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Analysis of Impedance Source Inverter Topologies for Grid Integration of PV Inverters

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ABSTRACT

In this paper, the performance of different Impedance Source Inverter (ZSI) topologies in implementing single stage power conversion for grid ingetertion of PV power converters is discussed. Unlike the traditional inverters, ZSI employs a distinctive impedance network, there by making shoot-through state is possible. The independent control variables are shoot-through duty ratio and modulation index. Simple Boost Control pulse width modulation technique was used in this work to vary the modulation index. Here the basic operation, simple boost control method, characteristics, requirements and harmonic analysis of the classical Z-Source Inverter (ZSI), TZ-Source Inverter (TZSI), Trans-Z-Source Inverter (Trans-ZSI) and Improved ZSI (IMZSI) topologies were compared for interfacing the wide range variable input energy to utility supply system. The performances were compared based on its MATLAB/SIMULINK simulation model and featured results are shown to confirm its validity.

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1. INTRODUCTION

In conventional voltage source or current source fed Inverters, the main circuit is not the same for buck and boost operations. They can operate either as buck or boost inverter and cannot operate as a buck-boost mode,Whereas ZSI employs a distinctive impedance network and it allows shoot through state in inverter operation which makes both buck and boost operations possible [1]. In recent times, it has been found that ZSI could overcome the theoretical barriers / limitations of the traditional converter and develop into a novel power conversion practice [2]-[4]. With its unique features, the ZSI inverter provides cheaper, simpler, single stage approach for distributed generation integration [5].

To date, many researchers around the globe have reported various ZSI techniques. Some have focused on developing the ZSI into Pulse-width modulation strategies, applications [6], control and modeling [7]-[12] and a few have worked on the development of ZSI topologies. The major difficulties related to voltage source and current source inverters are reduced power conversion efficiency because of the two stage configuration, reduced reliability and their having greater volume and weight [13]. For the wide varying renewable energy sources, ZSI has been projected as a feasible buck-boost inverter for grid-interfacing [14]. With the development of proper control the ZSI operates at any desired output AC voltage [15],[16] or as booster during irregular very low voltages. This paper provides performance analysis by comparison of basic ZSI, Trans-ZSI, TZSI, and IMZSI based on total harmonic distortion of the current, inductor inrush current, capacitor voltage stress, mis-gating-off, rating of passive components, cost and robustness particularly for grid integration of renewable energy sources.

In the distribution network integration systems the ZSI, basically the Z-Source network with a specific impedance acts as an interface between the renewable energy source output and three phase inverter [17]. Here six IGBT switches and six diodes are utilized. The output voltage is controlled using PWM control signal. The switching legs may contain the additional zero state.

2. VARIOUS Z-SOURCE INVERTER TOPOLOGIES

The normal Z-Source network has two inductors in series and two capacitors in parallel arm in the form of a bridge network. In TZSI the two inductors are replaced by transformers. By changing the turn ratio of the transformers very high boost voltage inversion ability with a very low shoot-through duty ratio is attained. Trans-Z-source inverter (TZSI) is being derived from the voltage/current fed Z or quasi-Z-Source Inverters to obtain a higher boost gain with the same shoot-through duty ratio and modulation index. Later Improved Z-source inverter is derived to limit the capacitor voltage stress and inductor inrush current.

2.1. Conventional Z-Source Inverter

A classical Z-source network consists of two identical inductors (L_1, L_2) and two identical capacitors (C_1, C_2). The Z-Source network connects the inverter main circuit with the variable voltage source as shown in Figure 1. The Z-Source Inverter is used to reduce the voltage stress and current ripples. The requirement of inductor and capacitor should be less compared with voltage source inverters. When the values of the inductors (L_1 and L_2) are small and move near zero, the Z-Source network reduces the number of capacitors.

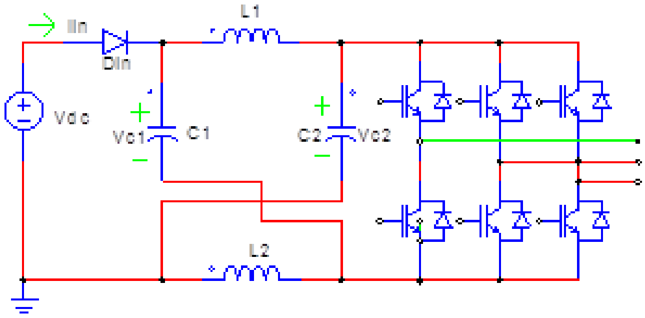


Figure 1. Z-Source Inverter

Similarly, when the values of the two capacitors (C_1 and C_2) are small and move near zero, the Z-Source network reduces to two inductors (L_1 and L_2) in series and becomes a traditional current source inverter. The size of the inductor is smaller than the conventional current source inverters.

