CHAPTER 1

INTRODUCTION

Energy is essential for our life and economy. The total energy usage of the world is increased and the generation of energy is still based on fossil fuels (i.e. coal, oil and gas). Fossil fuels are not being newly formed at any significant rate, and thus available in finite stock. In addition, it is the emissions from fossil fuel use that increases the environment pollution. Thus from statements of: (i) finite nature of fossil fuels, (ii) the harm of emissions and (iii) ecological sustainability, it is essential to identify, establish and expand a variety of alternative energy solutions, some of which should be based on renewable forms of energy. Several renewable sources of energy are being thought of, including the solar, geothermal, wind, tidal and the biomass based. Of which solar energy is gaining popularity as it a clean form of energy. Other renewable energy means of power generation e.g., hydroelectric, wind and wave power also depend on the sun as the primary source. The use of photovoltaics as an energy source is imperative to help reduce the levels of green house gases in the atmosphere and reduce global warming.

The solar resource is enormous compared to our energy needs. It can be captured and transformed into heat or electricity. It varies in quantity and quality in places with respect to time, in ways that are not entirely predictable. An interesting way to convert the available energy from the sun is to convert it into electrical energy through photovoltaic (PV) technology. This gives us an infinite supply of energy with no harmful by-products.
A PV system is described as a combination of several components such as DC to AC conversion circuits, power conditioning devices and storage systems. The power conditioning system is used to manage the electrical energy obtained from the PV module by drawing maximum power and providing a high quality AC output. This research work mainly concentrates on the electronic means of heightening the performance of the power conditioning system as well as enhancing energy efficiency in a PV system.

1.1 POWER CONDITIONING IN PHOTOVOLTAIC SYSTEMS

Over the past few years, PV arrays have been connected to loads by direct coupled method. But direct connection of PV cells to the utility almost never allows optimum power transfer when the load, solar irradiance or temperature changes. A PV module can produce the power at a point, called an operating point, anywhere on the current-voltage curve. There is a unique point, called a maximum power point (MPP), at which the module produces the maximum output power. This MPP is the desired operating point for a PV module to get maximum efficiency. Also, in PV systems, when the solar irradiance changes rapidly, especially the irradiance decreases suddenly, the operating point will also change simultaneously. This leads to get a mismatch between the PV module and the load and it requires further over-sizing of the system and thus increases the overall cost. To extenuate this problem, a maximum power point tracker (MPPT) is used to maintain the operating point of PV module at the MPP.

To transfer energy from PV arrays into utility, power conditioning unit is required to convert the DC voltage obtained from PV array into AC voltage and to prevail the maximum power utilization of the PV array. The term power conditioning system refers to the general class of devices that
interface the PV array with the utility. These devices use power electronics technologies to convert electrical energy from one form to another; for example, converting between DC to DC or DC to AC, and/or converting between different voltage levels, and/or providing specific power qualities required by the subsystems being interfaced by the power conditioning system. In PV based power conditioning systems, the interface converter acts as a key component.

Presently, the voltage source inverter is employed as the interfacing converter for DC to AC conversion. But the main disadvantage of this inverter is it works only as a buck converter for DC to AC power conversion. When the PV array voltage is lower than the required AC voltage, a line frequency transformer is needed to boost the output voltage. Figure 1.1 shows the traditional power conditioning system utilizing a line frequency transformer after the DC-AC inverter stage. This line frequency transformer is having many drawbacks like huge in size, loud acoustic noise and high cost. In addition, the inverter is required to be oversized to contend with change in PV array output voltage.

![Diagram of Power Conditioning System with DC-AC inverter and transformer]

**Figure 1.1 Power conditioning system with DC-AC inverter and transformer**

In order to eliminate the transformer and to minimize the rating of the inverter, a high frequency DC to DC boost converter is used to boost the
voltage to a desired level. This system is shown in Figure 1.2. There are two stages of power conversion here, i.e. a boost converter stage followed by a DC to AC inverter stage. Again this two stage conversion increases the cost and reduces the efficiency of the system. Further, the voltage source inverter used in these schemes is forbidden to operate in shoot-through operation i.e. the two switches from the same phase leg of the inverter cannot be gated on simultaneously. Otherwise, a short circuit will destroy the devices. So, a dead time must be always exerted in the switching pattern, which will cause output current distortion.

