# Chapter 13
# Design and Investigation of Solar Powered Soft Switched Z-Source Inverter

**R. Uthirasamy, U.S. Ragupathy and R. Mithra**

**Abstract** This paper introduces the design and analysis of Zero Voltage Switching (ZVS) scheme of solar powered Z-Source Inverter (ZSI) topology for the UPS applications. The ZSI topology employs a unique impedance network which couples the solar power and the utility. A resonant circuit is designed to obtain ZVS of ZSI, thereby voltage stress across the inverter switches are minimized. The proposed configuration reduces the switching loss and improves the utilization of solar power. Moreover, it highly enhances the reliability of the inverter because the shoot through no longer destroys the inverter. The entire system is developed and simulated using SIMULINK tools. The performance of the proposed system is analyzed and necessary simulation results are obtained. A prototype model of single phase soft switched ZSI is developed and its results are validated.

**Keywords** Solar PV · Irradiance · Soft switching · Z-Source inverter · H-Bridge · Total harmonic distortion

## 13.1 Introduction

Soft switching techniques have been analyzed and enhanced in recent years for power converters to reduce voltage stress across the switches. Traditional inverters are Voltage Source Inverter (VSI) and Current Source Inverter (CSI), which can

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operate in either as a boost or buck inverter and cannot be a buck-boost inverter. To achieve buck and boost operation, separate chopper circuit is required. These limitations can be rectified through ZSI [1]. Normally, in AC–DC–AC converter system the rectified output voltage acts as an input voltage to ZSI and in solar powered AC system, solar panel output acts as an input to ZSI. The peak output DC voltage of both the systems is still high which acts as a voltage stress across the ZSI switches. To obtain ZVS of power converters, a resonant circuit module is required. The developed ZVS scheme averts any voltage or current spikes happening during switching operation. Soft switching techniques are not only adopted for inverter circuits but also for DC-DC converter circuits [2, 3]. A modular soft switched Pulse Width Modulation (PWM) technique is introduced to reduce high voltage and current stress in DC-DC converters, Flying capacitor and Diode Clamped Multi-level Inverter (DCMLI) [4, 5]. In the proposed paper ZVS technique is achieved through the development of resonant soft switching circuits in order to reduce voltage stress across solar powered ZSI switches. This paper is organized as follows; Sect. 13.1 shows the introduction of soft switched solar powered ZSI system. Solar PV panels are designed and analyzed in Sect. 13.2. Soft switching technique is analyzed in Sect. 13.3. Simulation of solar PV and soft switched solar powered ZSI is addressed in Sect. 13.4. Results and discussions are presented in Sect. 13.5. In Sect. 13.6 hardware model and its results are validated. Section 13.7 concludes the development of soft switched ZSI. The general structure of solar powered ZSI is shown in Fig. 13.1a. The voltage stress between the impedance source (Z-Source) and inverter switches are high. To minimize the voltage stress across the inverter switches, a resonant circuit is developed with solar powered ZSI is shown in Fig. 13.1b.

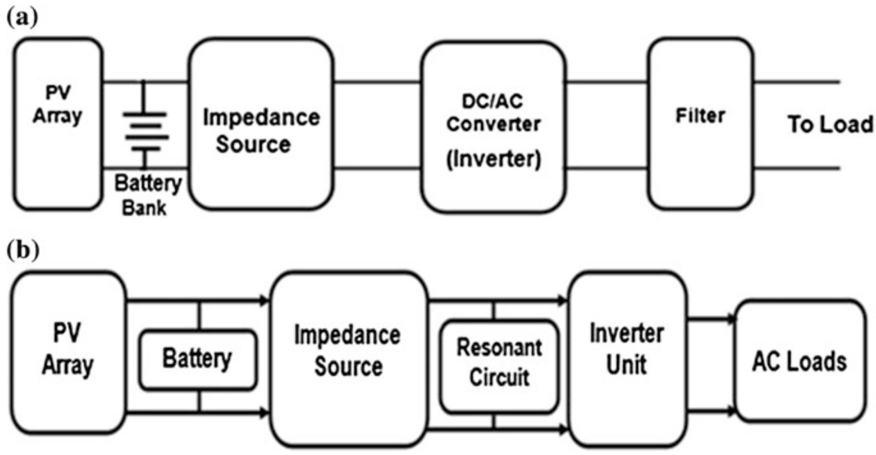


**Fig. 13.1** **a** Block diagram of solar powered ZSI. **b** Block diagram of soft switched solar powered ZSI

## 13.2 Modeling of Solar PV

The basic equation from the theory of semiconductors that mathematically describes the I-V characteristics of the ideal photovoltaic cell:

$$I = I_{pv,cell} - I_{0,cell}\left[\exp\left(\frac{qV}{akT}\right) - 1\right]. \tag{13.1}$$

where, $I_{pv,cell}$ is incident current generated, $I_{0,cell}$ is reverse saturation current of diode, $T$ is the temperature of p-n junction and 'a' is diode ideality constant. A single cell has a rated voltage of 0.5 V and rated power of 0.3 W. Practical arrays are composed of several connected photovoltaic cells [6–9].

## 13.3 Analysis of Soft Switched Z-Source Inverter

Design and analysis of ZSI is investigated [10–13], but in the analysis, voltage stress is not taken into account. The proposed system is used to reduce voltage stress across ZSI. The equivalent circuit of soft switched ZSI is shown in the Fig. 13.2. Solar panel voltage is stored in the battery bank and then it is get boosted through the Z-source network (L&C). The boosted voltage is transferred to the load by the proper switching of H-bridge inverter.

Resonant circuit is interfaced between the Z-source network and the H-bridge inverter to reduce the voltage stress in inverter switches.

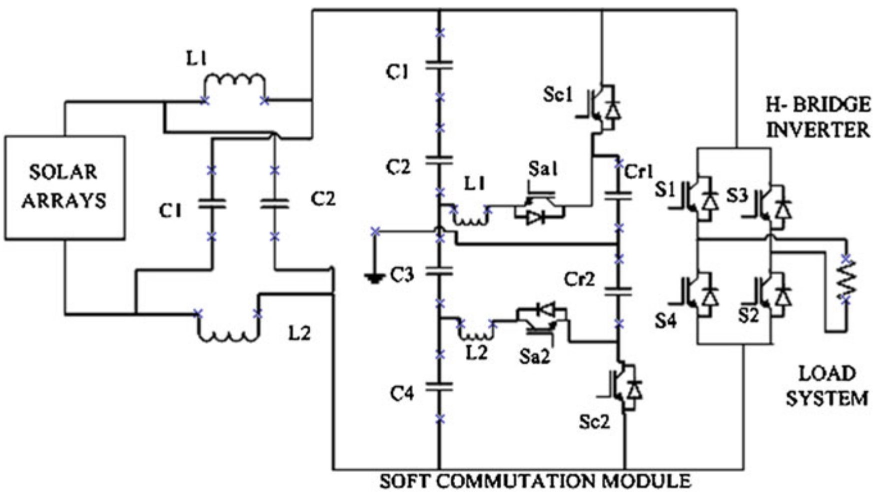


**Fig. 13.2** Equivalent circuit of soft switched ZSI

Voltage across the inductor during energizing;

$$V_L = L\left(\frac{dI_l}{dt}\right). \quad (13.3)$$

Current flowing through the capacitors;

$$Ic = C\left(\frac{dVc}{dt}\right). \quad (13.4)$$

Source voltage is the summation of $V_L$ and $V_P$

$$V_s = V_P + V_L. \quad (13.5)$$

where, $V_L$—Voltage across the inductor, $V_p$—Panel voltage, $V_s$—Source voltage (Boost voltage). By applying the Law of KVL and KCL, following are the expressions of Z-source network. The operation of soft switched ZSI has two modes of operation as those of ZSI are Non shoot through state and Shoot through state. Non shoot through state is considered as the normal switching state of ZSI as similar to that of VSI. It can be analyzed as follows; in Non Shoot-Through State 1, diode D and inverter switches $S_1$ and $S_2$ are in ON state and in Non Shoot-Through State 2, diode D and inverter switches $S_3$ and $S_4$ are in ON state. In Shoot-through state the inverter switches of the same-phase leg are gated ON at the same time. In shoot through state 1, diode D is in OFF state and the same leg switches $S_1$ and $S_4$ are get triggered and in shoot through state 2, diode D is in OFF state and the same leg switches $S_3$ and $S_2$ are get triggered. Resonant circuit is used to achieve zero voltage switching of inverter with Z-source network [14–16]. The resonant circuit can be operated into the following modes of operation;

(a) **Upper Bank Circuit Operation**

**Mode 1** The resonant capacitor, $C_{r1}$, has been charged up to one-half of the normal bus voltage. The clamping switch, $S_{C1,}$ is in the ON-state, and the positive bus voltage is clamped to the capacitor's level, which is equal to $V_s/2$.

