation. The conventional VSI have been seriously restricted due to their limited output voltage, shoot-through problems caused by misgating and high rating of switching devices due to low input voltage. Hence a DC-DC boost converter is bridged between the input and the inverter switches to accommodate the wide range of input voltage. This forms two-stage power conversion. Hence VSI is improved to Z-source Inverter (ZSI) and this novel power conversion topology was proposed by Peng (2003). ZSI utilizes a single circuit topology and only one controller to buck-boost the available input voltage. Different topologies and control methods using different impedance source networks has been presented in the literature (Loh *et al.*,2005; Quian *et al.*,2011;Li *et al.*, 2013;Tang *et al.*,2014). Nisha and Basavaraj (2014) reported that the cascaded solution to the PV powered impedance source inverters will also improve the boosting performance. Itozakura and Hirotaka (2011) suggested that in classical ZSI there are some limitations. The input voltage source is discontinuous due to reverse biased diode and hence continuous current will not flow in shoot-through mode. The voltage of Z-source capacitor in ZSI is as high as output voltage. Yam *et al.* (2015) stated that the boost factor of Z-source inverter is not so high and it depends on β, a factor determined by the impedance network chosen. Against these problems, Embedded Z-source Inverter (EZSI) was proposed by Loh *et al.* (2010). Since two PV sources are mandatory in EZSI, this may slightly translates to higher cost. This primary practical constraint of EZSI topology is overcome by using a modified topology, derived from EZSI called DC-link EZ-source inverter reported by Loh *et al.* (2010) and this is in agreement with results obtained by (Nisha and Basavaraj, 2013). In DC-link EZSI the PV source is included in the DC-link and the rear end of inverter bridge. The DC-link EZSI system has symmetric voltage and current distribution throughout the network with one or two sources. Inspite of change of position of the PV source to the DC-link side, the

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advantages of the impedance inverter are still maintained due to the embedded structure and ZSI. In this topology, the capacitor voltage is reduced more than half of the output voltage. But the shoot-through time period of traditional impedance source inverter is high which leads to deterioration of efficiency. Miao Zhu (2010) demonstrated that the performance of the impedance source inverter topologies could be improved by adding the switched inductors. Similar results were reported recently (Nguyen, 2011; Nguyen *et al*., 2013). Hence to enhance the boost performance with minimum shoot-through period and to reduce the voltage stress across capacitors and cost of the embedded topology, a PV powered switched-inductor DC-link EZSI system is proposed.

Modeling of the PV Array:

The demand of energy is increasing day by day and hence the need of secondary energy sources that do not pose any burden to the environment are of great importance. Recent projection states that the demand of energy will be tripled by the year 2050. PV array are built out of tiny identical blocks of solar cells. PV system naturally exhibits a non-linear I-V and P-V characteristics. The solar cells are connected in series and parallel combination on a module to obtain the required voltage. The rated voltage of the PV array is given by the number of cells connected in series and the rated current is given by the number of parallel paths of the cell. An appropriate equivalent circuit of the PV array is generalized and the modules in PV array are arranged with N_p parallel and N_s series and are shown in Figure 1.

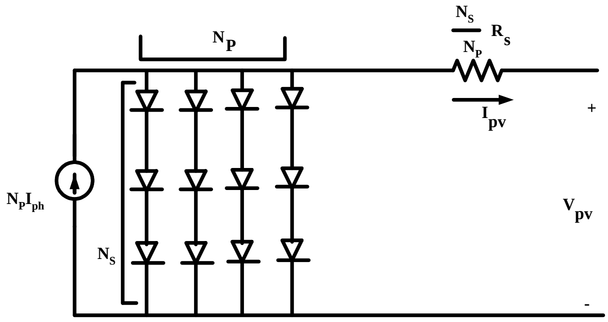


Fig. 1: Equivalent circuit of the generalized model of the PV array.