2.2. TZ-Source Inverter

The TZ-Source inverter is shown in Figure 2 where the inductors in the conventional ZSI are replaced by the transformers. It consists of one diode (Din), two capacitors (C_1 and C_2) and two transformers (T_1 and T_2). The turns ratio of the transformers is defined as $N_i = N_{i2}/ N_{i1}$, where i = 1 and 2 represents T_1 and T_2.

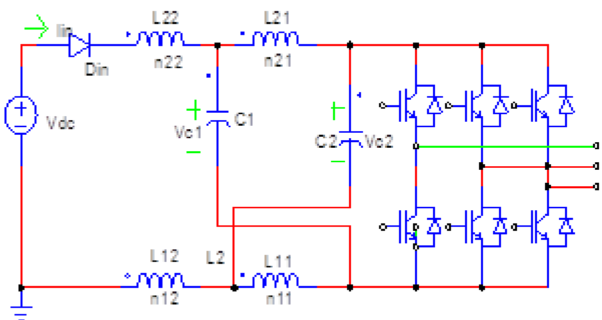


Figure 2. TZ-Source Inverter

In TZ-Source Inverter, the basic Z-Source impedance network structure is same as Z-Source Inverter and additional two transformers are used to vary the boost factor. The boost factor can be varied by varying the turns ratio of the transformer.The more efficient input current profile with less voltage stress can be attained by extending the TZ-Source Inverter to the quasi or embedded ZSI. Owing to voltage and current spikes in TZ-Source Inverter, the large startup resonant current is produced and it may destroy the devices. This is the major problem of TZ-Source Inverter. The current and voltage spikes are generated by the transformer’s windings and capacitors.

2.3. Trans-Z-Source Inverter

Figure 3 shows the voltage fed Trans-Z-Source Inverter. It has two DC inductors which can be coupled or separated. Also it has continuous input current; the inductors are coupled as shown in Figure 3. Owing to the magnetic coupling between the two inductors, the voltage across the inductor L_1 is appeared to the inductor L_2. Therefore, any one of the capacitors, for example C_2, can be removed from the circuit. When the turn’s ratio N_2/N_1 is changed, then the voltage across L_2 can be so adjusted as to be proportional to the voltage across L_1. Like the Z-Source Inverter, the Trans-Z-Source Inverter has an extra shoot-through zero state besides the six active states and two traditional zero states.

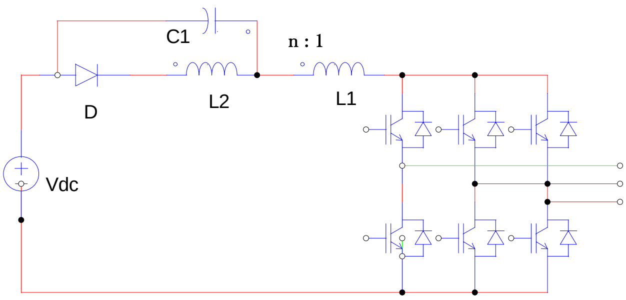


Figure 3. Trans-Z-Source Inverter

2.4. Improved Z-Source Inverter

Figure 4 shows the Improved Z-Source Inverter. In the traditional inverter, the inverter bridge is connected in parallel with the Z-source network, while in the IMZSI, the inverter bridge is in series with the Z-Source network. Another difference is that the positions of the Inverter Bridge and the diode are interchanged and their connection direction is reversed. The voltage polarities of the Z capacitors are same as the input voltage polarity; therefore, the Z capacitors voltage stresses are greatly reduced and the same boost voltage is produced across the inverter bridge. This topology has inherent inrush-current limitation ability.