**Mode 2** The clamping switch, $S_{C1}$ gets turn OFF so that the positive bus terminal is released from the capacitor bank. By turn ON the auxiliary switch, $S_{a1}$, a resonant path is formed with $L_{r1}$ and $C_{r1}$. The energy stored in $C_{r1}$ is transferred to the large capacitor bank through the inductor and the voltage crossing $C_{r1}$ is decreasing.

**Mode 3** At the end of one-half resonant cycle, the voltage across $C_{r1}$ has been discharged to zero. Any excess current in the inductor will flow through the anti parallel diodes of the inverter switches, as the voltage remains at zero. During this time, the positive bus, across the inverter is in the same potential as the neutral line. If the negative bus has also swung to the neutral line at that time, all the inverter switches will experience zero crossing-voltage and they are ready to safely turn ON and OFF according to the new PWM gating patterns.

**Mode 4** As the inductor current reverses, the anti parallel diode of the auxiliary switch will conduct and provide a path to charge $C_{r1}$. As a result, another resonance occurs between $L_{r1}$ and $C_{r1}$ with an opposite direction of current. The resonant energy is being transferred back to $C_{r1}$.

**Mode 5** When the voltage across $C_{r1}$ reaches its peak value, the clamping switch, $S_{C1}$, is turn ON at zero voltage, and the positive bus is clamped to the capacitor bank again. Thus, the entire soft commutation is completed.

(b) **Lower Bank Circuit Operation**

Similarly lower bank modes of operation are achieved to obtain the negative side peak voltage to zero.

## 13.4 Simulation of Solar Panels and Soft Switched ZSI

The SIMULINK model of the solar PV is shown in Fig. 13.3. Developed solar panel generates the output voltage of 96 V and the output current of 16 A at the irradiance of 1,000 W/m$^2$ and at the panel temperature of 25 °C. The solar panel output is fed to the Z-source network. Through the proper switching of resonant circuit and inverter switches solar panel voltage is utilized by the load system. The simulated model of soft switched ZSI system is shown in Fig. 13.4. Solar panel output voltage is boosted using ZSI circuit and soft switched by resonant circuit.