The mathematical equation of generalized model of an array can be given as

$$I_{PV} = N_P I_{ph} - N_P I_{cs}\left\{\exp\left[\frac{q\left(\dfrac{V_{PV}}{N_S} + \dfrac{R_S I_{PV}}{N_P}\right)}{AkT_C}\right] - 1\right\} \quad (1)$$

Where

I_{ph} - Photo current

I_{cs} - cell saturation of dark current

q - carrier charge $1.6*10^{-19}$ C.

K - Boltzmann's constant $1.38*10^{-23}$ *J* /*C*.

A - Diode Ideality factor.

T_c - Cell's working temperature

R_s - Series Resistance

PV Powered Switched Inductor DC-Link EZSI System:

The DC-link EZSI is an integrated boost-buck converter with a single power processing stage. In this topology instead of embedding the sources within the impedance network, the sources are shifted to the DC-link located between the X-shaped LC network and the switching legs of the inverter bridge. The circuit operates well even with single source. This reduced source DC-link EZSI topology is shown in Figure 2. To enhance the voltage boosting ability of the inverter topology, the switched inductor structure is embedded in the impedance network. SL-DC-link EZSI consists of additional two inductors (L_3 and L_4) and six diodes (D_1,D_2,D_3,D_4,D_5,D_6) placed within the impedance network as illustrated in Figure 3. This circuit topology is a combination of the DC-link EZSI and the SL-ZSI. The operating principle of the proposed inverter is similar to the classical ZSI. To regulate the varying input voltage, SL-DC-link EZSI works in two operational modes as non shoot-through and shoot-through. The inverter operates in inversion mode when the output voltage of solar reaches maximum and hence only buck operation is performed. The equivalent circuit in inversion mode is shown in Figure 4(a). In the active mode, the inverter bridge viewed from the DC side is equivalent to a current source and the inductors L_1, L_2, L_3 and L_4 are connected in series because the diodes D_s, D_3 and D_6 are on. During this mode the PV voltage charges up the capacitor and the inductor voltages are added in series to the solar voltage. On the other hand when the output voltage of PV is reduced below a predefined level, SL-DC-link EZSI operates in any one of seven different ways of shoot-through state performing boost operation, depending on the modulation index and shoot-through duty cycle. The bridge is viewed as short circuit from the DC link of inverter and the equivalent circuit is shown in Figure 4(b). In this mode the inductors L_1, L_2, L_3 and L_4 are connected in parallel as the diodes D_1, D_2, D_4 and D_5 conduct. The energy stored in the passive elements is transferred to the load in the next active state.

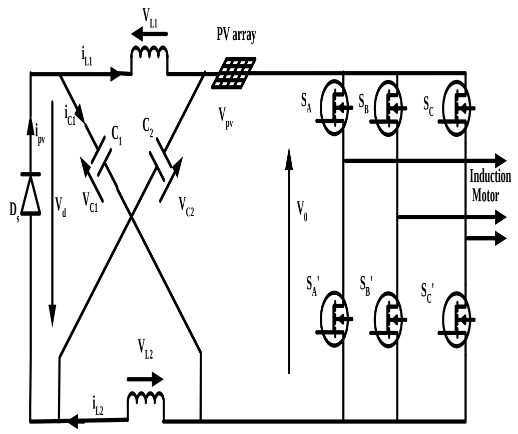


Fig. 2: DC-link EZSI system.