![Power Conditioning System Diagram](image)

**Figure 1.2  Power conditioning system with DC-DC converter and DC-AC inverter**

Z-source inverters are recently proposed and they can be utilized to realize boost and inversion functions in a single stage. Moreover, Z-source inverters provide alternative power conversion concept, which overcome the above mentioned disadvantages of voltage source inverter. This inverter employs a unique impedance network consisting of two inductors and two capacitors coupled between the input DC source and the inverter bridge. This unique impedance network allows the Z-source inverter to buck or boost its output voltage, and provides it with unique features that cannot be achieved in voltage source inverters (Fang Zheng Peng 2003).
1.2 LITERATURE SURVEY

The following literature review addresses the issues related to the research on effective action of Z-source inverter based PV power conditioning system.

Literature reviews in the following areas are presented:

1. Modeling of PV module
2. Z-source inverter
3. Power conditioning system

1.2.1 Modeling of PV Module

Geoff Walker (2001) developed a mathematical model for PV using MatLab M-file coding. This model is useful for obtaining the characteristics of PV module for different solar irradiance and temperature. However in this model the author did not consider the shunt resistance.

Alonso-Garcia and Ruiz (2006) suggested a new model. This model comes from the study of avalanche mechanisms in PV solar cells, and counts on physically meaningful parameters. It can be adapted to PV cells in which reverse characteristic is dominated by avalanche mechanisms, and to those dominated by shunt resistance or with breakdown voltages far from a safe measurement range. A procedure to calculate model parameters based on piecewise fitting is also proposed.

Huan-Liang Tsai et al (2008) developed a generalized five parameter model of a PV array using MatLab /Simulink software. The effect of solar irradiance and cell temperature on the output characteristics can be easily found by this simulation model.
Hiren Patel and Vivek Agarwal (2008) presented a MatLab based simulator cum learning tool, which can be used to enhance the understanding and predict the characteristics of large PV arrays. It can be used to study the effect of temperature and solar irradiance variation, varying shaded pattern (characterized by multiple peaks in the power-voltage curves), and the role of array configuration on the PV characteristics. A notable advantage of their work is that the PV model can be interfaced with the models of actual systems (e.g., power electronic converters) making it possible to simulate complete PV systems and their interaction with other systems.

Marcelo Gradella Villaiva (2009) proposed some modifications in a single-diode model with the method for adjusting the parameters to make this model more perfect for power electronics designers who are looking for an easy and effective model for the simulation of PV modules with power converters.

Yingying Kuai and Yuvarajan (2006) proposed a simple electronic load for testing a set of PV panels using linear metal oxide field effect transistor (MOSFET). The proposed test setup gives the current versus voltage and power versus voltage characteristics of PV panels by quickly scanning the load. Ramaprabha et al (2010) analyzed the development of a method for the complete mathematical modeling of PV modules. The PV module characteristics for various shunt and series resistances are analyzed. A simple method to measure the practical characteristics is also suggested in this work.

1.2.2 Z-source Inverter

Fang Zheng Peng (2003) introduced impedance source or impedance-fed power inverter (abbreviated as Z-source inverter) and its
control method for fuel cell applications. The Z-source inverter system can buck or boost the input voltage by controlling the boost factor, which cannot be achieved in traditional inverter systems. Thus the Z-source inverter is found to provide a novel power conversion concept and overcome the conceptual and theoretical barriers and limitations of the traditional voltage source inverter and current source inverter. The operating principle and circuit characteristics are explained. This work also proposed the simple boost pulse width modulation (PWM) technique which is similar to traditional sinusoidal PWM, but with two straight lines envelope for boosting mode operation. In this PWM, the voltage stress across the switching device is quite high, which restricts the obtainable voltage gain because of the limitation of device voltage rating. The analysis and control techniques are given based on the assumption that the impedance network inductor is large and the inductor current is continuous and has small ripple. This assumption becomes invalid when small value of inductance is used to minimize the size and weight for some applications. Under this condition, the inductor current may be discontinuous and has high ripple. This impedance network concept can be applied in DC to AC, AC to DC, DC to DC and AC to AC power conversions.

Fang Zheng Peng et al (2005) presented the operating principle of Z-source inverter with its equivalent circuits in active state mode, zero state mode and shoot-through state mode. The ride-through capability during voltage sags, reduction in line harmonics, improvement in power factor are analyzed for a Z-source inverter fed adjustable speed drive.

