A Novel Rotor Current Controller Scheme for Grid Connected Doubly Fed Induction Generators

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Abstract—This paper presents a novel robust stator voltage oriented rotor current controller structure for grid connected doubly fed induction generators (DFIG). Controller is based on a proportional controller with first order low pass filter disturbance observer which estimates machine parameter dependent nonlinear terms. Therefore, necessity of accurate knowledge of machine parameters is not required. The results are demonstrated in experimental laboratory setup.

Keywords-component: DFIG, disturbance observer, wind energy

I. INTRODUCTION

Penetration of renewable energy sources, especially wind energy conversion systems has been increasing due to rapid consumption of fuel sources and environmental issues in recent years. Doubly fed induction generator (DFIG) based wind turbines are very advantageous compared to other generator types due to variable speed operation, reduced inverter cost, and four-quadrant active and reactive power flow capability.

There are several studies associated with DFIG control for wind energy conversion systems. Conventional grid connected DFIG controllers usually consist of direct vector control (DVC) strategies which use stator flux [1] or voltage orientation [2] in which the alignment of the d-axis is along with stator flux or voltage in synchronously rotating frame. These DVC schemes control decoupled rotor currents with proportional-integral (PI) controllers.

Direct Power Control (DPC) techniques which control stator active and reactive power without inner current loops are given in [5, 6]. There are also reputable studies using DPC [7, 8, and 9] which are robust against machine parameter variations and grid voltage problems. Several contributions are also encountered which use sliding mode control (SMC). One of the important contributions given in [10] achieves the grid connected DFIG control in harmonically distorted and unbalanced voltages. Robustness against voltage problems is achieved in [11] with second order SMC.

The first contribution regarding the usage of disturbance observer [12] in grid connected DFIG structures first appear in [13]. This study presents the simulation results of a direct proportional power controller with a disturbance observer without current control loops.

Despite the robustness of the DPC and SMC techniques summarized above, conventional DVC schemes which use decoupled PI type rotor current controllers as given in [1,2] are very popular due to its simplicity and applicability in real DFIG based wind turbines. Nonlinear cross-coupling terms are fed forward to controller which is dependent on machine parameters. Performance of DVC structure is highly dependent on the accurate knowledge of machine parameters.
This study proposes a stator voltage oriented DVC scheme which is independent on any machine parameter. All the machine parameter dependent terms are estimated via first order low pass filter disturbance observer and fed forward to the current control loop. A proportional controller is sufficient to control decoupled rotor currents. The proposed methodology is validated by using constructed experimental laboratory setup.

This paper is organized as follows; Problem formulation and DFIG dynamics are given in Section 2. Controller design and disturbance observer concept are given in Section 3. Experimental results are demonstrated in Section 4. Section 5 contains the conclusion and future work.

II. PROBLEM FORMULATION

A. DFIG Operation

Typical DFIG based wind turbines are depicted in Fig. 1. The stator is directly connected to the grid, and rotor is directed through a back-to-back converter.

![DFIG Equivalent Circuit](image)

Figure 1. Typical DFIG based wind turbines

Rotor Side Control (RSC) controls the stator power flow via controlling the rotor currents. Grid Side Control (GSC) has a task of maintaining the desired DC bus voltage regardless of the power flow direction. The operation of DFIG could be subdivided into two main operation regions; subsynchronous or supersynchronous speed in which the rotor power flow direction is toward rotor circuit or grid side respectively.

B. Mathematical Model of DFIG

Mathematical model describing the dynamic behavior of DFIG is written considering set of three phase windings both at stator and rotor. DFIG dynamic equations could be written from the equivalent circuit in synchronously rotating dq frame as given in Fig. 2. For more detailed analysis and modeling of DFIG, one can refer several numbers of sources in literature e.g. [14, 15]. DFIG dynamics could simply be defined in the following form.

\[ L_{sn} \frac{di_{sd}}{dt} = v_{sd} - X_{sd}(i_{sd,q}, i_{sd,q}, \omega_s, L_m, R_s, \Delta L_s, t) \]  

(2)

\[ L_{sr} \frac{di_{sr}}{dt} = v_{sr} - X_{sr}(i_{sr,q}, i_{sr,q}, \omega_s, \omega_m L_m, R_s, \Delta L_s, t) \]  