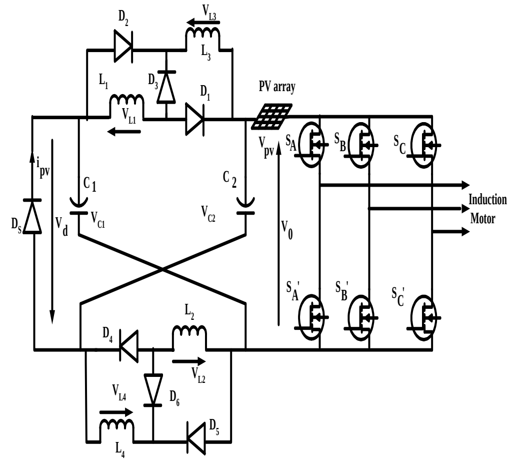
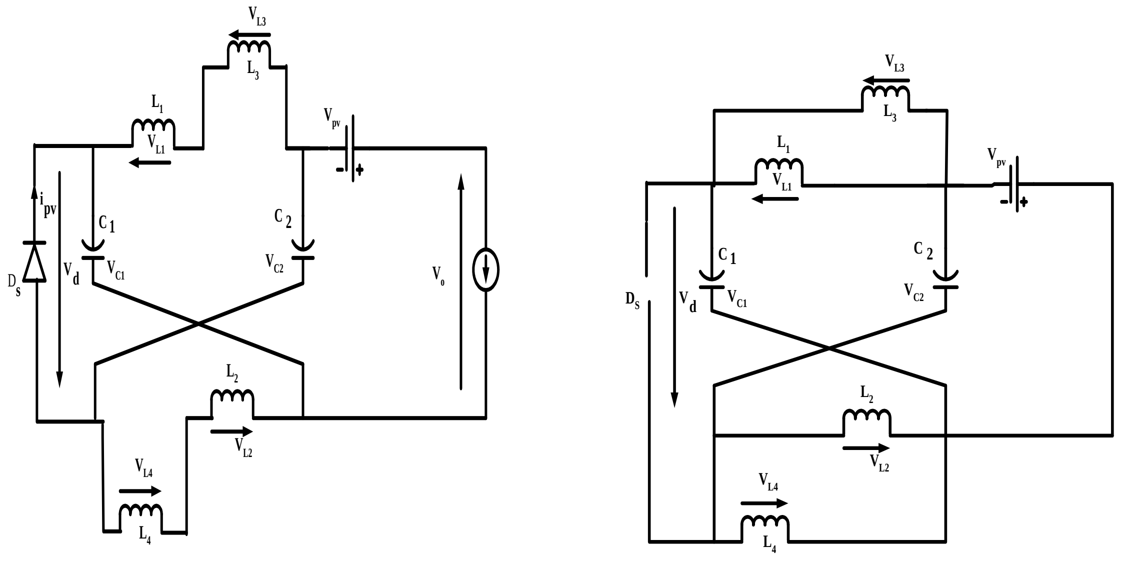


Fig. 3: Switched Inductor DC-link EZSI.



(a) (b)

Fig. 4: Equivalent circuit for SL-DC-link EZSI system (a) Non shoot-through mode (b) Shoot-through mode.

Applying the volt-second balance principle to inductors of SL-DC-link EZSI, we obtain the set of equations in the steady state as

$$V_{C1} = \frac{2\delta}{(1-3\delta)} V_{pv} \tag{2}$$

$$V_{C2} = \frac{(1-\delta)}{(1-3\delta)} V_{pv} \tag{3}$$

The peak DC-link voltage is expressed as

$$\hat{V}_0 = \frac{1+\delta}{1-3\delta} V_{pv} \tag{4}$$

The boost factor of the SL-DC-link EZSI is

$$B = \frac{1+\delta}{1-3\delta} \tag{5}$$

The shoot-through ratio of the SL-DC-link EZSI

$$\delta = \frac{B-1}{1+3B} \tag{6}$$

Peak AC output voltage $\hat{V}_{AC}$ can be derived as

$$\hat{V}_{AC} = 0.5M \frac{1+\delta}{1-3\delta} V_{pv} \tag{7}$$

Where M refers to modulation index and $\delta = T_0/T$, defines the shoot-through ratio per switching period. Equation (5) proves that the boost ability of proposed SL-DC-link EZSI is higher than classical DC-link EZSI system.

