Wind Energy Conversion System of Doubly Fed Induction Generator using Maximum Power Point Tracking Technique and Z-Source Inverter

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Abstract
The aim of this paper is to deliver the maximum power to the grid from the wind energy by using Doubly-fed Induction generator and Z-source Inverter. To harness the maximum wind power, Maximum Power Point Tracking technique was used. Z-Source Inverter is used to boost up the power from rotor side converter. The DFIG brings the advantage of utilizing the turns ratio of the machine, so the converter does not need to be rated for the machine’s full rated power. The rotor side converter (RSC) usually provides active and reactive power control of the machine while the grid-side converter (GSC) keeps the voltage of the DC-link constant. The Z-source inverter is an alternative power conversion topology that can both buck and boost the input voltage using passive components. With its unique structure, Z-source inverter can utilize the shoot through states to boost the output voltage. The shoot-through duty cycle is used for controlling the DC-link voltage boost and hence the output voltage boost of the inverter. Simple protection circuit was used here to protect the WECS. Simulation of induction generator and Z-Source Inverter are presented here.

Key words: Double Fed Induction Generator (DFIG), Z-source Inverter, Maximum Power Point Tracking, shoot through states, Duty Cycle, Wind Energy Conversion System

1.0 Nomenclature
\( \rho \) - Air Density, 
\( C_p \) - Power Coefficient, 
\( \lambda \) - Tip Speed Ratio (TSR), 
\( A \) - Cross Sectional Area of Turbine, 
\( V_w \) - Wind Velocity (m/s) 
\( R \) - radius of the wind turbine blade 
\( P_{\text{max}} \) - Maximum output power 
\( V_d \) - Diode bridge rectifier Voltage 
\( T_m \) - torque due to the load 
\( V_L \) - Line to Line Voltage 
\( B \) - Boost factor 
\( T_{\text{sh}}/T \) - Shoot through duty ratio

2.0 Introduction
Wind power has been recognized as a viable source of “free” energy for hundreds of years. Since it pre-dates the petroleum economy or even the industrial revolution, it seems odd to refer to it as an “alternative” energy source. Wind turbines have been a significant player as a renewable energy source since the early 1980s. Wind power covers a wide range of applications and can be harnessed by large wind turbine farms providing up to 800 MW of power, and small residential wind turbines providing 3 kW to a home. Wind energy has been intensively investigated in recent years in many different countries, which resulted in several different configurations like fixed speed system with a SCIG, the variable speed system with permanent magnet synchronous generator (PMSG) and the variable speed system with a DFIG to improve the efficiency, power rating, cost benefit effectiveness etc. Wind is highly variable in nature, so variable speed DFIG based WECS offers many advantages compared to the fixed speed squirrel cage induction generators, such as reduced converter rating, cost and losses in result of that an improved efficiency, easy implementation of power factor correction, variable speed operation and four quadrants active and reactive power control capabilities. Due to variable speed operation, total energy output is much more in case of DFIG-based WECS, so capacity utilization factor is improved and cost of per unit energy is reduced. A wind energy conversion system using DFIG is shown in Fig.1. When rotor rotates which is directly coupled with wind turbine generates inconstant voltage and frequency. The inconstant voltage and frequency is converted to DC voltage by Controlled rectifier and then fed to Z-Source inverter network.

3.0 Wind Turbine Characteristics
The power produced by a wind turbine is given by 
\[ P_w = 0.5 \rho A C_p \lambda^3 \] 
where \( \rho \) - Air Density, \( C_p \) - Power Coefficient, \( \lambda \) - Tip Speed Ratio (TSR), \( A \) - Cross Sectional Area of Turbine, \( V_w \) - Wind Velocity (m/s) 
The tip speed ratio is given by 
\[ \lambda = \frac{\Omega R}{V_w} \] 
where \( \Omega \) is the turbine rotor speed and \( R \) is the radius of the wind turbine blade.

\[ \frac{d\omega_r}{dt} = (1/J) \left[ T_m - T_L - F \omega_r \right] \] 
Where \( J \) is the moment of inertia, \( F \) is the viscous friction coefficient, \( T_m \) is the torque developed by the turbine, \( T_L \) is the torque due to the load which in this case is the generator torque. The target optimum power from a wind turbine can be written as 
\[ P_{\text{max}} = K_{\text{opt}} \omega_{\text{opt}}^3 \] 
where 
\[ K_{\text{opt}} = 0.5 \rho C_{p_{\text{max}}} R^2 / \lambda_{\text{opt}}^3 \] 
\[ \omega_{\text{opt}} = \lambda_{\text{opt}} V_w / R \] 
In Fig.2, WECS maximum power point tracking (MPPT) characteristics is shown. In this figure, the turbine output at
different wind speed is shown for $\beta = 0$. The WECS is capable to capture the maximum power from the available wind regime.

