1. INTRODUCTION

Wind energy is the most competitive renewable energy source and its cost-competitiveness is being improved as wind power technology advances. The future of wind-electric conversion is tied to advances in power electronics technologies. Traditionally, various electric machines have been used for wind power generation. DC shunt generators with battery storage were used in early small systems. Their commutators and brushes required regular maintenance. Synchronous or asynchronous ac generators are now universally employed, with simple diode rectifiers used to convert the ac power into DC, if needed.

1.1. Wind generators

Advantage of a synchronous generator compared with a DC generator is its higher efficiency. When it is directly connected to the grid, this machine requires synchronising equipment. With controllable excitation current, synchronous generator can carry out automatic voltage regulation and maintain high power factor operation, but requires field control equipment and hence it is more expensive than an induction generator. Permanent Magnet (PM) generators do not require field excitation control facilities, however the generated internal voltage is proportional to the machine speed, and so the power factor is not controllable by the machine itself. Due to its greater power capture and its ability to absorb loads caused by sudden wind speed changes without undue mechanical stresses, the variable speed system is becoming more and more popular.

Permanent Magnet (PM) generator has fixed field excitation, which does not require a power supply, but the output voltage magnitude, and therefore the dc link voltage vary with the turbine speed. A significant feature of the PM machine is that it is suitable for the development of a direct drive system without a gear box. Permanent magnets can provide loss free excitation for synchronous electric machines to replace electromagnetic excitation. Larger machines have not used permanent magnet excitation since at large scales power /weight ratio and cost are more. However, eliminating excitation control field coils, brushes and the excitation power loss is significant benefit, particularly for large multipole synchronous machines. Continued advances in the development of new materials have increased the usage of permanent-magnet machines considerably.
1.2. Control Method

With the evolution of wind energy conversion system (WECS) during the last decade, many different control methods have been developed. The control methods developed for WECS are usually divided into the following two major categories:

- Constant-speed methods, and
- Variable-speed methods.

In constant-speed turbines, there is no control on the turbine shaft speed. Constant speed control is an easy and low-cost method, but variable speed brings the following advantages:

- Maximum power tracking for harnessing the highest possible energy from the wind,
- Lower mechanical stress,
- Less variations in electrical power, and
- Reduced acoustical noise at lower wind speeds.

![Comparison of power produced by a variable-speed wind turbine and a constant-speed wind turbine at different wind speeds](image)

To review the advantages mentioned above [1] compares the power extracted for a real variable-speed wind turbine system, with a 34-m-diameter rotor, against a constant-speed wind turbine at different wind speeds. The results are illustrated in Figure 1.1. The figure shows that a variable-speed system outputs more energy than the constant-speed system.

1.3. Power Electronic Converter

The power electronic (PE) converter has an important role in modern WECS with variable-speed control method. The constant-speed systems hardly include a PE converter, except for
compensation of reactive power. The important challenges for the PE converter and its control strategy in a variable speed WECS are

- To attain maximum power transfer from the wind, as the wind speed varies, by controlling the turbine rotor speed, and to change the resulting variable-frequency and variable-magnitude AC output from the electrical generator into a constant-frequency and constant-magnitude supply which can be fed into an electrical grid.

As a result of rapid developments in power electronics, semiconductor devices are gaining higher current and voltage ratings, less power losses, higher reliability, as well as lower prices per kVA. Therefore, PE converters are becoming more attractive in improving the performance of wind turbine generation systems. It is worth mentioning that the power passing through the PE converter (that determines the capacity the PE converter) is dependent on the configuration of WECS. In some applications, the whole power captured by a generator passes through the PE converter, while in other categories only a fraction of this power passes through the PE converter. The most common converter configuration in variable-speed wind turbine system is the rectifier inverter pair.

1.4. Drawbacks of traditional PWM converter system

- System with traditional voltage source inverter (VSI) and current source inverter (CSI) operate in either boost mode (CSI) or buck mode (VSI), not in buck–boost mode. Most of the system uses VSI cannot produce output more than the input.
- Sufficient protection from electromagnetic interference (EMI) is required otherwise it may cause misgating or shoot-through in a VSI or may cause an open inductor circuit in CSI, which can damage the switches because of high current or voltage stresses.
- Dead times are required to introduce for switching pulses in case of VSI to avoid simultaneous turning on of switches in a same leg leading to short circuit. Similarly for CSI overlap time is introduced. Both of them can cause distortion in output sinusoidal waveform.
- The power circuit topology of VSI and CSI are not interchangeable, that is VSI main circuit cannot be used forCSI or vice versa.

A few of the drawbacks above can be eliminated by adding a dc-dc boost chopper between the rectifier and inverter bridge, but this reduces the power conversion efficiency as it is a two-stage
conversions (DC–DC boost and DC–AC). It uses additional switch that raises the system cost/weight and size.