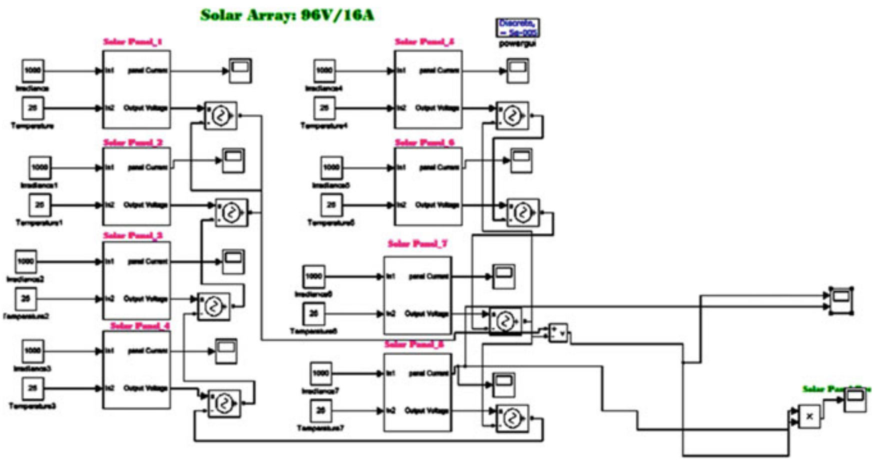


**Fig. 13.3** Simulation model of solar PV panels

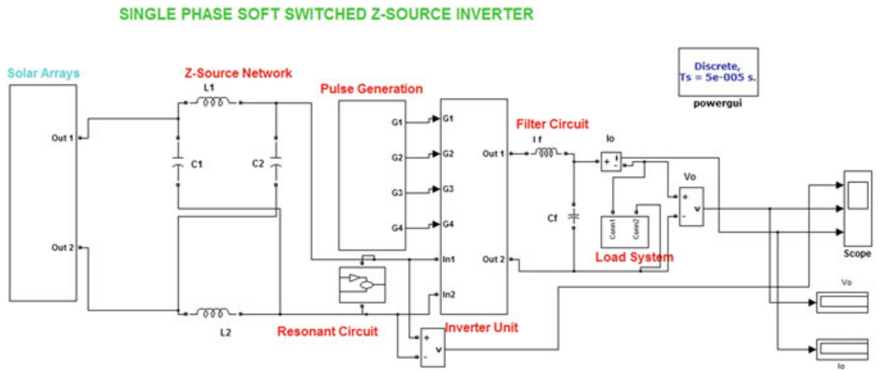


**Fig. 13.4** Simulation model of soft switched ZSI system

## 13.5 Results and Discussion of the Proposed System

For the maximum irradiance, the solar panels are developed to obtain 96 V and 16 A. The obtained solar panel output voltage of 96 V is stored in battery bank. Battery bank voltage is boosted through Z-Source network and H-Bridge inverter switches. The output voltage of resonant soft switching circuit is shown in Fig. 13.5. The main aim of the proposed system is to develop the zero voltage state of battery output voltage for soft switching of inverter switches. The obtained output voltage is fed to the H-bridge inverter switches.

Figure 13.6a, b represents switching pattern for resonant circuits and inverter switches $S_1$, $S_2$, $S_3$ and $S_4$ respectively. The starting time of resonant switch pulse and non shoot through time period of inverter switches coincides with each other. Figure 13.6c shows the soft switched ZSI AC output voltage of 283.7 V ($V_{max}$),

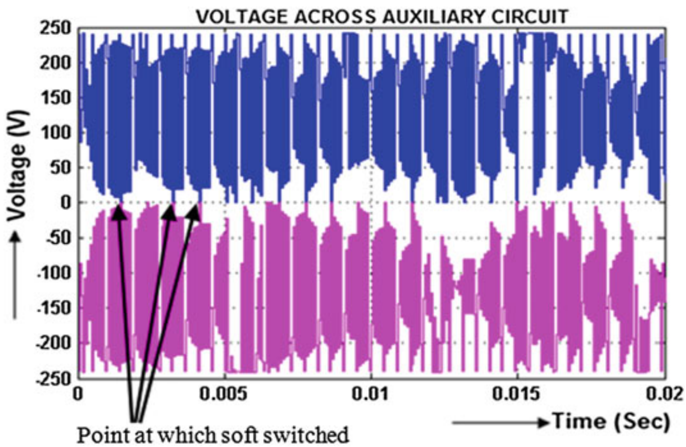


**Fig. 13.5** Soft switched output voltage

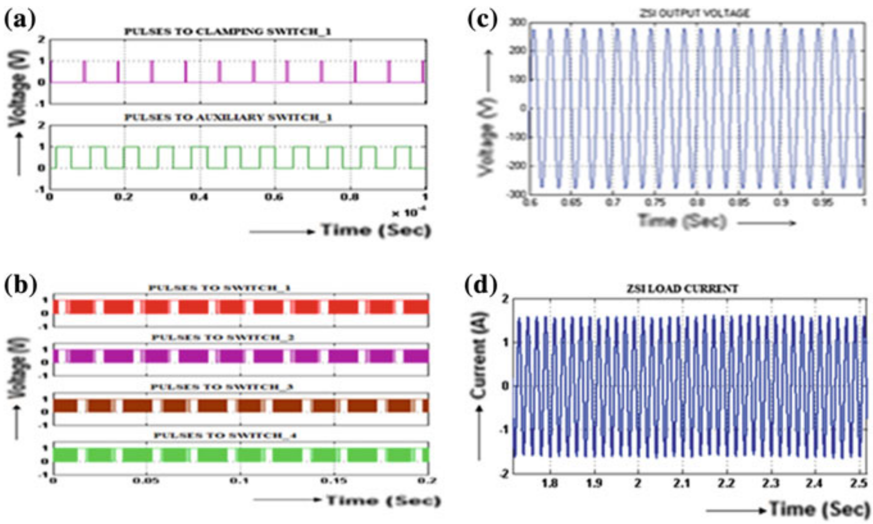


**Fig. 13.6** Firing pulses to **a** resonant circuit switches **b** inverter switches **c** output voltage waveform **d** output load current waveform