Poh Chiang Loh et al (2005) described the detailed analysis about the modifications of various conventional PWM strategies to switch a voltage type Z-source inverter either in continuous or discontinuous operation without changing the unique harmonic performance features of these conventional
modulation strategies. In this work, single phase full bridge topologies, three phase leg and four phase leg inverter topologies with the modulation concepts are analyzed and the corresponding carrier-based reference equations are derived. Jin-Woo Jung et al (2005) presented PWM implementation and controller design for the Z-source inverter employed in distributed generation systems under varying load conditions. The circuit model of Z-source inverter in continuous-time state space equation is derived and a space vector PWM technique with six shoot-through states to boost the DC link voltage of Z-source inverter is implemented. The proposed model and control methods are demonstrated using MatLab /Simulink.

Fang Zheng Peng et al (2005) proposed maximum boost PWM control for Z-source inverter. In this technique, all zero states are turned in to shoot-through states without changing the active states. Compared to simple boost PWM technique, this method achieves high value of shoot-through duty ratio and boost factor for any given modulation index without distorting the output waveform. In addition, third harmonic injection based maximum boost control is suggested to increase the modulation index range so as to increase the voltage gain range. Another advantage obtained from this method is that the voltage stress in is much lower. But, the major drawback in this PWM control is the making of variable shoot-through duty ratio in a cycle. Hence the ripple in inductor current and capacitor voltage increases. The inductor current becomes significant if the output frequency is low and it requires a large inductor in the impedance network.

Miaosen Shen (2006) introduced the concept of maximum constant boost PWM control. The shoot-through duty states are generated by two sinusoidal envelopes of three times the frequency of modulating signals. This PWM accomplishes high voltage boost while always keeping the shoot-through duty ratio constant. The voltage gain obtained by this control is larger
than that of simple boost PWM but lesser than that of maximum boost PWM for a given modulation index without producing any low frequency ripple. This PWM technique increases the voltage stress across the switching device by a smaller amount when compared to the maximum boost PWM method.

Tae-Won Chun et al (2006) presented a new switching pattern based on space vector PWM. The symmetrical pulse pattern used in conventional voltage source inverter is modified here with injection of shoot-through states. These shoot-through states fill part or whole of the zero state time without changing the active state times. Totally six shoot-through states are inserted in a sampling period for boosting operation. An algorithm for controlling the AC output voltage in the Z-source inverter while minimizing the voltage stress across the switching device is developed. Gao et al (2006) formulated a random switching technique for Z-source inverter by randomly changing the durations of the inverter shoot-through states in the state sequences. The random PWM is achieved by replacing the zero states with nearest active vectors and their complements or with adjacent active vectors.

Rostami and Khaburi (2009) compared the voltage gain of the three PWM techniques. Husodo et al (2010) provided detailed comparison between simple boost PWM and maximum boost PWM techniques in their boost factor, voltage gain, duty ratio, and the voltage stress across the switches. Thangaprakash and Krishnan (2010) and Cong-Thanh Pham et al (2012) presented a much more detailed comparison including total harmonic distortion (THD) on voltage and current for the PWM control schemes applied on Z-source inverter.

Xinpeng Ding et al (2007) proposed a PID control strategy for DC-link boost voltage in Z-source inverter. A control technique based on simple boost PWM technique is presented to control linearly the capacitor voltage, which improves the transient response of the Z-source inverter. The PID
controller enhances the rejection of disturbances, including the input voltage ripple and load current variation, and has good ride-through for voltage sags. Quang-Vinh Tran et al (2007) developed an algorithm to control the capacitor voltage linearly which helps to improve the transient response of the system during boost control operation of the Z-source inverter. This algorithm is used to control both the DC boost and AC output voltage of the Z-source inverter. The signal corresponding to the peak value of AC output voltage is assigned as a feedback signal to the PI controller. The output of the PI controller is used as the reference signal for generating PWM pulses.

Poh Chiang Loh et al (2007) presented the transient modeling and analysis of voltage type Z-source inverter. The transient behavior of the impedance network is studied and analyzed using small signal and signal flow graph methods. Jingbo Liu et al (2007) presented the dynamic modeling of Z-source inverter in continuous conduction mode. The dynamics introduced by the impedance network is studied. The selection of impedance network elements is established from small signal equivalent circuits by plots with different parametric sweeps in the frequency domain.