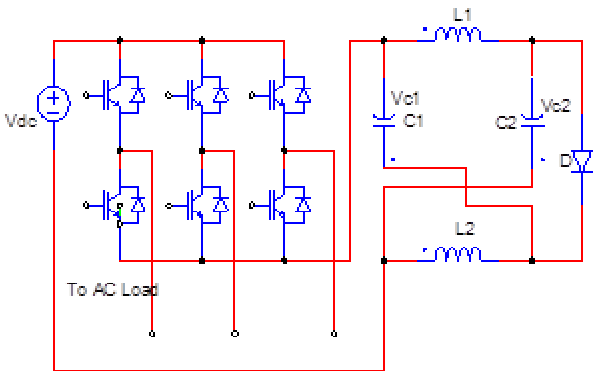


Figure 4. Improved Z-Source Inverter

The impact of the phase leg shoots through is analysed. After simplification the average of the voltage across a Z-source inductor over a switching period (0 to T) is given by

$$V_L = \frac{T_1}{T_1 - T_0} V_{dc} \quad (1)$$

B is a boost factor, T-Switching period, the impedance source inverter output voltage is given by

$$V_{ac} = M \frac{V_i}{2} = B.M \frac{V_{dc}}{2}$$

In the conventional converter,

$$V_{ac} = M.\frac{V_{dc}}{2} ,$$

Where, M is modulation index and V_{dc} is DC input voltage

The output voltage can be boosted or reduced by selecting an appropriate Buck –Boost factor

$$B_B = B.M , \quad (2)$$

Where B_B is Buck Boost factor varying from 0 to α.

The boost factor is controlled by the shoot through zero state duty cycle. The modulation index determines the zero state periods. The magnetizing inductance is very important in theTZ-Source Inverter. Magnetizing Inductance Design,

$$L_{m1} = L_{m2} = \frac{D(1-D)TV_{dc}^{2}}{(1+N)[1-2ND]P_0} \quad (3)$$

In the case of Trans-Z-Source network, during shoot-through zero state, the peak value of the phase voltage is given by

$$\hat{V}_{ph} = M\frac{V_i}{2} = M.B\frac{V_{dc}}{2} , \quad (4)$$

Where, M is the modulation index. Voltage gain is

$$G = MB = \frac{M}{M - (1+n)\left(1 - \frac{\sqrt{3}}{2}M\right)} \quad (5)$$

If the turns ratio is 1, then the inverter boost gain of DC link voltage is same as that of conventional Z-Source Inverters, but in the new Trans-Z-Source network, one capacitor is saved. If the turns ratio is above 1, it produces the same AC output voltage as Z-Source Inverter and it requires a smaller shoot-through duty ratio Dsh. This is the major advantage of Trans-Z-Source Inverter. In improved Z-Source Inverter during shoot through mode, there will be linear increase in the voltage which equates inductor voltage and the capacitor voltage. During shoot-through the capacitor charges the inductors and current through the capacitor equals the current through the inductor. The calculation of inductance and capacitance plays a vital role in the design. Therefore the required capacitance was found to be

$$C = \frac{I_{L(avg)}T_0}{\Delta V_C} \quad (6)$$

Calculation of required inductance is done by using the formula,

$$L = \frac{T_0 V_C}{\Delta I_L} \tag{7}$$

Table 1 and Table 2 show the simulation parameter of interfacing device with the various inverters.

Table 1. Source Parameters

Parameter	Value
PV Panel Voltage (Single)	16.54 V
PV Panel Current (Single)	2.25 A
Grid Voltage	415 V
No. of Cells (single PV Panel)	36 in series
PV array size	14x2
PV array Voltage	230V
PV array Current	4.5A

Table 2. Parameters of different inverter topolgies

Inverter topology	Inductance	capacitance	No. of Transformers
ZSI	L_1=L_2=1nH	C_1=C_2=2nF	NA
TZSI	NA	C_1=C_2=1nF	2
Trans-ZSI	NA	C=320µF	1
IMZSI	L_1=L_2=1nH	C_1=C_2=2nF	NA

3. PULSE WIDTH MODULATION TECHNIQUE

Simple boost control PWM technique is used in Z-Source Inverter, which adds shoot through in all the conventional zero states. The simple control method is illustrated in Figure 5 in which only two straight lines are used to identify the shoot through. The pulses for the six switches are shown. Shoot through duty ratio (Do) decreases with rising modulation index (M).