50 Hz and Fig. 13.6d shows the load current of 1.5 A, 50 Hz for the following load parameters. Proposed system has following load arrangements; Compact Florescent Lamp (2 Nos.) = (20 * 2) W = 40 W; Fan (1 No.) = 60 W; Mixer = 75 W; Personal computer = 100 W; Total power consumption = 275 W.

The output voltage harmonic analysis for the proposed system with Total Harmonic Distortion (THD) value of 2.83 %. As per IEEE standard 519: 1992 the acceptable THD is less than 5 %.

## 13.6 Experimental Results and Analysis

Figure 13.7a shows output voltage of resonant circuit (soft switched voltage). At time of every zero crossing state of DC voltage, H-bridge inverter switches get triggered.

Figure 13.7b shows the output voltage of soft switched Z-source inverter. Inverter gets the input from the solar panel through the Z-source network and resonant circuit.

Figure 13.7c shows the prototype setup of the proposed system. The entire system is assembled in a single board.

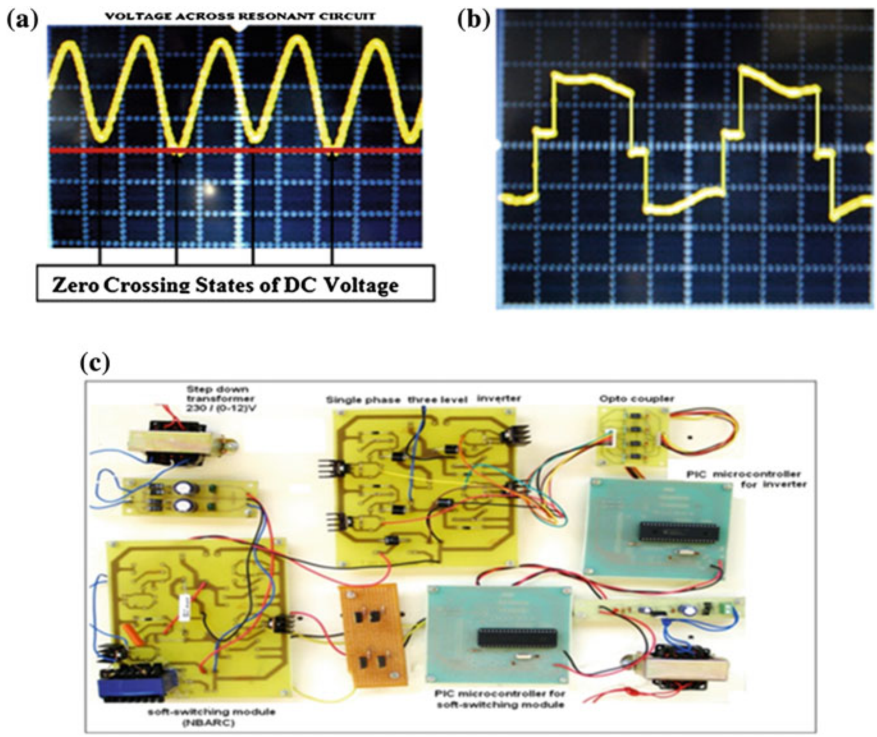


**Fig. 13.7** **a** Output voltage of resonant circuit **b** output voltage of soft switched ZSI **c** prototype model of soft switched ZSI

## 13.7 Conclusion

In this paper a solar powered soft switched ZSI system is obtained using LC resonant circuit. The proposed system has maximum boost capability with high efficiency. The voltage stress across the inverter switches can be minimized through the proposed system. The proposed system enhances the maximum utilization of solar power.

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