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ORIGINAL ARTICLE

Performance evaluation of Z-source inverter and voltage source inverter for renewable energy applications

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Abstract

There have been a technological advancement in the traditional current source inverter (CSI) and voltage source inverter (VSI), by reducing the number of power processing stages as well as reducing the number of components used in the system; impedance network does it all, whereas in case of traditional inverter complex circuitries are required to buck and boost the input DC voltage. Some modifications have been done in traditional pulse width modulation (PWM) pulses to achieve shoot-through pulses, which is only suitable for the Z-source inverter, (in VSI and CSI, it may destroy the inverter bridge due to short-circuiting) for boosting or bucking of input DC voltage. Impedance network consists of passive elements which help in converting direct current (DC) to alternating current in a single stage. This paper compares conventional as well as the up-coming Z-source inverter and discusses operating modes of the Z-source inverter, mathematical equations, and different pulse width modulation techniques. ZSI is the most suitable configuration for solar photovoltaic applications where sunlight is abundantly available. Simulink modelling is done using software MATLAB. A laboratory prototype is prepared and the results are verified. Spartan-3E is used for giving PWM pulses for voltage source and Z-source inverter.

Keywords Solar photovoltaic inverter · Single stage · Renewable energy application · Total harmonic distortion

Introduction

At every point of time, power generation has been a task and using it efficiently is a bigger task. Conventional power generation sources such as coal, oil and gas are depleting and will end sooner or later. These types of sources are stable in power generation, but at the same time, they are destroying the nature and creating problems in the environment. So researchers found a way to cope up with this problem. The solution is renewable energy. As the name suggest energy which will last for ever, such as hydro, wind, and solar. These three are the main renewable energy sources and we had preferred solar energy above all, as it is abundant in nature and the technologies to harness it is mature enough. Sunlight helps in many ways to do our daily work, and apart from it, it is also used for generating of electricity. Solar cells made of silicon are used to generate electricity. Sunlight is made incident on solar cells which influences the change in energy levels of the valence electrons inside the solar cell, which in turn leads to flow of electrons from anode to cathode, thus generating electricity. Solar cells made of silicon are used to generate electricity. Sunlight is made incident on solar cells, by which the temperature of solar cell increases leads to flow of electrons from anode to cathode, thus generating electricity. The best part of using solar energy is unavailability of any rotational part which makes the life of system quite high in respect to others. But the generated power from solar cells is DC (direct current) in nature, and as we all know the equipment's used in our daily life, either in residential or commercial applications, works on AC (alternating current), so we require a combination of active and passive components such as inverters. An inverter is a device composed of several passive and active components which converts DC to AC and makes it usable by the consumers.

Inverters are classified into three types VSI (voltage source inverter), CSI (current source inverter), and ZSI (Z-source inverter). Among these three topologies, voltage source inverter and current source inverter are the conventional topologies having merits and de-merits. VSI is a voltage-fed inverter which has a smaller value of the source impedance. A

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ripple-free DC voltage source is fed as an input to the inverter. In case of AC as an input, a controlled rectifier is used to convert AC into DC and then it is fed to the inverter. The available inverters in the literature as well as in the commercial market are of two types—single-phase inverter and three-phase inverter. Mostly, in industrial and commercial purpose, three-phase inverters are used, whereas in residential purpose, single-phase inverter is used. For industrial purpose, for some applications variable output voltage from the inverter is essential which is used to supply explicit loads which requires frequency variation such as induction motor. The basic nature of the voltage source inverter is buck in nature. The output of the voltage source inverter (VSI) is limited and cannot exceed the available input voltage. So any additional boost converter or DC–DC converter is required for boosting up of input DC voltage. Boost converter itself employs number of passive devices which leads to more passive devices in the circuit and it leads to complex circuitry. These types of systems are two-stage systems, in which first boosting of DC voltage is done and in second stage conversion of DC voltage into AC voltage is processed using inverter or multilevel inverters. In case of current source inverter, the current from the available DC source is maintained at a constant level, heedlessly of connected load. A large inductance is employed, in case of CSI is employed, in series with the DC source to lower down the high value of di/dt. A controlled rectifier bridge is used for feeding DC input to the CSI from fixed AC source. Commutation, in case of CSI, depends on power factor. In case of leading power factor, load commutation and in case of lagging power factor, forced commutation is possible. In case of CSI commutating, capacitors are used for forced commutation. This research paper looks into the inversion of power (DC–AC) and boost action of the inverter section, using the state-of-the-art impedance source inverter or Z-source inverter (ZSI) technology. When compared to the traditional topologies, Z-source topology offers abridged topology, i.e. system having single power processing stage (conversion of DC–AC in a single stage). Not only this, the system is having an added advantage that even during shoot-through (closing of two switches from same leg), the rise in current cannot destroy the system. Z-source topology eliminates maximum problems which are found in VSI and CSI. Lastly, Z-source inverters can step-up and step-down the voltage. (Kulka and Undeland 2008; Shen et al. 2007; Kerekes et al. 2008; Farhangi and Farhangi 2006; Peng et al. 2003; Peng 2003; Tran et al. 2007).

Comparison of inverter topologies (VSI/CSI and ZSI)

There has been advancement in traditional inverters (CSI and VSI) after the evolution of impedance source. The Z-source inverter consists of two-port network [combination of inductance (L) and capacitance (C)] which links the inverter and the DC input power, therefore reduces the problems faced in conventional inverter (VSI/CSI). Z-source inverter does the boosting and bucking of the DC voltage generated through PV array, i.e. the output voltage of the inverter can be greater than the input DC voltage, and also it can be lower than the input DC voltage. Figures 1 and 2 depict the traditional (VSI/CSI) inverters. (Kerekes et al. 2008; Shen et al. 2007; Faruqui and Anwer 2017; Hanif et al. 2011).