The operation of Z-source inverter is analyzed with small valued inductor in its impedance network (Miaosen Shen and Fang Zheng Peng 2008). The continuous conduction mode and discontinuous conduction mode operations are analyzed with maximum constant boost PWM technique. The sequence of operation modes, output voltage, capacitor voltage, voltage stress and voltage gain relationships are obtained. The analysis is verified by simulation and experimental results. But the results provided are valid only under the specific control method. The circuit can have different sequence of operation modes with different control methods and different circuit parameters, which yields different circuit characteristics.
A more detailed analysis of all possible operating states of the impedance network in steady state is described by Sumedha Rajakaruna, and Laksumana Jayawickrama (2010). The voltage-current variation in each of the six states is analyzed with equations to predict the behavior of Z-source inverter. The analysis shows that the ripples of the capacitor voltage increases the ripple in the DC link voltage, which will degrade the waveform of the inverter output by giving rise to unexpected harmonics besides increasing the voltage rating of the inverter. Similarly, the ripple of the inductor current increases the rating of the input diode and source. To eliminate the voltage and current ripples, a method is proposed based on the derived equations to design the inductor and capacitor in the impedance network for any operating conditions. But the design involves high mathematical complex solution process.

The concept of bidirectional Z-source inverter is developed by Jacek Rabkowski (2007) as the interfacing element between three phase grid and energy storage. This idea is to make possible energy exchange between DC and AC sides in both directions without any change in the principles of operation. This work also explained the control of switches in both inverter mode and rectifier mode operation. This idea is also presented by Yeyuan Xie et al (2006) in Z-source rectifier concepts.

The operational principles and seven modes of bidirectional Z-source inverter are explained by Haiping Xu et al (2008). The design guidelines for the impedance network elements and main circuit power devices are provided. Due to additional switch in the impedance network, the PWM approach is different from that of basic Z-source inverter. Jacek Rabkowski et al (2008) presented the concept of carrier based PWM strategies for bidirectional Z-source inverter. The developed control strategies
are compared for output current THD. The impact of the proposed PWM methods on the design process is explained.

1.2.3 Power Conditioning System

A PV power conditioning system using Z-source inverter for residential applications is proposed by Yi Huang et al (2006). The basic requirements of the power conditioning system converter to transfer energy from PV array to load are explained. The possible advantages of Z-source inverter based power conditioning system as compared to traditional transformer based inverter and DC-DC boosted inverter are explained. The simple boost PWM technique is applied for controlling the Z-source inverter. The design guidelines are provided based on voltage and current ripples. The authors did not discuss the MPPT algorithm to receive the maximum power from PV array.

Miaosen Shen et al (2007) made a comparison between conventional pulse width modulated inverter, DC to DC boosted inverter and Z-source inverter in a power conditioning application. Switching device power, passive components requirements, reliability and efficiency are the parameters taken for comparison. Mathematical expressions and curves of the parameters are derived. Z-source inverter provides superior results in efficiency, reliability, and the average switching device power. But the passive component requirement is slightly increased in Z-source inverter compared to other inverters. This work also explained how the Z-source inverter decreases the cost, volume and thermal requirements in practical applications.

Po Xu et al (2006) presented a work on Z-source inverter for PV grid connected generating system. This paper explained PV array output voltage control and MPPT realization by shoot-through duty cycle control.
The perturbation and observation (P&O) MPPT approach is employed in this system for extracting the maximum power from the PV array. The boosting capability of the Z-source inverter in PV power generation is investigated by Pattanaphol et al (2011).

The summary of Z-source inverter technology based power conditioning systems is presented by Fang and Yi Huang (2007) for renewable energy sources like PV, fuel cells and wind power based power generation. This paper explained the superiority of Z-source inverter by comparing with the traditional PWM inverter and the DC-DC boosted converter in terms of efficiency, reliability and cost.

Babak Farhangi and Shahrokh Farhangi (2006) developed a single phase PV power conditioning system based on Z-source inverter. The switching pattern for the modulation of the single phase Z-source inverter is presented. Since in single phase applications, the output power is not constant and leads to a low frequency ripple in the inverter elements, an approximate analysis which considers this effect is proposed. The proposed methods are verified by simulation. Chen et al (2007) presented an integrated single phase single stage PV grid connected inverter based on the Z-source inverter. The inverter integrates three functional blocks including MPPT, voltage boost and output grid connected current. This paper utilizes P&O algorithm for MPPT.

Richard Badin et al (2007) explained the process involving tracking the maximum power point of the PV array to output a certain level of power onto the grid. The conventional perturb and observe MPPT method is used. This paper also explained the method to obtain the reference signal from the MPPT controller to control the Z-source inverter. The maximum boost PWM technique is used in this work along with MPPT. The given simulation results proved that Z-source inverter can perform maximum power tracking and produce the AC voltage to the grid for the entire PV range.
Mo Wei et al (2012) presented the MPPT method for a Z-source inverter based grid-tie system. Conventional incremental conductance MPPT algorithm is used in this work to extract the maximum solar power from PV array. Uthirasamy and Ragupathy (2013) presented the realization of maximum boost Z-source inverter for solar battery charging applications. Delesposte Paulino et al (2011) reviewed different inverter topologies intended to interface the renewable energy sources to the utility.