PWM Strategy for the Proposed Sl-Dc-Link EZSI:

All traditional PWM schemes can be used to control the impedance source inverter switches. When the output voltage of PV array is high enough to meet the load demands, impedance source inverter operates in traditional VSI mode and hence conventional sinusoidal PWM technique is used to generate gating signals. In this method, a high frequency isosceles triangular carrier wave is compared with three sinusoids of 120° phase shift in three phase configuration and two sinusoids of 180° phase shift in single phase configuration, to generate the gate signals. When the sine wave is greater than the carrier signal, the comparator generates a pulse that can turn on the inverter switches during active mode. When the output voltage of PV module is reduced due to dip in solar irradiation the inverter enters into shoot-through mode and therefore a modified carrier based PWM scheme is employed. During shoot-through mode, top and bottom contours of the sine waves act as upper and lower shoot-through references. These references are compared with carrier waveform to insert shoot-through. In this PWM scheme, the shoot-through states are inserted only in the zero states and the active states are unaltered in order to maintain the sinusoidal output. Also, minimum insertion of shoot-through improves the efficiency with less switching losses. Using the modified carrier based PWM control strategy the obtained boost factor of the PV powered inverter system is

$$B = \frac{4\pi - 3\sqrt{3}M}{-4\pi + 9\sqrt{3}M} \quad (8)$$

The voltage gain (G=MB) is defined by

$$G = [\frac{4\pi - 3\sqrt{3}M}{-4\pi + 9\sqrt{3}M}]M \quad (9)$$

It is observed from (8) that the proposed SL-DC-link EZSI exhibits stronger voltage boosting ability compared with that of classical DC-link EZSI.

Simulation Results and Discussion:

Matlab/Simulink platform is selected to verify the advantages of the proposed SL-DC-link EZSI. The PV controller calculates the correct voltage and current with respect to the maximum power point (MPPT). The PV curve for ASL-P18200 is shown in Figure 5. It is observed that the P_{max} and V_{mp} strongly agree with manufacturer specification. Specifications of the PV module used in the simulation are summarized in Table 1.

Table 1: Specifications of PV module.

Parameter	ASL-P 18200 at STC
Maximum Power(P_{max})	200W
Maximum Power voltage (Vmpp)	26V
Maximum Power current (Impp)	7.692
Open Circuit Voltage(V_{oc})	33V
Short Circuit Current(I_{sc})	8.769A
Number of cell per module (N_s)	54

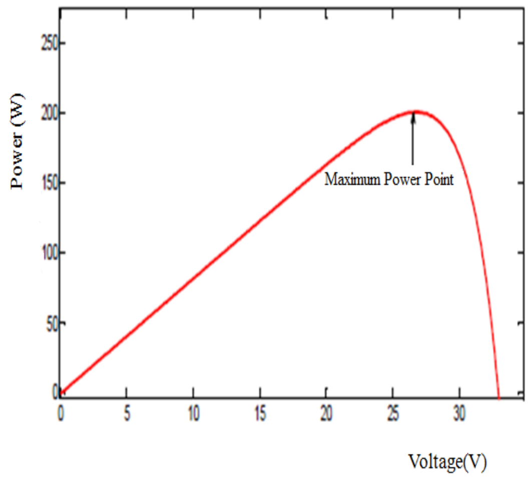


Fig. 5: Volt-Ampere characteristics of PV module.

A. Single Phase SL-DC-Link EZSI System:

Single phase inverter is always preferred for small scale power conversion applications like domestic grid-connected photovoltaic arrays. The output of single phase inverter is applied to the induction motor. The induction motor is represented by its equivalent circuit. The purpose of the system is to control a single phase induction motor whose PV output voltage varies with climatic condition. The parameters are selected as L_1=L_2=L_3=L_4=0.5mH and C_1=C_2=540µF and the initial values of the capacitors are set to zero. The switching frequency was 10 KHz, and the input voltage was V_{pv}=24V. The driving pulses given to the MOSFETS in shoot through state are shown in Figure 6. The output voltage and current waveforms of the system, when the output voltage of PV array is V_{pv}=24V and V_{pv}=220V is shown in Figure 7 and Figure 8 respectively. It is clear from Figures that with varying input voltage, the system could hold the DC-link voltage constant and therefore the output quality is improved. To verify the performance analysis of the inverter, FFT analysis for output voltage is performed and is shown in Figure 9. It is observed that the harmonic spectra value is greatly improved in SL-DC-link EZSI system.