Problems faced by conventional inverter (VSI/CSI) are:

- The operation of the conventional inverter is either buck in (VSI) mode or boost in (CSI) mode. An additional circuitry is implanted before the inverter to make it work as a buck–boost inverter, which leads to higher number of components and complex circuitry.
- Cautiously designing of gate drivers for the conventional inverter is required; so that EMI-induced false gating of switches can be avoided, else there could be a shoot through in voltage source inverter or it may be an open inductor circuit in case of current source inverter, which will put an end to the system due to high voltage.
- High voltage stress and current stress across the switches.
- In case of CSI, overlap time, and in case of VSI, dead time may lead to distorted wave.
- The power circuit for the conventional inverter (VSI/CSI) is not interchangeable.

The above drawbacks in the conventional inverter are minimised with the addition of DC–DC converter sandwiched among inverter and input DC source. This type of system uses two conversion stages, that is, first boosting of DC power using DC–DC boost converter, and second, converting DC–AC using Inverter Bridge. These types of system are dual-stage systems. The overall conversion efficiency is lower due to additional circuitry, which increases the system size, cost and weight, also distortion in the output waveform is generated because of dead time. (Kerekes et al. 2008; Farhangi and Farhangi 2006) Comparative

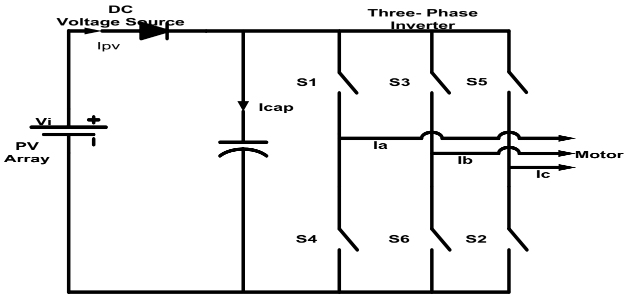


Fig. 1 Circuit diagram of VSI (Farhangi and Farhangi 2006; Shen et al. 2007)

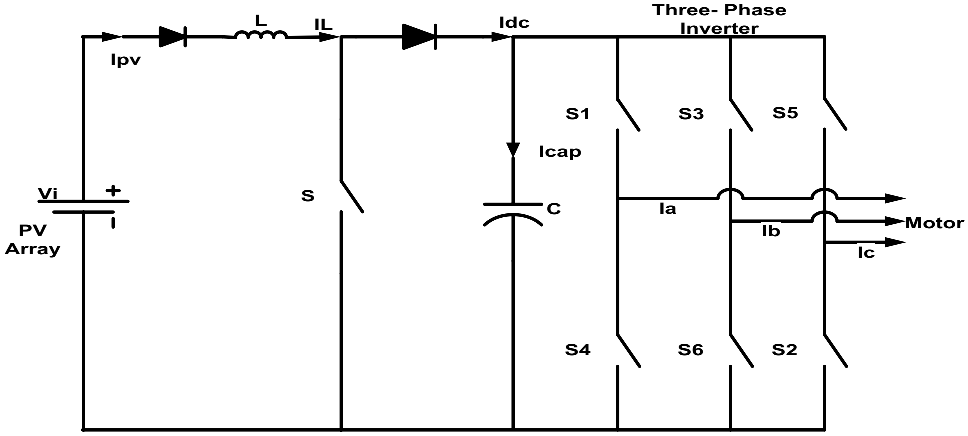


Fig. 2 Circuit diagram of VSI with boost converter (Farhangi and Farhangi 2006; Shen et al. 2007)

analysis of traditional and impedance source inverter on the basis of component count, complexity, voltage stress and THD is the main aim of this research article. Just using two inductors (L) and two capacitors (C) called impedance source network between the inverter bridge and the input DC source, all the above mentioned drawbacks can be removed without any extra switch. Impedance source network act as a second-order filter which suppresses the voltage ripple efficiently compared to the large capacitors and inductors required in traditional inverters (VSI/CSI) to shrink the harmonics present in the current as well as reducing inrush current. Furthermore, the conventional PWM switching techniques are utilised by the addition of shoot-through pulses in the course of zero states which help in boosting of input DC voltage generated by PV array (Peng 2003; Shen et al. 2007; Tran et al. 2007; Peng et al. 2005).

Efficiency

The amount of useful work did by a machine or a device is said to depend on its efficiency. Efficiency is one of the important parameters for rating the device, correctly. Types of semiconductor switches used, type of pulse width-modulated technique deployed, and a number of passive components used, totally contribute to the overall efficiency of the power conditioning unit. Fuel cell as an input source is used for three different types of inverter topologies and an efficiency contrast is showed by 'Oak Ridge National Laboratory' in (Peng 2003). Some points discussed are:

- Traditional inverter or PWM inverter functions at modulation index (M) of 1
- Dual-stage system or PWM inverter with DC–DC converter boost the input DC voltage to 420 V
- The output of the impedance source inverter is the maximum obtainable voltage while maintaining the switch voltage less than 420 V

The passive elements used to model inverters in (Peng 2003; Shen et al. 2007) is shown in Table 1.

