A DOUBLY-FED INDUCTION GENERATOR DRIVE FOR A WIND ENERGY CONVERSION SYSTEM

P. S. Barendse* and P. Pillay**

* University of Cape Town, Dept. of Electrical Engineering, Private Bag, Rondebosch, 7701, South Africa
** Clarkson University, Dept. of Electrical and Computer Engineering, Potsdam, NY 13699, USA

Abstract: In recent years, there’s been a renewed interest in renewable energy sources due to the associated environmental problems and eventual shortage of fossil fuels. Wind energy has gained the most interest of all the renewable energy sources due to the progress in wind related technology [1, 2]. The ability of the doubly-fed induction generator (DFIG) to achieve variable speed control with the reduced cost of converter requirements proves to be extremely attractive for the purpose of wind generation [3]. The reduction in cost is achieved through the control of the torque-speed characteristics of the DFIG from the rotor-side. While this system is commercialized, the companies have not published details of the control strategies. This paper provides the necessary background and results to fill the void between the commercial product produced by a company like Vesta’s, and the literature. The hardware setup, simulated results and experimental results are also presented.

Key words: Wind energy conversion systems, Doubly-fed induction generator.

1. NOMENCLATURE

<table>
<thead>
<tr>
<th>Symbols</th>
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<tbody>
<tr>
<td>(v_a, v_b, v_c)</td>
<td>- 3-phase supply voltage (output of variac)</td>
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<tr>
<td>(i_a, i_b, i_c)</td>
<td>- 3-phase supply-side converter input currents</td>
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<tr>
<td>(v_D, v_Q)</td>
<td>- 2-axis supply voltage</td>
</tr>
<tr>
<td>(i_D, i_Q)</td>
<td>- 2-axis supply-side converter input currents</td>
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<tr>
<td>(T)</td>
<td>- Torque</td>
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<tr>
<td>(E)</td>
<td>- DC-Link Voltage</td>
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<tr>
<td>(s)</td>
<td>- slip</td>
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<tr>
<td>(L, R)</td>
<td>- inductance and resistance of supply-side converter</td>
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<tr>
<td>(\theta_s, \theta_r, \theta_e)</td>
<td>- stator flux, rotor, supply voltage vector position</td>
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<tr>
<td>(\theta_r)</td>
<td>- rotor position</td>
</tr>
<tr>
<td>(\omega_r)</td>
<td>- rotor speed</td>
</tr>
<tr>
<td>(C)</td>
<td>- DC-Link Capacitance</td>
</tr>
<tr>
<td>(L_s, L_m, L_r)</td>
<td>- machine inductances</td>
</tr>
<tr>
<td>(R_s, R_r)</td>
<td>- machine resistances</td>
</tr>
<tr>
<td>(P)</td>
<td>- pole pairs</td>
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<tr>
<td>(\lambda)</td>
<td>- flux</td>
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Suffixes, Superscripts

<table>
<thead>
<tr>
<th>Symbols</th>
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<tbody>
<tr>
<td>s, r</td>
<td>- stator, rotor</td>
</tr>
<tr>
<td>D, Q</td>
<td>- D-Q axis</td>
</tr>
<tr>
<td>(\alpha, \beta)</td>
<td>- (\alpha-\beta) axis</td>
</tr>
<tr>
<td>*</td>
<td>- reference value</td>
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2. INTRODUCTION

Due to the economical and environmental benefits, Wind Energy Conversion Systems (WECS) have received tremendous growth in the past decade. The increased interest in wind energy has made it necessary to model and experimentally evaluate entire WECS, so as to attain a better understanding and to assess the performance of various systems. This paper describes a control strategy for a doubly-fed induction generator (DFIG) drive that is in commercial production, but whose technical details have not been published by the manufacturers.

3. FUNDAMENTALS OF WIND POWER

Wind turbine power depends on both the rotor speed and wind speed. The captured power is given by the following equation [4]

\[
P = \frac{1}{2} \rho C_p A V^3
\]

where

- \(\rho\) mass density of air
- \(A\) area swept by rotor blades
- \(V\) wind speed
- \(C_p\) non-dimensional power coefficient

The relationship between rotor speed and wind speed can be given by

\[
\lambda = \frac{\omega_r R}{V}
\]

where

- \(R\) wind turbine rotor radius
- \(\lambda\) tip speed ratio
- \(\omega_r\) rotor speed
The non-dimensional power coefficient $C_p$ is a function of the tip-speed ratio $\lambda$ [4]. Fig. 1 illustrates a typical $C_p$ versus $\lambda$ curve. It is evident from Fig. 1 that for maximum energy capture, the maximum power coefficient and, thus, the optimum tip-speed ratio should be maintained at all wind speeds. The need to vary the rotor speed in accordance to the wind speed for maximum energy capture, establishes the foundation for the preferred choice of Variable Speed WECS.