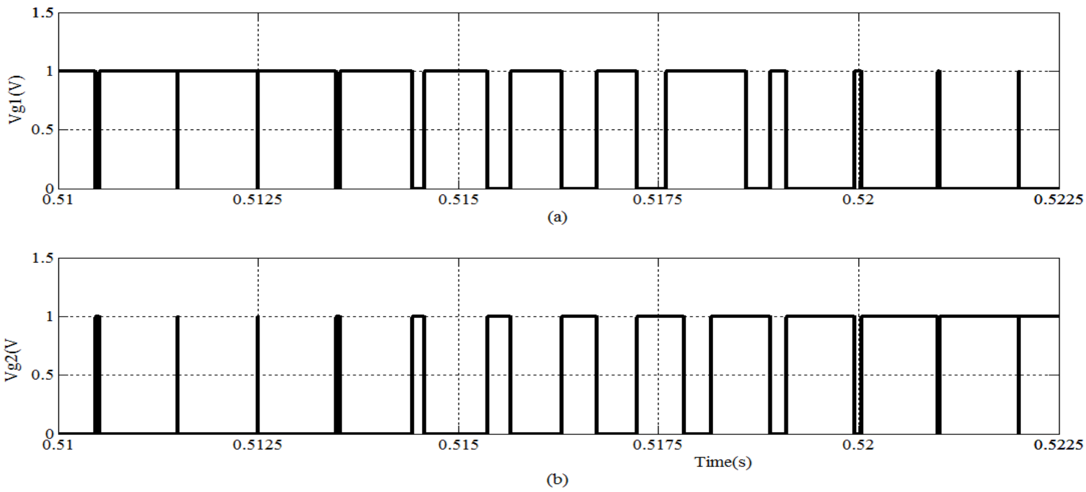


Fig. 6: (a) Gate pulses in shoot-through state for switch S_1 (b) Gate pulses in shoot-through state for switch S_2

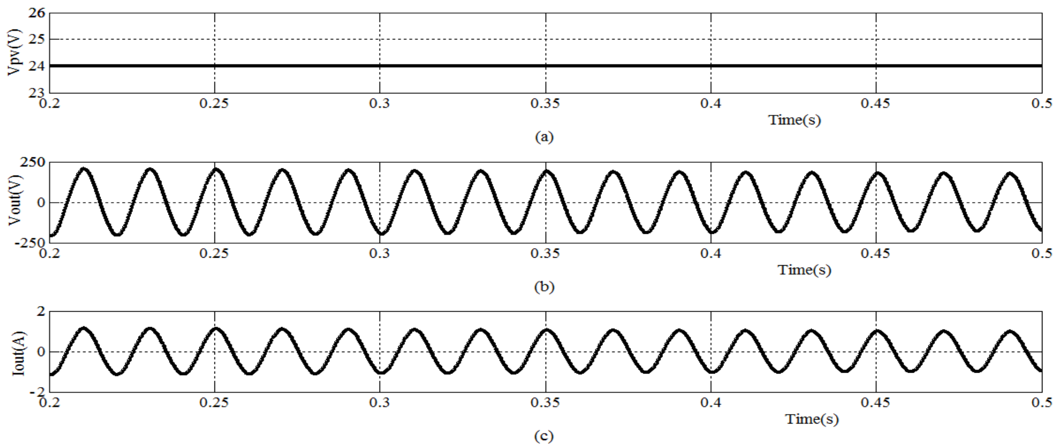


Fig. 7: (a) Output voltage waveform (b) Output current waveform of the single phase SL-DC-link EZSI system with V_{pv}=24V and T_0/T=0.29.