This research paper is all about inverter's configuration using single DC source or multiple DC sources such as PV, battery, and fuel cell. It is to be noted that the efficiency for Z-source inverter drops down at low loads when connected to it. But at the same time for higher power rating system, Z-source inverter offers highest efficiency among the presented inverters. This could be an important feature of the Z-source inverter and making it different in the crowd. Overall, Z-source inverter offers boosting of input voltage by a practical factor of 1.4–2, by reducing the cost of the system, decrease in the size of the system and maintain the efficiency at the highest. Also, with these features, it is capable of tracking maximum power (Peng et al. 2005). The boost factor when compared with other conventional topologies is less when compared to ZSI. This paper gives a comprehensive review on performance of Z-source inverter with other inverters utilised for converting DC–AC for PV applications (mostly for stand-alone type). This section is focussed on Z-source inverter in detail in terms of shoot through, boost control method, circuitry, L and C design and selection of device (Deshpande et al. 2014; Sharma et al. 2016; Hossam-Eldin et al. 2017; Yadav et al. 2017; Islam et al. 2016).

Table 1 Number of passive elements used in traditional and Z-source inverter

Inverter system	Number of inductors (L)	Number of capacitors (C)
Conventional PWM inverter	0	1
DC/DC boost PWM inverter	1	1
Z-source inverter	2	2

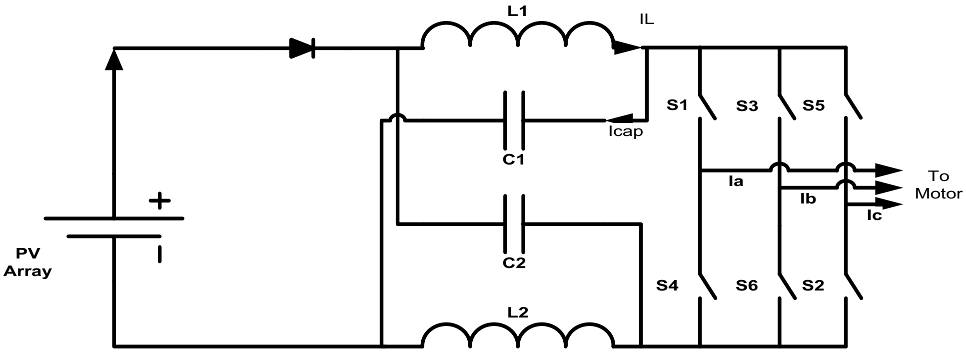


Fig. 3 Circuit diagram of Z-source inverter (Farhangi and Farhangi 2006; Shen et al. 2007)

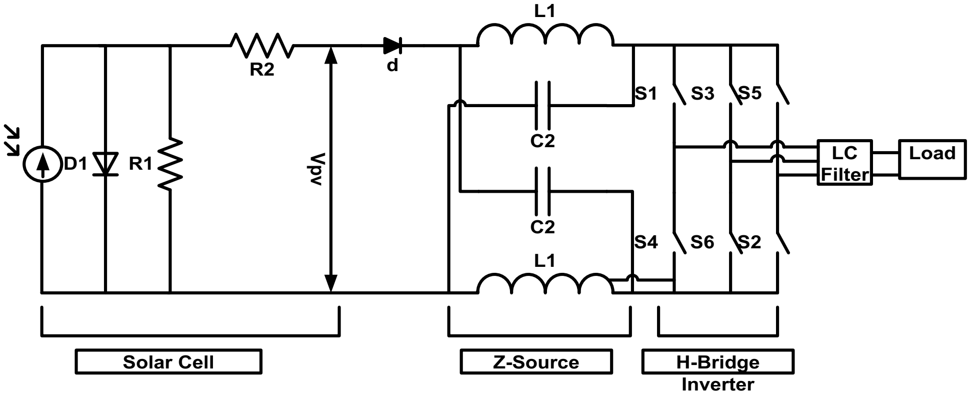


Fig. 4 Circuit diagram of there-phase Z-Source SPV Inverter

Z-source Inverter

Z-source inverter is constructed using two divided capacitors and inductors which are connected in X-shaped, as shown in Fig. 3 (Shen et al. 2007). For a three-phase two-level Z-source inverter bridge, it has nine acceptable switching states, where as in voltage source inverter it has only eight switching states. Z-source inverter has six active states and two zero states. When system is connected across load, the system is in one of the six active states, and when the load terminals are shorted through upper and lower legs of the inverter bridge, the system is said to be in one of the two zero states. The ninth state which is not available in the traditional inverters can be seen in Z-source inverter and is said to be shoot-through state. The ninth state is forbidden in conventional inverters as it can destroy the system by shorting the upper and lower leg semiconductor switches using load (Kerekes et al. 2008; Farhangi and Farhangi 2006; Peng et al. 2003) (Figs. 4, 5).

The available traditional pulse width modulation technique can be utilised with slight modifications to the zero states. Only zero states are converted into shoot-through states, while no change is seen in eight active states. Some or all zero states can be converted into shoot-through states which depend on modulation index (M). In case of Z-source inverter, without destroying the semiconductor switches or passive components, it gives a distinct feature of bucking-boosting which makes it different from the available conventional inverters. Figure 6 shows the circuit diagram of three-phase Z-source inverter with PV as a source of input. This circuit will be utilised later in the simulation and in experiment for the evaluation of Z-source inverter. (Peng et al. 2003; Peng 2003; Shen et al. 2007; Tran et al. 2007; Peng et al. 2005; Shen et al. 2006; Van der Broeck and Miller et al. 1995; Justus Rabi and Arumugam 2005; Rajashekara 2003; Loh et al. 2004; Xu et al. 2006; Holland et al. 2005; Yi et al. 2006; Shen et al. 2004; Rabkowski 2007; Peng et al. 2005; Faruqui and Anwer 2017; Raveendhra et al. 2014; Qi et al. 2014; Hanif et al. 2011; Deshpande et al. 2014; Sharma et al. 2016; Hossam-Eldin et al. 2017; Yadav et al. 2017; Islam et al. 2016).