![Power coefficient versus tip speed ratio](image)

Fig. 1. Power coefficient versus tip speed ratio

4. VARIABLE SPEED DOUBLY-FED INDUCTION GENERATOR FOR A WECS

There are essentially two types of WECS – Constant Speed WECS and the Variable Speed WECS. With Constant Speed WECS, the generator is directly connected to the electrical grid. As a result the speed of the wind turbine is determined by the grid frequency and varies based only on slip [5]. With Variable Speed WECS, the wind turbine rotational speed is allowed to vary so as to extract maximum energy from the wind turbine [6].

For variable speed generation, the wound rotor induction generator proves to be extremely attractive since the converters are located in the rotor circuit, thus reducing the rating and cost of the converter requirements since they need only handle the rotor power [7]. When both the stator and rotor are responsible for the transfer of power in an induction generator they are known as doubly-fed induction generators (DFIG). Fig. 2 illustrates a layout of a Variable Speed DFIG WECS with back-to-back converters in the rotor circuit.

![Variable speed WECS using a DFIG](image)

Fig. 2. Variable speed WECS using a DFIG

5. DESCRIPTION OF THE OVERALL SYSTEM

As shown in Fig. 2, the DFIG system uses an AC-AC converter in the rotor circuit. Fig. 3 represents a schematic of the vector control strategy used for the DFIG system. Field orientated control (FOC) of the machine is achieved via the rotor-side converter, which allows for independent control of torque and rotor excitation. The supply-side converter is responsible for maintaining a constant DC-link voltage and control of the power factor. A DC drive is used to emulate the wind turbine [6].

The system operates in two regions:
1. Sub-synchronous region: the rotor speed lies below synchronous speed, and the rotor absorbs power from the grid.
2. Super-synchronous region: the rotor speed lies above synchronous speed, and the rotor delivers power to the grid. The amount of power absorbed and delivered by the rotor is slip dependant [8].

5.1. Control of the Supply-Side Converter

The supply-side converter is used to maintain a constant DC-link voltage, regardless of the direction of rotor power flow. A vector control approach is used, as shown in Fig. 4, whereby independent control of active and reactive power is achieved.

![Schematic of a vector control system for a doubly-fed induction generator using back-to-back converters](image)

Fig. 3. Schematic of a vector control system for a doubly-fed induction generator using back-to-back converters
The supply voltage angular position is calculated as

\[ \theta_v = \arctan \left( \frac{v_q}{v_d} \right) \]  

(3)

where \( \theta_v \) represents the supply voltage vector position [7].

The DC-link voltage can be controlled via \( i_o \). The control scheme thus derives the \( i_o \) demand from the DC-link voltage error through a PI controller. The \( i_o \) demand is responsible for the transfer of reactive power. Once the setpoint 3-phase currents have been determined, they are processed by a hysteresis current controller, which determines the switching pattern of the IGBT converter.

The stator flux is determined as follows

\[ \lambda_{aS} = \int (V_{rS} - R_i \lambda_{oS}) \, dt \]  

(6)

\[ \lambda_{oS} = \int (V_{AS} - R_i \lambda_{oS}) \, dt \]  

(7)

The stator flux angle is calculated as follows

\[ \theta_s = \arctan \left( \frac{\lambda_{oS}}{\lambda_{aS}} \right) \]  

(8)

where \( \theta_s \) represents the stator flux position [7]. The \( \omega_s \) error is processed by a PI controller to give the setpoint torque (\( T^* \)). The diagram below indicates the complete vector control for the rotor-side converter using the above formula’s to calculate the stator flux and stator flux angle.

5.2. Control of the Rotor-Side Converter

Field orientated control from the rotor-side is achieved in the synchronously rotating \( DQ \) reference frame. The \( D \)-axis is aligned with the stator-flux vector position, which sets the \( Q \)-axis stator-flux component to zero. In this way, a decoupled control between the electrical torque and the magnetic field is obtained [7].

Since

\[ \lambda_{QS} = 0 \]  

(4)

the torque is described as follows

\[ T = -\frac{P}{3} \frac{L_m}{L_a} \lambda_{aS}^2 \theta_r \]  

(5)

Fig. 5 illustrates the schematic block diagram for the machine control. \( i_{Dn}^* \) is used to control the rotor excitation, however assuming that the reactive power to the machine is supplied by the stator, \( i_{Dn}^* \) may be set to zero [7]. The torque is proportional to \( \lambda_{aS}^2 \theta_r \), thus once \( T^* \) is determined via the speed controller, \( i_{Dn}^* \) is calculated (using the above torque equation). The 3-phase current setpoints are then achieved using the correct transformations, and the desired currents into the machine are attained via the use of the hysteresis current controller.