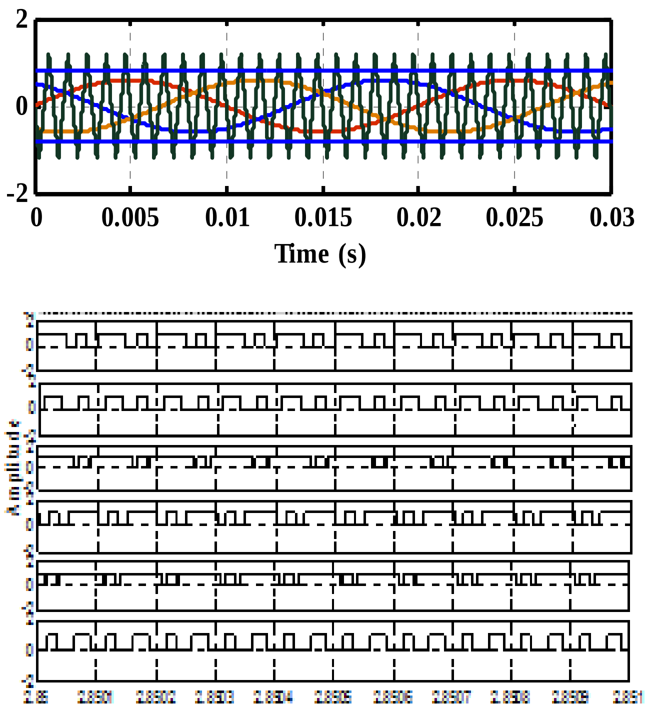
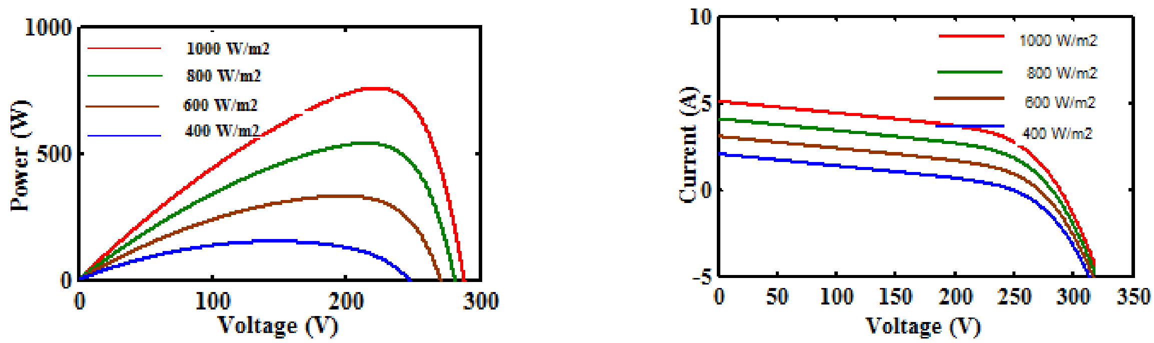


Figure 5. Switching sequence with Simple Boost Control PWM Technique

4. SIMULATION RESULTS AND DISCUSSION

The Z-Source topologies were modeled and performance outputs of the solar fed grid connected Z-Source Inverters were studied with three phase full bridge inverter using PWM switching technique as MATLAB/SIMULINK model [18]. In general the outputs of inverter are connected to the grid by means of L and C filter. Grid is a voltage source of infinite capability. The variable energy input was modeled as a variable voltage source. The simulation output voltages and currents were obtained for all the four inverters. The current Total Harmonic Distortion was calculated for all inverter topologies by performing Fourier analysis by Fast Fourier Algorithm (FFT).

The PV system was modelled using single diode model as discussed in [19]. The array size of 14 x 2 was used to obtain the desired voltage of 230 V. The VP and the VI characteristics are shown in Figures 6 (a) and (b) respectively.



(a) (b)

Figure 6. (a) V-P curves (b) V-I curves of solar panel for various irradiations

Figure 7 shows the simulated circuit of Z-Source Inverter fed grid connected PV system. The phase to phase output voltage and current waveforms of Z-Source Inverter are shown in Figures 8 (a) and (b) respectively.