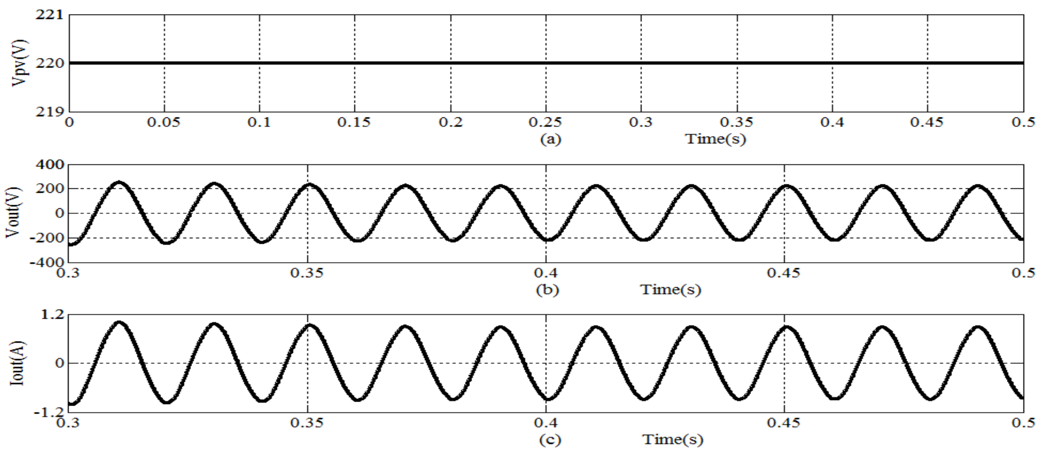


Fig. 8: (a) Output voltage waveform (b) Output current waveform of the single phase SL-DC-link EZSI system with V_{pv}=220V and T_0/T=0.

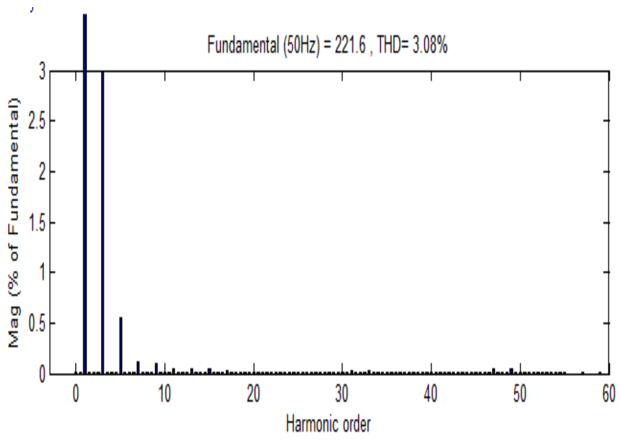


Fig. 9: THD for the voltage waveform.

B. Three Phase SL-DC-Link EZSI System:

Three phase inverters are generally used for high power applications. The gating signals of single-phase inverters should be ahead or delayed by 120º with respect to each other to get three phase balanced voltages. To assess the operational and performance analysis of the PV powered SL-DC-link EZSI fed three phase induction motor, simulation model has been built using Matlab/Simulink package. The system is designed to control the three phase induction motor for PV applications. The parameters were $L_1=L_2=L_3=L_4=1mH$ and $C_1=C_2=1000\mu F$, the initial values of the capacitors are set to zero. The switching frequency was 10 KHz, and the input voltage was $V_{pv}=65V$. A modified PWM carrier method is used to operate the system in shoot-through mode. Modulation index is chosen to be 0.87 to produce the peak line-line output voltage of 400V from the 65V solar voltage. It is noted that the, DC-link voltage is boosted to 488V with a gain of G=6.536 and a reduced shoot-through of δ=0.290, and high boost factor B=7.513. Because of its asymmetry, the voltages across two capacitors are unbalanced. The capacitor voltages are shown in Figure 10.