![Maximum power tracking line](image)

**Fig 2.** WECS maximum power point characteristics

### 4.0 Z-Source Inverter

#### 4.1 Control of Z-Source Inverter

The distributed power system proposed is shown in Fig.1. The system is a one stage converter which includes a variable speed wind turbine, Z-source network, and inverter system connected to the grid. The purpose of the input capacitors is to serve as the dc source feeding the Z-source network. The voltage of the generator fed to the Z-source inverter varies according to the wind speed. It is assumed that the DC voltage fed to the Z-source inverter is defined in where \( V_{LL} \) is the line to line voltage of the generator. In the normal operation mode, the inverter bridge voltage, \( V_{PN} \), is equal to the dc input voltage obtained from the diode rectifier bridge, \( V_d \).

\[
V_d = \frac{3\sqrt{2}}{\pi} V_{LL} = 1.35 V_{LL}
\]

However, in the boost operation mode where the shoot through states are applied, the voltage across the inverter bridge is a function of the boost factor, \( B \) and \( Vd \).

\[
V_{PN} = BV_d
\]

In the boost mode, the output peak phase voltage, \( V_{ac} \), generated by the inverter is expressed in where \( M \) is the modulation index.

\[
\hat{V}_{ac} = M \frac{V_{PN}}{2} = MB \frac{V_d}{2}
\]

There are several methods used to control the boost function of the Z-source inverter such that

(i) Simple boost control
(ii) Maximum boost control
(iii) Maximum constant boost control methods

These control methods have been detailed in [4]-[6]. Among them, the maximum boost control is chosen for this design since it provides lower voltage stress across the inverter bridge switches. In this control method, all six-active states are still unchanged, whereas all zero states are basically turned into shoot-through states. The shoot-through states are determined by comparing the triangle carrier wave with reference signals. With this comparison, the shoot-through states are introduced when either the triangle wave is bigger or smaller than the reference. The capacitor voltage can be expressed as in below equation, where \( V_{C1} \) and \( V_{C2} \) are the voltages across capacitor \( C1 \) and \( C2 \), respectively.

\[
V_{C1} = V_{C2} = V_C = \frac{1-\frac{T_0}{T}}{1-2\frac{T_0}{T}} V_d = \frac{B+1}{2} V_d
\]

\( T_0 \) is the shoot-through interval of one switching cycle \( T \). \( T_0/T \) is known as the shoot-through duty ratio, \( D_0 \). For maximum boost control, the shoot-through duty ratio is expressed as the average of shoot through duty ratio, \( T_0/T \), as shown and \( B \) is the boost factor

\[
B = \frac{1}{1-2\frac{T_0}{T}} = \frac{\pi}{3\sqrt{3}M - \pi}
\]

#### 4.2 Boost Control

Like conventional inverter control, the PWM signal is generated by comparing the reference signal and the carrier signal. However, for the Z-source inverter where shoot through states are needed, the maximum boost control method creates the shoot-through states by turning all zero states of a conventional inverter into shoot-through states of the Z-source inverter. In the closed loop boost control, the block diagram of the control system is shown in Fig. 3. This control is used to regulate the voltage across the capacitor of the Z-source network in order to ensure that the power can be effectively delivered to the utility grid.

There are two control loops, the inner loop or current loop and the outer loop or voltage loop. The inner loop is used to direct the inductor current, \( ILZ \) where its reference signal is introduced by the outer loop. The outer loop is used to maintain the voltage across the capacitor of the Z-source network, \( V_{CZ} \). In this outer loop, the voltage across the capacitor is compared to the capacitor voltage reference signal, \( V_{CZ}^{*} \). The error of these two signals is fed to the PI controller to create the current reference for the inner loop.