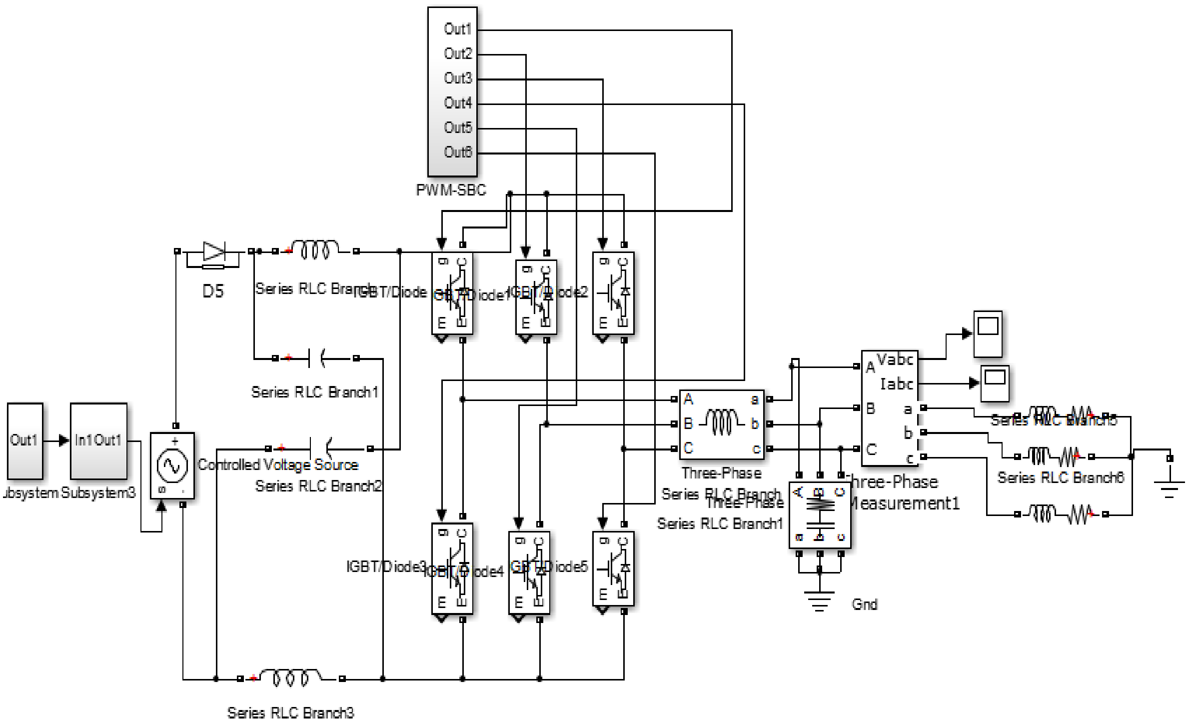
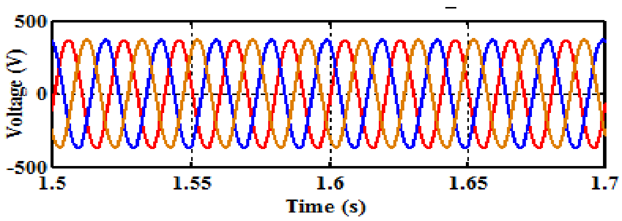
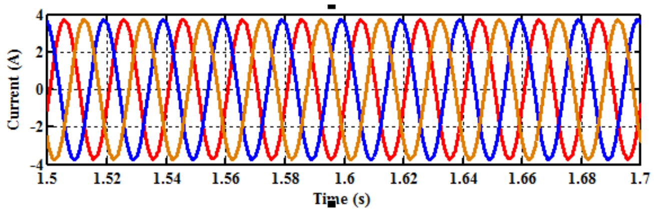


Figure 7. Simulation circuit of grid connected solar fed Z-Source Inverter



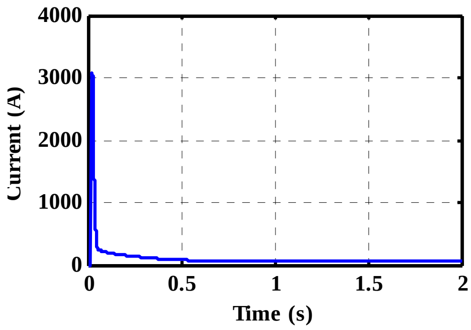
(a)

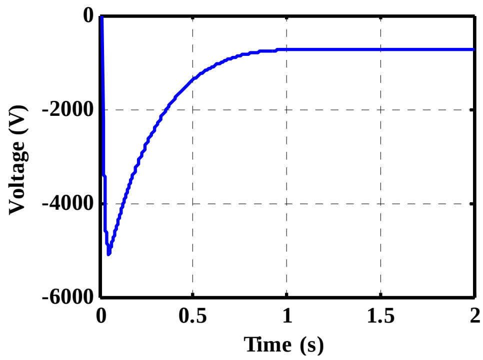


(b)

Figure 8. (a) Phase to phase voltage of output waveform (b) Output phase current of Z-Source Inverter

The inrush current and the capacitor voltage stress of Z-Source inverter are shown in figures 9 (a) and (b) respectively.