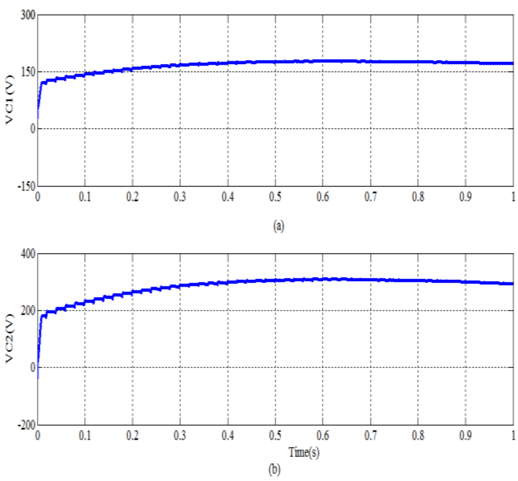


Fig. 10: (a) Capacitor voltage V_{C1} (b) Capacitor voltage V_{C2} when δ=0.290 and $V_{pv}=65V$.

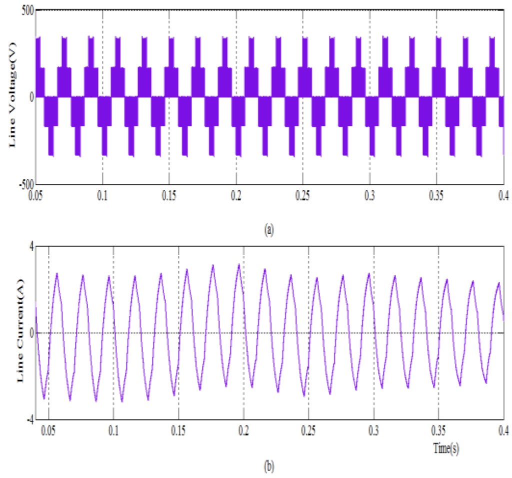


Fig. 11: Line voltage and current waveform of DC-link EZSI system with Vpv=65V and δ=0.290.

The line to line voltage waveform is shown in Figure 11. In the case of classical DC-link EZSI to achieve the same boost factor, the shoot-through required is δ=0.430. Due to increased solar irradiation and temperature variation if the PV module outputs higher input voltage, the proposed system is still able to control the induction motor by keeping the DC-link voltage constant. This is achieved by decreasing the shoot-through period. In this case, BF=3.75, δ=0.224, G=3.26. It is observed that for the proposed system the shoot-through will not exceed approximately one third of the switching period. This is a greater advantage because for a lesser shoot-through, higher boosting ability is obtained. The speed response curve of the system is shown in Figure 12. The rotor speed increases and the rotor speed settles at 1400 rpm and this is achieved after a time period of 0.6 seconds. DC-link EZSI and EZSI systems are compared with SL-DC-link EZSI system. The classical EZSI and DC-link

EZSI systems have the same boost factor. The proposed SL-DC-link EZSI has stronger boost factor than EZSI systems. Boost factor as a function of shoot-through ratio is shown in Figure 13(a). It is observed that proposed system possess higher boost performance. The characteristic of capacitor voltage as a function shoot-through ratio is shown in Figure 13(b). Compared to SL-ZSI and SL-EZSI with same boost factor, the proposed SL-DC-link EZSI has the least capacitor voltage and hence voltage stress across the elements is greatly reduced. For the given shoot-through ratio the DC-link voltage of proposed circuit is higher for a wide range of input voltage as illustrated in Figure 14.