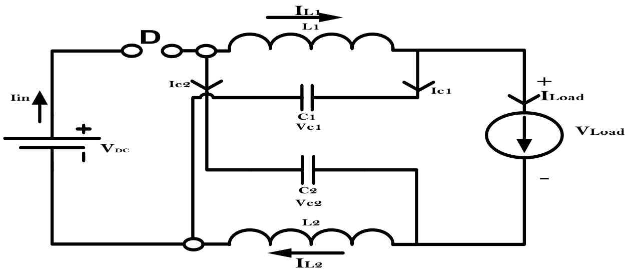


Fig. 5 Equivalent circuit of Z-source inverter in shoot-through mode

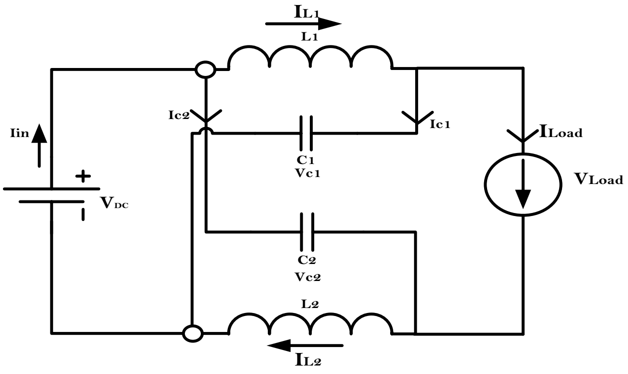


Fig. 6 Equivalent circuit of Z-source inverter in non-shoot-through mode

Z-source inverter does not only help in boosting the input DC voltage but also help in tracking the maximum power point (MPP). Using any maximum power point technique (MPPT), such as P & O or INC, the shoot-through duty cycle T_0/T can be decreased or increased depending upon the (Shen et al. 2006) change in power absorbed by the input DC source. In case of voltage source inverter with boost converter, maximum power point remains same as ZSI.

Operating modes of Z-source inverter

Basically, the operation of the Z-source inverter depends upon switching states of the inverter bridge. According to that, Z-source inverter is divided into two modes, first, the shoot-through mode shown in Fig. 5, and second, the non-shoot-through mode shown in Fig. 6. It is assumed that the values of the inductors L_1 and L_2 are of same magnitude, and capacitors C_1 and C_2 are of same magnitude. (Hanif et al. 2011; Deshpande et al. 2014; Sharma et al. 2016).

$$V_{L1} = V_{L2} = V_L$$

$$V_{C1} = V_{C2} = V_C$$

Mode1: in case of shoot through mode as shown in Fig. 5, diode 'D' at the input side is reversed biased, and the two capacitors C_1 and C_2 charge the inductors L_1 and L_2. During the shoot-through mode at time interval T_0,

$$V_L = V_C; V_d = 2V_C; V_i = 0 \tag{1}$$

Applying KVL to the circuit shown in Fig. 5, we get

$$L_1 \frac{dI_{L1}}{dt} - V_{c1} = 0 \tag{2}$$

$$L_2 \frac{dI_{L2}}{dt} - V_{c2} = 0 \tag{3}$$

Now Applying KCL in the circuit shown in Fig. 5, we get

$$C_1 \frac{dV_{C1}}{dt} - I_{L1} = 0 \tag{4}$$

$$C_2 \frac{dV_{C2}}{dt} - I_{L2} = 0 \tag{5}$$

Using the above equations, the state matrix formed is

$$\begin{bmatrix} \dot{I}_{L1} \\ \dot{I}_{L2} \\ \dot{V}_{C1} \\ \dot{V}_{C2} \end{bmatrix} = \begin{bmatrix} 0 & 0 & \frac{1}{L_1} & 0 \\ 0 & 0 & 0 & \frac{1}{L_2} \\ \frac{-1}{C_1} & 0 & 0 & 0 \\ 0 & \frac{-1}{C_2} & 0 & 0 \end{bmatrix} \begin{bmatrix} I_{L1} \\ I_{L2} \\ V_{C1} \\ V_{C2} \end{bmatrix} \tag{6}$$

Mode2: in case of non-shoot-through mode shown in Fig. 6, the Z-source inverter is operating as voltage source inverter and inverter is in one of the six active states, therefore the inverter bridge can be seen equivalent to a current source as shown in Fig. 6. During this mode, the Z-source network is symmetrical in nature, and therefore, the current across the capacitors and inductors is equal.

$$I_{L1} = I_{L2} = I_{C1} = I_{C2} \tag{7}$$

During this mode, the flow of energy to the load in the circuit is through the inductors, while the capacitors are charged and they remain charged till the steady state.

Now, the diode 'D' at the input conducts and the voltage through the inductor will be V_L,

$$V_L = V_{\text{DC}} - V_C \tag{8}$$

$$V_C = V_{\text{DC}} - V_L \tag{9}$$

$$V_d = V_{\text{DC}} \tag{10}$$

{V_d = Voltage across diode, V_{DC} = Input DC voltage}

During this mode, at time interval T_1, voltage across DC link is

$$V_i = V_C - V_L$$

Using Eq. (1), we have

$$V_i = 2V_C - V_{\text{DC}} \tag{11}$$

where V_{DC} is the DC source voltage at time 'T', $T = T_0 + T_1$.