(a) (b)

Figure 9. Z-Source Inverter (a) Inrush current (b) Capacitor voltage stress

FFT analysis of Z-Source Inverter is shown in Figure 10. The total harmonic distortion was found to be 1.17%. Figures 11 (a) and (b) shows the inrush current and capacitor voltage stress of TZ-Source Inverter.

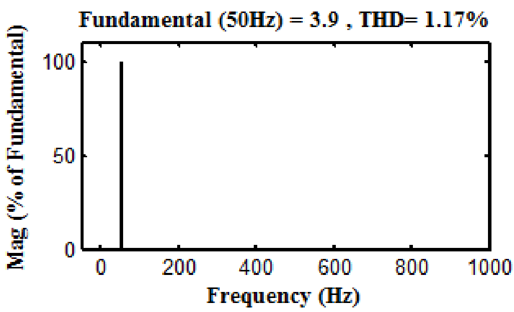
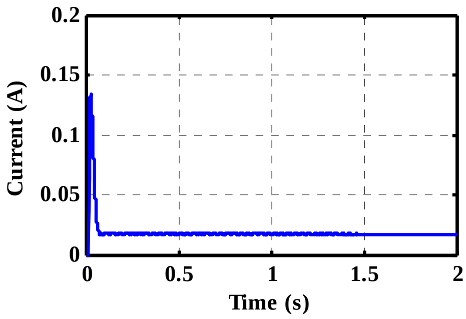
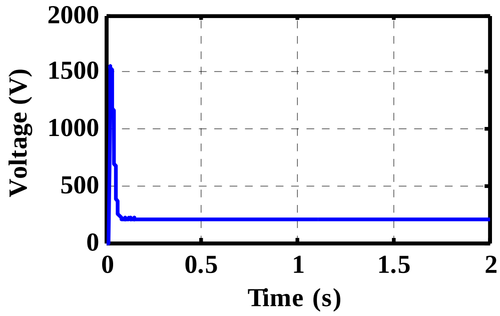


Figure 10. FFT analysis of Z-SourceInverter



(a)



(b)

Figure 11. TZ-Source Inverter (a) Inrush current (b) Capacitor voltage stress

FFT analysis of TZ-Source Inverter fed grid connected PV system is shown in Figure 12. The total harmonic distortion was found to be 15.18 %.

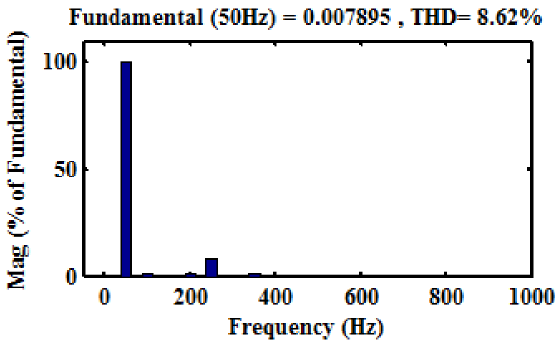
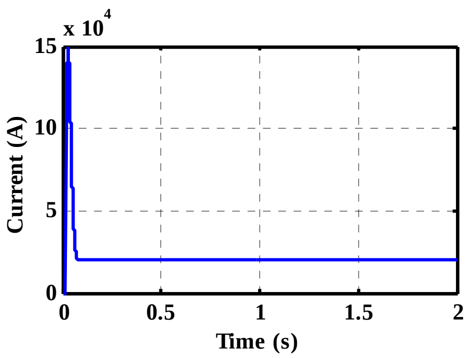
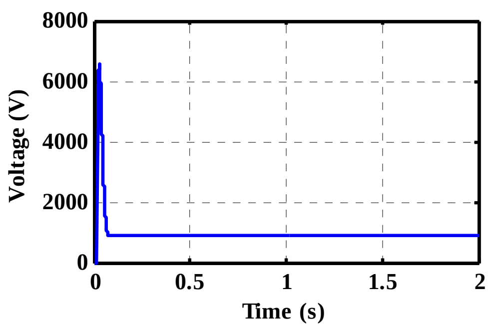


Figure 12. FFT analysis of TZSource Inverter

Similarly the inrush current and the capacitor voltage stress of Trans-Z-Source Inverter are shown in Figures 13 (a) and (b) respectively.