The controller card forms part of the Advanced Control...
7. SIMULATION RESULTS

7.1. Supply-side converter

The DC-link voltage is maintained at 300V while the converter is connected to a 100V supply. The diagrams below indicate the ability of the supply-side converter to allow for bidirectional power flow. Figs 7 and 8 indicate the supply voltages and currents for one of the phases. These results were attained, with \( i_p^* \) set to zero. Fig. 7 shows a phase displacement of 0° between the phase voltages and phase currents for the converter operating in rectifying mode, corresponding to sub-synchronous operation. Fig. 8 shows a phase displacement of 180° between phase voltages and phase currents for the converter operating in inverting mode, corresponding to super-synchronous operation.
7.2. Rotor-side converter

The simulation results indicate the generator operating at speeds 25% below (1120rpm) and 25% above (1880rpm) the synchronous speed at a constant Torque of 7Nm. Fig. 10 shows a speed profile of the DFIG as it is ramped up in speed from 1120rpm to 1880rpm over 5 seconds, through the synchronous speed. Fig. 11 shows the rotor phase currents when passing through the synchronous speed.

Figs 12 and 13 illustrate the bi-directional power flow capabilities of the rotor during sub-synchronous and super-synchronous operation. If the stator generates 1p.u. at a slip \( s \), the power delivered by the rotor is \(-s\) p.u. (neglecting losses).

8. EXPERIMENTAL RESULTS

8.1. Supply-side converter

The experimental results shown below were attained from similar conditions and tests as that of the simulations. The DC-Link voltage is maintained at 300V, while the variac is kept at 100V. Figs 14 and 15 show the supply voltages and currents for a single phase, during sub- and super-synchronous generation. The 0º and 180º phase displacement between the phase voltages and currents for the two respective modes are again evident, as with the simulations.
Fig. 16 shows the dynamic response of the experimental DC-Link voltage for a ramp up in generator speed. The use of the slow PI controller is evident by the slow response of the voltage to track the setpoint voltage of 300V.

![Image of DC Link voltage response](image1)

**Fig. 16. Experimental DC-Link voltage for operation through synchronous speed**

8.2. **Rotor-side converter**

Numerous tests were performed in both steady state and transient conditions, to test the performance of the rotor-side converter. The results shown below show the generator operating at 25% below (1120rpm) and 25% above (1880rpm) the synchronous speed, at a constant torque of 7Nm. This is identical to the conditions under which the simulations were performed.

Fig. 17 shows the speed response of the generator as the speed is ramped up from 1120rpm (sub-synchronous speed) to 1880rpm (super-synchronous speed) over 5s. The system requires approximately 4 seconds for the generator to stabilise at 1880rpm, unlike the immediate clamping of the simulated results. This is contributed to certain non-ideal conditions, which the simulations do not take into account. Fig. 18 displays the rotor phase currents as the generator passes through synchronous speed.

![Image of rotor speed response](image2)

**Fig. 17. Rotor speed response for operation through synchronous speed**

Figs 19 and 20 show the power delivered by the rotor during sub- and super-synchronous operation. The bi-directional capabilities of the system is once again evident, however the losses are greater than predicted by the simulations.

![Image of rotor phase currents](image3)

**Fig. 18. Rotor phase current response for operation through synchronous speed**

![Image of power delivered](image4)

**Fig. 19. Power delivered by the rotor sub-synchronous operation**

![Image of power delivered](image5)

**Fig. 20. Power delivered by the rotor during super-synchronous operation**
9. CONCLUSIONS

The paper has described the vector control strategy for a doubly-fed wind energy drive, with vector control from the rotor-side. The results attained for the system have been shown and discussed. They show the system operating under various steady state and transient conditions. The DFIG system was simulated so as to validate the control strategies and operation of the experimental system. The supply-side converter was shown to control the DC-link voltage and the reactive power flow while the rotor-side converter was shown to control the speed of the generator, with the use of a PI controller. The bi-directional power flow capabilities of the drive were also shown as the generator operated within the sub-synchronous and super-synchronous regions. This paper fills the void in the literature by describing mathematically and experimentally verifying a commercial product, thus allowing further research from the community.

10. REFERENCES


11. APPENDICES

Wound rotor induction machine ratings:

- Rated Power = 2.2kW
- Rated Voltage = 380V
- Rated current = 4A
- Speed at rated power = 1375 rpm

- Stator connection = wye
- Rotor connection = wye
- Pole pairs = 2

\[ R_s = 6.60 \] \[ R_r = 4.61\Omega \]
\[ L_s = 0.4459H \]
\[ L_r = 0.4459H \]
\[ L_m = 0.4178H \]