1.5. Z-source converters

Impedance (z) source converters are introduced recently [2]. Z-source converters are proposed both for dc-ac and ac-ac conversions. For dc-ac conversion, a z-network of two inductors and two small capacitors connected between DC power source and the inverter bridge eliminates all the above-mentioned problems and it requires no extra switch. The network acts as a second-order filter to suppress voltage ripples more effectively than capacitor used in traditional PWM inverter and the inrush current and harmonics in the current can be reduced via the inductor [3]. Moreover the VSI based ZSI provides some special features that cannot be observed in the traditional inverter They are

- It acts as a boost converter for dc- ac power conversion, desired ac voltage can be obtained, which is even greater than the source voltage.
- A short circuit across any phase leg is allowed, and so the provision of dead time is not necessary.

However, in case of dc-ac z-source inverter(ZSI), depending of the topologies of impedance network, they are categorised as simple ZSI, Quasi ZSI, Trans Quasi ZSI and Trans ZSI as shown in the Fig1.2. There are different switching techniques employing shoot-through pulses namely simple boost control (SBC), maximum boost control (MBC), maximum constant boost control (MCBC) etc.

Again in case of ac-ac z-source converter proposed recently [4] has the capability to buck/boost the output voltage with minimal components. In single phase configuration it uses two inductors and two capacitors in a symmetric manner and in three phase ac-ac conversion it uses three inductors and three capacitors and can transfer the energy from ac to ac directly. It can overcome voltage sag or voltage surge in power system easily. Though it is suitable for variable voltage power source, it is not applicable in variable frequency power source.

1.6. The Proposed Wind Energy Conversion System

Impedance (z) source inverter proposed recently has effectively replaced the conventional inverter system. The buck-boost capabilities of impedance (z) source inverter take care both the generator power source and load variations. The variable voltage-variable frequency wind generator output due to unpredictable variation in wind speed is suitably controlled through a closed loop system
employing the buck-boost capability of z-source converters. The conventional PWM inverter is replaced by simple z-source inverter, quasi z-source inverter and trans-quasi z-source inverter one by one and performances are studied. Ac-ac z-source converter with different topologies are also tried for direct conversion of ac power, may be used for discrete variable voltage system. The closed loop controller carefully monitors wind generator voltage and controls the shoot-through duty cycles of the converter employing different switching control techniques to develop a three phase regulated stable boosting voltage, which is not possible by conventional PWM control. Each system is modeled, analyzed and verified through simulation and experimented through hardware prototype. It provides the unique output voltage regulation by making an appropriate choice of boost factor under both variable voltage and variable load conditions. The proposed closed loop system, therefore, can be used for smooth and effective dynamic and steady state control maintaining the level of three phase output at a desired level.

![Figure 1.2 Topologies and control methods of z-source converter](image)

**1.7. Thesis Objectives**

This work aims to investigate the application of different ZSC in wind energy conversion systems for two reasons: first, ZSC is an emerging technology with the potential of replacing conventional converter, and second, no thorough study of this application has been made so far.

The main objectives of this thesis are as follows:
1- Detailed extended analysis of different topologies of DC-AC and AC-AC ZSC and justification of using for wind power application.
2- Developing a comprehensive dynamic model for the above converters and design of impedance network and controller.
3- Development of suitable closed loop system for effective wind power control using different ZSC topologies and different switching techniques. To find its performance through simulation.
4- Developing hardware prototype of the proposed system with microcontroller based control system and verifies its performance through experimentation for different ZSC topologies.

1.8. Thesis Outline

Chapter 2 is dedicated to the extensive literature survey in the area of wind power converters, z-source converters.
Chapter 3 presents an overall analysis of z-source converters topologies in open loop mode. Performance with derivation of different parameters are evaluated All the parameters are compared between all z-source inverter topologies under three different switching techniques. Suitable switching technique is selected from the study.
Chapter 4 presents the modeling of z-source converters with different topologies using state space averaging technique and small signal analysis. It also presents the design of the parameters of z-source network components used in different topologies.
Chapter 5 presents all the simulation results of WECS based on z-source inverters (ZSI) having different topologies in MATLAB-SIMULINK environment. Simulation is done on the basis of feed-forward closed loop controller designed and developed using selected switching technologies. All the results are explained on the basis of effective wind power conversion. This chapter also presents a study of ac-ac ZSC both single phase and three phase with a design of novel closed loop system for possible use with variable voltage discrete source.
Chapter 6 explains the details of hardware prototype developed in the laboratory for microcontroller based closed loop z-source inverter. It describes all the hardware components separately with detailed circuit diagram and physical view. Experimental results in line with the simulation work are presented and verified in this chapter.
Chapter 7 summarizes the thesis main points and contributions, and proposes future directions for research.
Finally, the thesis ends with appendixes as listed in the table of contents.