(a)



(b)

Figure13. Trans-Z-Source Inverter (a) Inrush current (b) Capacitor voltage stress

FFT analysis of Trans-Z-Source Inverter fed grid connected systemis shown in Figure 14. The total harmonic distortion was found to be 0.94 %.

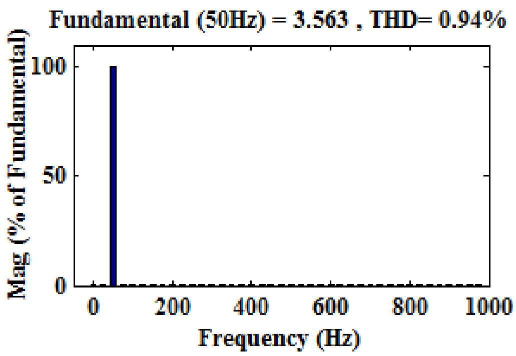
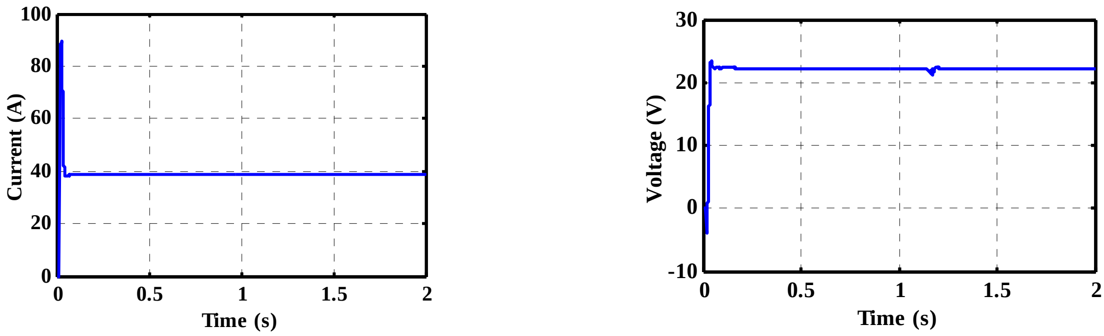


Figure 14. FFT analysis of Trans-Z-Source Inverter

Similarly Figures 15 (a) and (b) show the inrush current and the capacitor voltage stress of Improved Z-Source Inverter.



(a) (b)

Figure 15. Improved Z-Source Inverter (a) Inrush current (b) Capacitor voltage stress

FFT analysis of Trans Z-Source Inverter fed grid connected systemis shown in Figure 16. The total harmonic distortion was found to be 3.09 %.

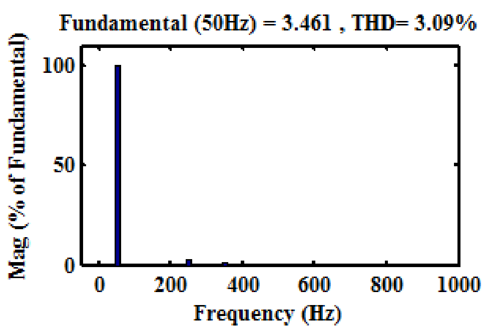


Figure 16. FFT analysis of Improved Z-Source Inverter

From the simulated results with a comparison of ZSI, TZSI, Trans-ZSI, and Improved ZSI are presented in Table 3.

Table 3. %THD Comparisons of ZSI, TZSI,Trans-ZSI, and IMZSI

INVERTER TYPE	Current THD %
ZSI	1.17
TZSI	8.06
Trans-ZSI	0.94
IMZSI	3.09

5. CONCLUSION

The simulation of Z-Source, TZ-Source, and Trans-Z-Source, and Improved Z-Source Inverters was carried out using MATLAB/SIMULINK software and output waveforms were obtained. From the THD analysis, it was clear that for the same setup and filter circuit, the Trans-Z-Source Inverter (TZSI) had less harmonic disturbance than the basic ZSI, TZSI, and IMZSI. The maximum possible boost gain could be obtained in Trans-Z Source Inverter when the transformer ratio was greater than one. The capacitor voltage stress and the inrush current were also be measured for all the Z-Source Inverter topologies and it was found that the improved Z-Source Inverter had very less inrush current and the capacitor voltage stress when compared with the other Z-Source Inverter topologies.

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