During steady state, over one switching period (T), the average voltage across the inductor should be zero.So using Eqs. (4) and (6),we have

$$V_L = \frac{T_o.V_C + T_1(V_O - V_C)}{T} = 0$$

$$\frac{V_C}{V_{\text{DC}}} = \frac{T_1}{T_1 - T_0} \tag{12}$$

Therefore, the average DC link voltage for one switching cycle (T) across the inverter bridge is

$$V_i = \frac{T_0.0 + T_1(2V_c - V_{\mathrm{DC}})}{T}$$

$$V_i = \frac{T}{T_1 - T_0} = Vc \tag{13}$$

Using Eq. (11), we get

$$V_i = V_C - V_L = 2V_C - V_0 = \frac{T.V_0}{T_1 - T_0} = \mathrm{B}.V_0$$

$$\mathrm{B} = \frac{T}{T_1 - T_0} = \frac{1}{1 - 2\frac{To}{T}} \geq 1 \tag{14}$$

B indicates boost factorVoltage gain of the Z-source inverter:

$$V_{\mathrm{AC}} = \mathrm{M.B.}\frac{V_{\mathrm{DC}}}{2} \tag{15}$$

Voltage gain for the conventional inverter:

$$V_{\mathrm{AC}} = \mathrm{M}\frac{V_{\mathrm{DC}}}{2},$$

where $M \leq 1$.

'*M*' represents the modulation index. However, electing the correct buck–boost (B_B) factor, the output voltage can be boost or buck.

$$0 < B_B < \infty$$

Overall, capacitor voltages are articulated below. Using Eq. (12), we have

$$V_C = \frac{T_1}{T_1 - T_0}V_{\mathrm{DC}}$$

$$V_C = \frac{1 - \left(^{To}/_{T}\right)}{1 - \left(^{2To}/_{T}\right)}V_{\mathrm{DC}} \tag{16}$$

Using Eq. (14), we can derive

$$\frac{T_0}{T} = \frac{B-1}{2B} \tag{17a}$$

This implies

$$1 - \frac{T_0}{T} = \frac{B+1}{2B} \tag{17b}$$

Using Eqs. (14), and (17b) and substituting in Eq. (11), we have

$$V_C = \frac{1 - \left(^{To}/_{T}\right)}{1 - \left(^{2To}/_{T}\right)}$$

$$V_{\mathrm{DC}} = \frac{B+1}{2B} * \mathrm{B}{*}V_{\mathrm{DC}} = \frac{B+1}{B}V_{\mathrm{DC}}$$

$$V_C = \frac{B+1}{B}V_{\mathrm{DC}} \tag{18}$$

Applying KVL to the circuit shown in Fig. 6, we get

$$V_{\mathrm{dc}} = L_1\frac{\mathrm{d}I_{L1}}{\mathrm{d}t} + V_{C2} \tag{19}$$

$$V_{\mathrm{dc}} = L_2\frac{\mathrm{d}I_{L2}}{\mathrm{d}t} + V_{C1} \tag{20}$$

Now applying KCL to the circuit shown in Fig. 6, we get,

$$C_1\frac{\mathrm{d}V_{C1}}{\mathrm{d}t} - I_{L2} + I_{\mathrm{dc}} = 0 \tag{21}$$

$$-C_2\frac{\mathrm{d}V_{C2}}{\mathrm{d}t} + I_{L1} - I_{\mathrm{dc}} = 0 \tag{22}$$

So the state matrix for the non-shoot through state becomes

$$\begin{bmatrix} \dot{I}_{L1} \\ \dot{I}_{L2} \\ \dot{V}_{C1} \\ \dot{V}_{C2} \end{bmatrix} = \begin{bmatrix} 0 & 0 & 0 & \frac{-1}{L_1} \\ 0 & 0 & \frac{-1}{L_2} & 0 \\ 0 & \frac{1}{C_1} & 0 & 0 \\ \frac{1}{C_2} & 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} I_{L1} \\ I_{L2} \\ V_{C1} \\ V_{C2} \end{bmatrix} + \begin{bmatrix} \frac{V_{\mathrm{dc}}}{L_1} \\ \frac{V_{\mathrm{dc}}}{L_2} \\ \frac{-I_{\mathrm{dc}}}{C_1} \\ \frac{-I_{\mathrm{dc}}}{C_2} \end{bmatrix} \tag{23}$$

On solving matrices (6) and (23), and by taking Laplace transformation, we get

$$\frac{V_C(s)}{\hat{d}(s)} = \frac{\left(2V_C + V_{\mathrm{dc}}\right)(1 - 2D) - SL(2I_L - I_{\mathrm{dc}})}{S^2LC + (2D - 1)^2} \tag{24}$$

$$\frac{\hat{\imath}_L(s)}{\hat{d}(s)} = \frac{\left(2V_C + V_{\mathrm{dc}}\right) - (2D - 1)(2I_L - I_{\mathrm{dc}})}{S^2LC + (2D - 1)^2} \tag{25}$$

Passive component designing

Inductor designing

Designing of passive components {inductors (*L*) and capacitors (*C*)} are required in Z-source inverter. During non-shoot-through mode, the inverter behaves as a traditional voltage source inverter (VSI), where no boost action is required. Throughout the mode, the input generated voltage appears across the capacitors, and no voltage is seen across the inductors, because of ripple-free DC across the inductor, during this mode. However, during impedance mode (shoot-through), when the circuit is boosting the input DC voltage, the main job is done by inductor, by limiting the current ripples for the duration of boost mode. The current through the inductor increases linearly and the voltage across the inductors and the capacitors are almost equal. During non-shoot-through, when inverter is in one of the eight traditional states, the current across the inductor decreases linearly and the voltage across it is the difference in magnitude of the voltages across the capacitor and the input voltage. (Van der Broeck and Miller 1995; Justus Rabi and Arumugam 2005; Rajashekara 2003; Loh et al. 2004; Xu et al. 2006; Holland et al. 2005; Yi et al. 2006; Shen et al. 2004; Rabkowski 2007; Peng et al. 2005; Raveendhra et al. 2014; Qi et al. 2014).