The error of the current difference is fed through the proportional gain of the inner loop to produce the reference signal of the shoot-through states. To avoid the effect of shoot-through states on active states, the shoot-through reference signal should be restricted according to the possible input voltage and the required output voltage. This is defined in above equations. \( Y_{min} \) is the minimum of the generated shoot through reference and \( Y_{max} \) is the maximum of the generated shoot-through reference; these are used to create the shoot through duty ratio, \( D_0 \). Note that the lower shoot-through reference provides the higher boost factor. Finally, the output of the boost control is sent to the PWM modulator to generate the shoot-through duty ratio.

![Fig. 3. Block diagram of the boost control](image)

### 5.0 Simulation Modeling and Result

The energy is fed to the grid through the Z-source inverter system and the three phase transformer. The grid was modeled as a three-phase voltage source. The rotor of the generator is connected to the rotor side converter through switch in the actual setup. The crowbar protection is also depicted in Figure 3. By switch, the resistor bank may be connected to the rotor windings. This is activated when a fault occurs and transients are so high that the generator must be
protected by short-circuiting the rotor. For a doubly fed induction generator connected to grid side with wind turbine protection schemes involved for protection from single phase faults and ground faults.

![Fig. 4. Simulation Model](image)

![Fig. 5. PWM Signal Generator](image)

![Fig. 6. Generator Voltage and Current](image)

![Fig. 7. Output of RSC](image)

![Fig. 8. Inverter Voltage Waveform with filter inductor](image)

![Fig. 9. Inverter Current Waveform](image)

### 6.0 Conclusion

In this project, a control system that improves the efficiency of the whole wind energy conversion process has been proposed. The control system provides minimum resistive power loss of the Doubly Fed Induction Generator in combination with maximum power tracking of the wind turbine. Thus, by making use of the existing wind energy potential, the electrical energy extracted from the WECS is increased and expansion of the exploitable wind speed region toward the lower speeds can be achieved. The generator is connected to the power grid by means of Z-Source Inverter. The current study verifies the theoretical analysis through an experimental laboratory setup with an emulated wind turbine and demonstrates the improvements over conventional WECS control schemes. However, the future direction is to apply the proposed control system on a real wind turbine in order to verify its effectiveness in actual wind conditions.

### Appendix

#### Doubly Fed Induction Generator machine parameters

<table>
<thead>
<tr>
<th>P</th>
<th>Number of poles</th>
<th>6</th>
</tr>
</thead>
<tbody>
<tr>
<td>R_s</td>
<td>Stator resistance</td>
<td>0.029 ohms</td>
</tr>
<tr>
<td>L_s</td>
<td>Stator inductance</td>
<td>0.7 mH</td>
</tr>
<tr>
<td>L_m</td>
<td>Magnetizing inductance</td>
<td>0.3 H</td>
</tr>
<tr>
<td>R_r</td>
<td>Rotor resistance</td>
<td>0.022 ohms</td>
</tr>
<tr>
<td>L_r</td>
<td>Rotor inductance</td>
<td>0.7 mH</td>
</tr>
<tr>
<td>V_a</td>
<td>Stator phase voltage</td>
<td>575 V</td>
</tr>
<tr>
<td>Grid frequency</td>
<td>50 Hz</td>
<td></td>
</tr>
<tr>
<td>Nominal mechanical rotor speed</td>
<td>100 rad/sec</td>
<td></td>
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<tr>
<td>Rated Maximum Power</td>
<td>100 kW</td>
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</table>

#### Z-Source Inverter Parameters

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Z-source inductors ($L_1 = L_2$)</td>
<td>550 μH</td>
</tr>
<tr>
<td>Z-source Capacitors ($C_1 = C_2$)</td>
<td>400 μF</td>
</tr>
<tr>
<td>Input Capacitors($C_a, C_b$, and $C_c$)</td>
<td>12 μF</td>
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<tr>
<td>Switching frequency, $f_s$</td>
<td>10 kHz</td>
</tr>
</tbody>
</table>

### 7.0 References


[9]. Dr Sandy Smith, Rebecca Todd, Dr Mike Barnes & Prof. Peter J. Tavner, “Improved Energy Conversion for Doubly Fed Wind Generator”, 0-7803-9208-6/05 © 2005 IEEE.