1.3 PROBLEM DEFINITION AND OBJECTIVES

1.3.1 Problem Definition

Based on the literature review, the following challenges are identified. Besides DC to AC conversion, the ability to boost the PV voltage without additional DC to DC boost converter or transformer makes the Z-source inverter very attractive for the PV power conditioning applications. The main focus of this research work is to improve the performance of the Z-source inverter which is employed in PV power generation. The output voltage waveforms of the Z-source inverter are usually non-sinusoidal in nature as such contain harmonics. These harmonics should be mitigated because of their negative effects on the power system equipment and power quality. The aim is to propose a new switching scheme for Z-source inverter, which offers an improved performance in comparison with the existing PWM strategies in terms of voltage stress and harmonic content on output voltage and current. The second stage is the development of efficient MPPT algorithms to deliver the maximum power to the utility under varying ambient conditions.

1.3.2 Research Objectives

The main objectives of this research are summarized as:
i. Development of the mathematical model of a photovoltaic module and study its characteristics for various operating conditions by simulation and validate the model using conduction of experiments.

ii. Modeling and simulation of three phase Z-source inverter to analyze the steady state and dynamic state characteristics. Analysis of the model for the proper selection of the impedance network components for minimal voltage ripple, current ripple and transient time period for the given system specifications.

iii. Minimization of output THD and voltage stress by proper selection of PWM schemes for Z-source inverter.

iv. Analysis of the performance parameters of Z-source inverter for various PWM techniques.

v. Implementation of MPPT strategies for Z-source inverter based power conditioning system to extract the maximum power from the PV module with high overall efficiency.

vi. Development of modified space vector PWM switching strategy for bi-directional Z-source for its performance improvement.

1.3.3 Methodology of Research Work

The mathematical model of the PV module has been developed using MatLab/Simulink at different environmental conditions and it has been validated practically using electronic load method. Z-source inverter and
associating power conditioning unit have also been modeled with MPPT methods. The parameters of the impedance network have been tuned using steady state and dynamic analysis.

To minimize output THD and voltage stress across the switching devices, the different PWM techniques have been applied for the system and the analysis have been carried out. The simulated models have been practically implemented. The control logic has been implemented using TMS320LF2407A DSP processor.

1.4 ORGANIZATION OF THESIS

Chapter 1 Introduction

The need of the Z-source inverter in the photovoltaic power generation is highlighted in Chapter 1. A detailed survey of literature is carried out. This chapter also includes research methodology, research objectives, and the organization of the thesis.

Chapter 2 Photovoltaic System

Chapter 2 gives a brief description of the PV materials and basic function of PV cell. A generalized PV model is built based on the single diode equivalent circuit for a given SOLKAR PV module and simulated. A simple electronic load method is also presented to validate the model.

Chapter 3 Z-Source Inverter

The operation principles, steady state analysis and transient state analysis of Z-source inverter are explained in this chapter. The state-space averaging method is explained to derive the small-signal model of Z-source
inverter. The verification of effectiveness of the derived mathematical model by comparing with the actual switching circuit is presented.

Chapter 4 Pulse Width Modulation Techniques for Z-Source Inverter

This chapter describes different PWM strategies for controlling a three phase Z-source inverter. Two carrier based PWM techniques and a modified space vector PWM technique are proposed in this chapter. The simulation and experimental results of all the proposed PWM techniques are presented. A comprehensive comparison of the various modulation strategies for Z-source inverter is also presented.

Chapter 5 Maximum Power Point Tracking Techniques

This chapter explains the modified P&O algorithm, incremental conductance algorithm and fuzzy logic based MPPT techniques for Z-source inverter based MPPT controller. Simulation results are provided for different operating solar irradiance conditions. The experimental results are provided to validate the simulation results.

Chapter 6 Bi-directional Z-Source Inverter

Chapter 6 presents the modes of operation and control of bi-directional Z-source inverter for energy storage applications. Based on the space vector PWM technique, two different control methods are proposed. The output THD of these methods is compared with that of existing PWM techniques. The comparative results for showing the effectuality of the proposed PWM methods are presented.
Chapter 7 Conclusions and Scope for Future Work

Chapter 7 presents the conclusion and suggestions for future work that can be carried out. The salient features of this work and the major contributions are summarized.