Amount of average current flowing through the inductor

$$I_L = \frac{P}{V_{\mathrm{DC}}} \tag{26}$$

where 'P' denotes the total power.

It is found that maximum current ripple is seen across the inductors when maximum shoot-through occurs. Therefore, for designing the inductors, for the impedance source inverter, we need to take consideration of inductor's peak to peak current ripple. As a thumb rule, according to many research papers mentioning about inductors used in impedance source inverter, about 30% current triple is chosen or 60% peak to peak.

$$\text{Inductor maximum current } = I_{L\max} = \mathrm{I}_{L} + 30\%$$

$$\text{Inductor minimum current } = I_{L\min} = \mathrm{I}_{L} - 30\%$$

During shoot through mode:

$$V_L = V_c = V$$

$$V = \frac{\text{Boosted voltage} + \text{Input voltage}}{2}$$

Relation below can be utilised in calculating inductor value,

$$V = \frac{V * T_0}{\Delta I} \tag{27}$$

$$\Delta I = I_{L\max} - I_{L\min}$$

Capacitor designing

The main function of the capacitor is to absorb the ripples present in the current, by which we can get a stable voltage, which further helps in getting sinusoidal voltage at the output. During shoot-through mode, when diode is reversed biased, capacitor charges the inductor. During this operation, the current through the capacitor is equal to the current through the inductor.

$$I_L = I_C$$

Value of capacitance can be calculated using the following relation. The capacitor voltage ripple should be limited to 3%.

$$V = \frac{I_L . T_0}{\Delta V_C} \tag{28}$$

$$T_0 = \text{Shoot} - \text{through period for one switching cycle.}$$

$$I_L = \text{Average current flowing through the inductor.}$$

$$\Delta V_C = \text{Voltage current ripple} = V * 3\%$$

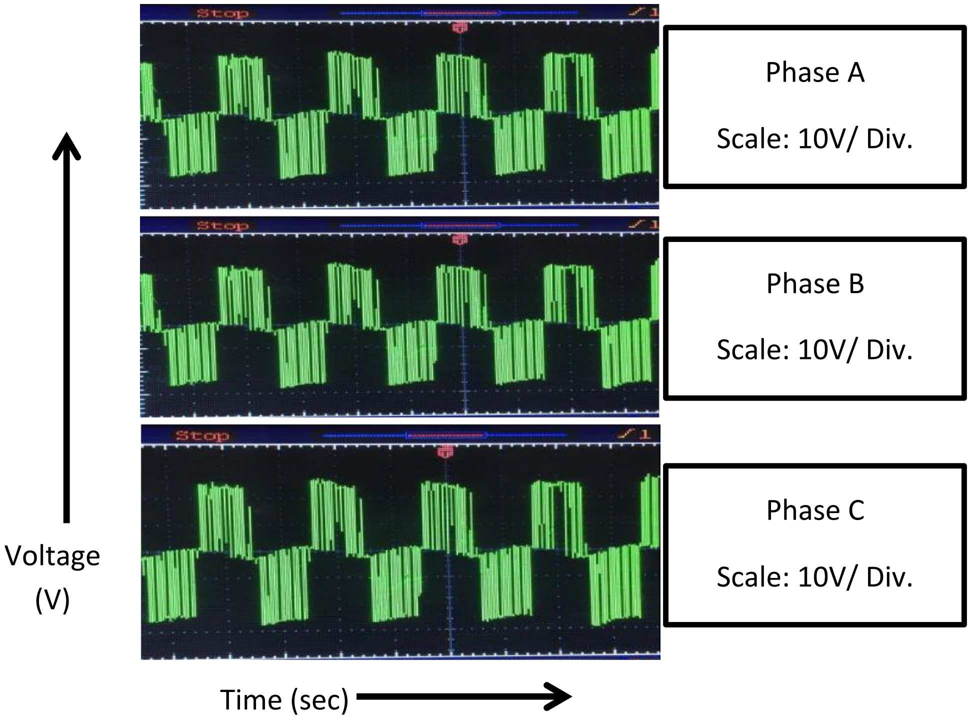
PWM control for VSI and ZSI

There are many techniques presented in the literature for the generation of PWM pulses for the inverters. In case of traditional inverter, along with the active states, zero states are available. During zero states, the output voltage at the load is zero. But in case of Z-source inverter, these zero states are converted into shoot-through states, which result in boosting of input DC voltage. The available PWM techniques for traditional inverter are sinusoidal pulse width modulation (SPWM), space vector pulse width modulation (SVPWM), multicarrier pulse width modulation (MCPWM), etc. For Z-source inverter, available techniques are simple control, maximum boost control, etc. In this research paper, we have used SPWM for the control of VSI inverter. For Z-source inverter, we have used simple boost control (SBC) technique to control the Z-source inverter. (Hossam-Eldin et al. 2017; Yadav et al. 2017; Islam et al. 2016; Jokipii and Suntio et al. 2015; Abdelhakim 2015; DebBarman and Roy 2014; Kumar and Barai 2015).

SPWM

SPWM, i.e. sinusoidal pulse width modulation uses one reference signal which compared with carrier signal. In SPWM, sinusoidal wave is compared with triangular wave for the generation of PWM pulses. When the reference (sinusoidal) wave is higher than the carrier (triangular) wave, the output of the inverter is a positive voltage, when the reference wave is lower than the carrier wave the output of the inverter is negative voltage. The main advantage of this technique is that, it is easy to implement. Not only this, the effective switching frequency of the load voltage is greater

Fig. 7 Two-level three-phase output AC voltage waveform Phase A, Phase B, and Phase C



than the switching frequency of individual cell. (Faruqui and Anwer 2017; Raveendhra et al. 2014).