(3)

\[ L_{sr} \frac{di_{sr}}{dt} = v_{sr} - X_{sr}(i_{sr,q}, i_{sr,q}, \omega_s, \omega_m L_m, R_s, \Delta L_s, t) \]  

(4)

The terms \( L_{sn} \) and \( L_{sr} \) are the nominal value of the stator and rotor. Inductances could be expressed as follows;

\[ L_{sn} = L_{sr} + \Delta L_{sr} \]  

(5)

The function \( \chi \) represents the nonlinear and parameter dependent equations. All above derivation is realized in stator voltage oriented synchronously rotating frame and the alignment of the stator voltage is considered in d-axis which means that \( v_s = v_{sd} \). All the rotor variables are referred to the stator side.

Equation of motion could be simply defined by the following relation:

\[ \frac{d\omega_m}{dt} = \frac{1}{J}(T_m - T_e + b\omega_m) \]  

(6)

Finally, Stator active and reactive power could be described by the equations below.

\[ P_s = \frac{3}{2} (v_{sd}i_{sd} + v_{sq}i_{sq}) \]  

(7)

\[ Q_s = \frac{3}{2} (v_{sq}i_{sd} - v_{sd}i_{sq}) \]  

(8)

Dynamic behavior of DFIG is fully described, and rotor current controller is discussed in the following section.

III. ROTOR SIDE CURRENT CONTROLLER DESIGN

Rotor current dynamics are given in Eq. (3) and Eq. (4). It is obvious from definition that dynamic equation is separated into nonlinear parameter dependent function \( \chi \) and measurable rotor currents and voltages. Current errors could be given as following equation.

\[ \varepsilon_{sd} = i_{sd}^{ref} - i_{sd} \]  

(9)
The derivative of the errors is defined as follows.

\[ \frac{dE_{el}}{dt} = \frac{dE_{el}^{ref}}{dt} - \frac{dE_{el}}{dt} \]  
\[ \frac{dE_{eq}}{dt} = \frac{dE_{eq}^{ref}}{dt} - \frac{dE_{eq}}{dt} \]  

If Eq. 3 and 4 are substituted into Eq. 11 and 12 respectively, the following equations could be obtained.

\[ \frac{dE_{el}}{dt} = -\frac{V_{el}}{L_{m}} + \left( \frac{dE_{el}^{ref}}{dt} + \frac{X_{el}}{L_{m}} \right) \]  
\[ \frac{dE_{eq}}{dt} = -\frac{V_{eq}}{L_{m}} + \left( \frac{dE_{eq}^{ref}}{dt} + \frac{X_{eq}}{L_{m}} \right) \]  

The terms \( f_{d} \) and \( f_{q} \) are highly nonlinear and exact calculation of those terms are almost impossible. Therefore these terms will be considered as disturbance.

Next, the desired closed loop dynamics can be written as;

\[ \frac{dE_{el}}{dt} + k_{p}E_{el} = 0 \]  
\[ \frac{dE_{eq}}{dt} + k_{q}E_{eq} = 0 \]  

The terms \( f_{d} \) and \( f_{q} \) are estimated disturbances. These terms could be estimated by using first order low pass filter disturbance observer [12].

Finally, desired voltage references are obtained as follows.

\[ v_{el}^{ref} = L_{m}k_{p}E_{el} + \hat{f}_{d} \]  
\[ v_{eq}^{ref} = L_{m}k_{q}E_{eq} + \hat{f}_{q} \]  

Where \( \hat{f}_{d} \) and \( \hat{f}_{q} \) are estimated disturbances. These terms could be estimated by using first order low pass filter disturbance observer [12].

Decoupled rotor currents are controlled via proportional controller with first order low pass filter disturbance observer. Space vector pulse width modulation (SVPWM) is used to generate voltage references in the experiments. PI controllers in the outer loops realize the desired power references. Voltage angle detection is realized by conventional three-phase synchronous reference frame phase-locked loop (3Φ- SRF-PLL) [16].