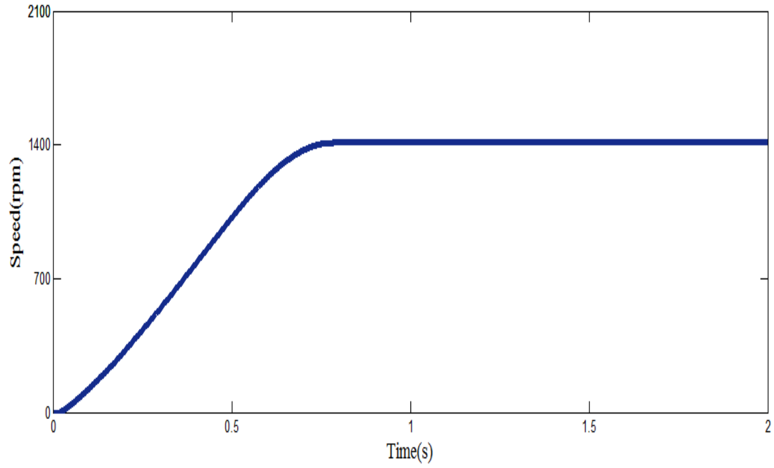
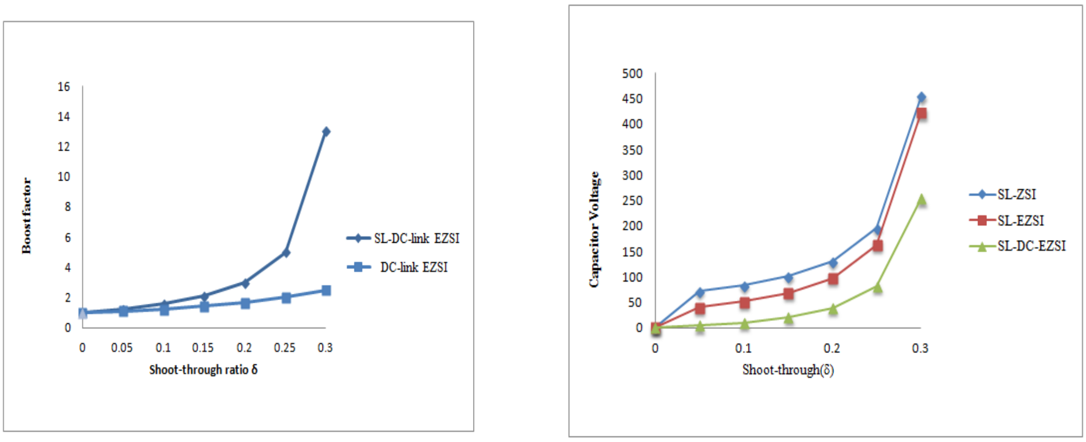


Fig. 12: Rotor speed curve of SL-DC-link EZSI.



(a) (b)

Fig. 13: Characteristics of (a) Boost factor as a function of shoot-through duty ratio (b) Capacitor voltage as a function of shoot-through duty ratio.

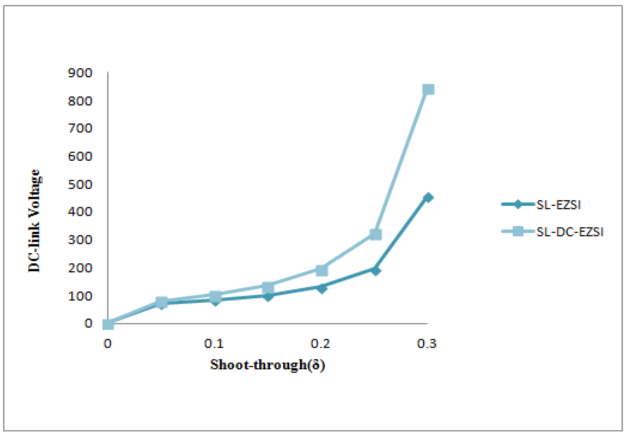


Fig. 14: Characteristics of DC-link voltage as a function of shoot-through duty ratio.

Conclusion:

In this paper, DC-link embedded Z-source inverter with switched inductor has been proposed. The most important aspect of this switched inductor topology is its high boosting ability, less voltage stress across capacitors and short shoot-through period are realized. DC-link voltage as a function of shoot-through duty ratio is theoretically compared for the proposed system and also SL-ZSI and SL-EZSI systems. SL-DC-link EZSI system exhibits the highest DC-link voltage for the given shoot-through ratio. For the same input voltage, proposed system shows higher voltage boost factor than the classical systems. In spite of increased element counts, it is interesting to note that stronger voltage boosting ability is achieved with smaller shoot-through, thereby improving the performance of the overall system. Analytical models are verified using Matlab/Simulink and the results are presented. Operational analysis and mathematical calculations prove that proposed strategy has improved the performance of the impedance-source inverter systems that are more suitable for PV applications.

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