Simple boost control (SBC)

In case of simple boost control, the method consists of four conventional signals with two straight lines. The conventional signals are similar to normal PWM signals. The three reference signals, i.e. sinusoidal wave which are compared with carrier signal, i.e. triangular wave. The basic step to start with the simple boost control is to compare the reference signal with the carrier signal. The output of this comparison is a normal PWM signal. Like-wise for all the three-phase reference, waves are compared to produce PWM. The three reference signal will be 120° apart from each other. That means one will be leading and other will be lagging w.r.t the third considered as reference. A NOT gate will be used to generate pulses for the lower switches of the inverter bridge. Shoot-through pulses will be generated by comparing the carrier wave with the straight lines. For this method, the magnitude of the straight lines will be same as the amplitude of the reference wave. V_P and V_N are the two straight lines used in simple boost control. At the time when carrier signal (triangular wave) is greater than V_P, the pulse will be high, and when the carrier signals (triangular wave) are smaller than V_N, the pulse will be low. At the time when pulses are high, it means that shoot through is occurred for Z-source inverter for positive half cycle and at that moment all the switches from same leg are turned ON and vice versa for negative half cycle. This process of turning on both the switches from the same leg will be a reason for ensuring the shoot-through. After this process, when shoot-through pulses are generated, OR gate is used to combine all the pulses. Now the pulses will be fed to the inverter switches. The pulses linked with the NOT gate will be fed to lower switches of the inverter and rest will be fed to the upper switches (Hanif et al. 2011).

Design parameters for ZSI and VSI

To understand the working principle of traditional and Z-source inverter, simulation has been done using MATLAB, and the results are verified through an experimental setup. The design parameters for the two topologies are given below.