**IV. EXPERIMENTAL RESULTS**

Experimental setup in Fig. 4 is used in the experiments. Squirrel cage induction machine (SCIM) is driven by a commercial inverter representing the wind. Commercial drive adjusts the speed of DFIG. DFIG plate data is given in table 1; gain and cut off frequency of the controllers are given in Table 3. dSPACE ds1103 controller board is used. Algorithms are generated in Controldesk by using C programming language. Sample time of the controller is 100μs. Semikron Semistack (21f_b6u_e1c1f_b6c1_i12_y12) inverter is used in the experiments. Stator and rotor three phase currents are measured and sent to ds1103 controller board. Stator and grid voltages simultaneously measured for synchronization purposes. DFIG will only be operated in subsynchronous speed. Hence, DC link voltage is kept constant at 120V with a
power supply. Stator active and reactive power step response tests are applied and the performance of the controllers is demonstrated.

A. Stator Active Power (Ps) Step Response Test

Ps step response test is applied at subsynchronous speed (143 rad/s). Ps reference is increased to 180W (Fig. 5) at arbitrary instant of experiment. Qs is kept constant at zero (Fig. 6). It is obviously shown from the results that Ps and Qs successfully follow the references.

The resultant \(i_{rd} & i_{rq}\) and \(i_{sd} & i_{sq}\) change according to applied steps are shown in Fig. 7 and Fig. 8, respectively. The plots of Qs and Ps (Fig. 5 and 6) and the resultant rotor and stator currents (Fig. 7 and Fig. 8) obviously show that decoupled stator active (Ps) and reactive power (Qs) control is achieved.

Rotor phase currents at arbitrary instant are in Fig. 9. Stator voltage vs. stator current is shown in Fig. 10 which definitely shows that power flow is toward the grid.

![Experimental Setup](image)

### Table I. DFIG Plate Data in Experiments

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Quantity</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power</td>
<td>1.1</td>
<td>KW</td>
</tr>
<tr>
<td>Stator Voltage</td>
<td>220/380 Volt(D/Y)</td>
<td></td>
</tr>
<tr>
<td>Stator Current</td>
<td>6.4/3.7 Amper</td>
<td></td>
</tr>
<tr>
<td>Power Factor</td>
<td>0.67</td>
<td></td>
</tr>
<tr>
<td>Speed</td>
<td>1360</td>
<td>rpm</td>
</tr>
<tr>
<td>Rotor Voltage</td>
<td>70 Volt</td>
<td></td>
</tr>
<tr>
<td>Rotor Current</td>
<td>12 Amper</td>
<td></td>
</tr>
</tbody>
</table>

![Active Power (Ps) at Ps step response test](image)

![Reactive Power (Qs) at Ps step response test](image)

![The resultant rotor currents to achieve power control](image)

![Stator a phase voltage (vsa) vs. current (isa) at arbitrary instant](image)
B. Stator Reactive Power ($Q_s$) Step Response Test

$Q_s$ step response test is applied at subsynchronous speed (143 rad/s). $Q_s$ reference is increased to 160W (Fig. 11) at arbitrary instant of experiment. $P_s$ is kept at constant at zero (Fig. 12).

The resultant $i_{rd}$&$i_{rq}$ and $i_{sd}$&$i_{sq}$ change according to applied $Q_s$ are shown in Fig. 13 and Fig.14, respectively. The plots of $Q_s$ and $P_s$ (Fig. 11 and 12) obviously show that decoupled stator active and reactive power control is achieved. Rotor and stator currents reasonably change according to decoupling (Fig. 13 and Fig. 14).

Rotor and stator phase currents at arbitrary instant are shown in Fig. 15 and Fig. 16, respectively. Stator phase a current ($i_{sa}$) vs. stator phase a voltage ($v_{sa}$) obviously show that power factor is leading (Fig. 17).

Grid voltage and calculated voltage angle by applied PLL algorithm in [16] is shown in Fig. 18 which definitely shows the accurate calculation of PLL voltage angle.
CONCLUSION

DFIG is the most popular generator type in wind turbines because of several advantages summarized in introduction. Robustness of the system is essential due to direct connection of stator windings to the grid. This study demonstrated a novel current controller which is robust against machine parameter variations. Experimental results obviously show decoupled active and reactive power is achieved with proposed controller. The proposed methodology could simply be applied to real wind turbine structures due to its simplicity and applicability. Future work will mainly consist of developing the same control structure to GSC.

REFERENCES