For voltage source inverter

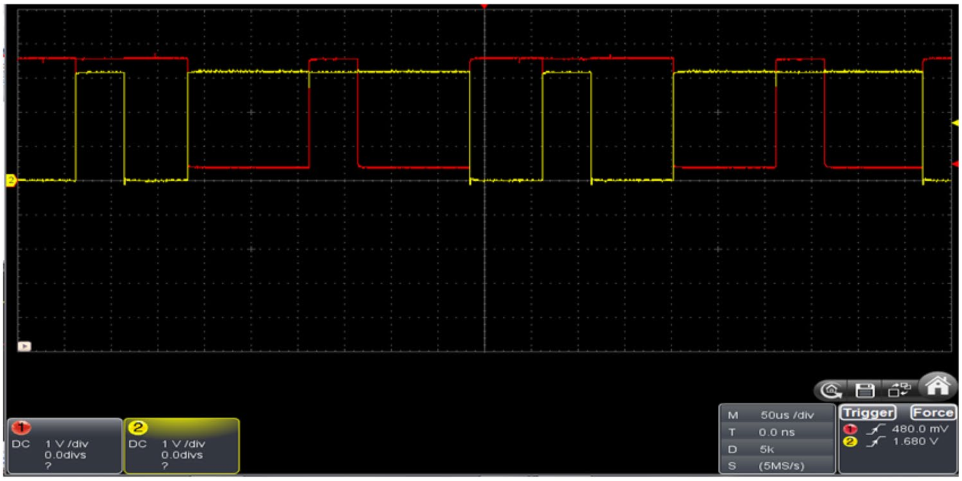
DC input voltage = 34 V

AC output voltage = 25 V

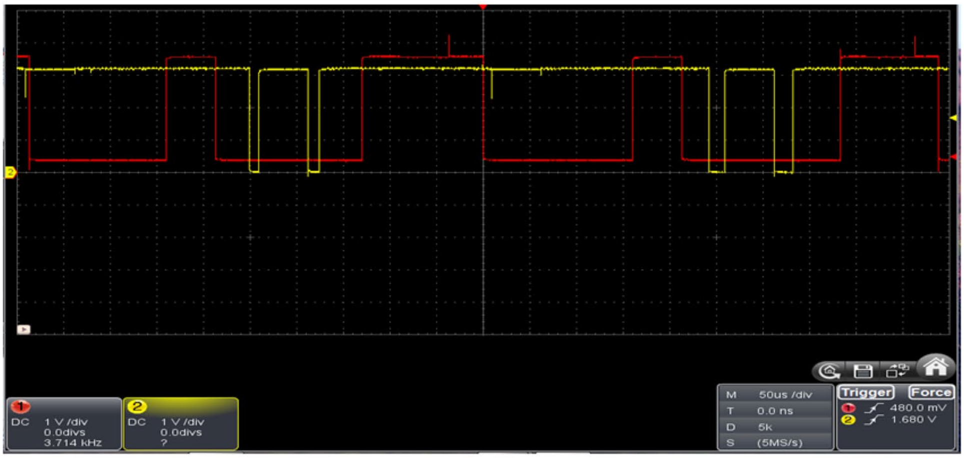
Switching devices (IGBT) = KGF15N120NDS

PWM control: SPWM using FPGA SPARTAN-3E Kit

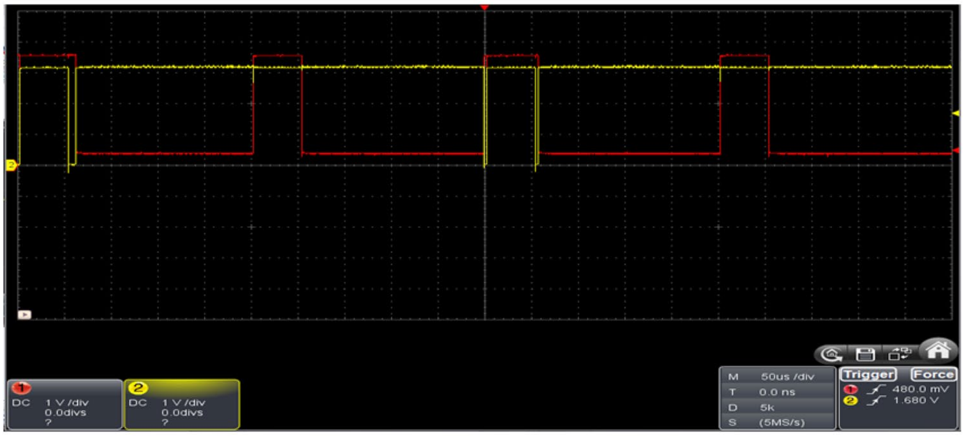
Fig. 8 PWM pulses for switches S1–S6



Switch S1 and S4



Switch S2 and S5



Switch S3 and S6

For Z-source inverter

DC input voltage = 6.6 V
AC output voltage = 13 V
Capacitor (C_1 and C_2) = 300 μF
Inductor (L_1 and L_2) = 1.03 mH
Switching devices (IGBT) = KGF15N120NDS
PWM control: SBC using FPGA SPARTAN-3E Kit

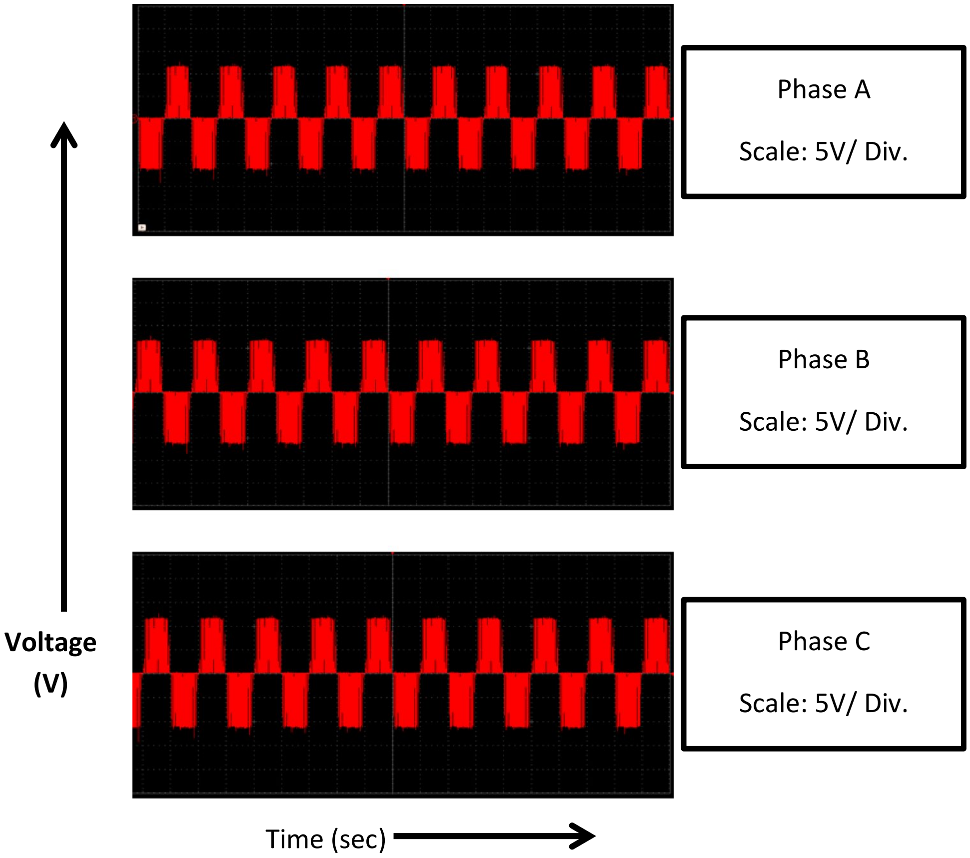


Fig. 9 Three-phase output AC voltage waveform Phase A, Phase B, and Phase C

Results and discussion

In this section, the experimental results for the developed laboratory prototype of VSI and ZSI have been described.

This section gives the output waveforms of the three-phase two-level voltage source inverter and two-level Z-source inverter.

Figure 7 shows the three-phase two-level voltage outputs of voltage source inverter. The x axis denoted the time, and y axis shows output voltage. The scale used for three phase output voltage is 10 V/divisions.

The output voltage waveforms for three-phase two-level Z-source inverter are shown below. PWM pulses for switches S1–S6 are shown in Fig. 8. The switching pulses shown clears the concept of opening and closing of two switches from the same leg for a short interval of time. This situation is said to be shoot-through state, which is forbidden in traditional inverter.

For short interval of time, switch one of the two switches opens, which helps in boosting the input DC voltage as can be seen in Fig. 7. The shoot-through time is less as compared to normal pulse.

Finally, the three-phase output AC voltage waveform is shown in Fig. 9. The input DC voltage for Z-source is 6.6 V and the output is 13 V. So the system is working as a step-up system.

Conclusion

This paper clears the concept about both the traditional inverters (VSI and CSI) and Z-source inverter on the basis of limitation of traditional inverters, advantages of Z-source over traditional inverters and difference between the available two topologies. Moreover, designing of inductor and capacitor is clearly stated and the operation of Z-source circuit is also explained using mathematical equations. Difference of shoot-through and non-shoot-through states is stated and explained using experimental results. Two different PWM techniques are studied and explained with the help of MATLAB and implemented using FPGA. The simulated results are verified by the experimental results for VSI and ZSI. Finally, Z-source inverter having exclusive impedance network, makes it suitable for renewable energies, such as PV and fuel cell. Last but not the least, different control schemes, performance of VSI and ZSI, and guidelines for designing the system, are presented.

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