Control of direct-driven PMSG for wind energy system

F. Khater, A. Shaltout, and A. Omar

Abstract—This paper introduces a novel control of wind energy system with directly-driven permanent magnet synchronous generator (DDPMSG) connected to grid. The proposed controller is based on the concept of multi-degree of freedom (MDOF). To obtain the largest wind power and improve the wind energy utilization rate the maximum power point tracking (MPPT) is applied using MDOF. The system is modeled and simulated during wind speed changes. The system includes: variable speed wind turbine, DDPMSG, and full sized voltage source back-to-back converter connected to grid. The control system is developed using PI and MDOF controllers to prove effectiveness of the proposed control in dynamic performance utilizing space vector pulse width modulation (SVPWM).

Keywords—Control, Direct-driven, MPPT, MDOF, PMSG, SVPWM, Wind turbine.

I. INTRODUCTION

Wind energy is one of the most important renewable energy resources because wind power extraction technology is the fastest growing one among various renewable energy generation systems [1]. Several developed generation systems are used to extract wind energy using different wind turbine systems. Using direct-driven permanent magnet synchronous generator (PMSG) is a competitive choice between other generation systems. The direct drive concept is known with its advantages of eliminating the gear train, smaller size, and consequently less weight and losses [2], [3]. PM generator has many competitive advantages, because of its great energy yield, good reliability, and high efficiency [4].

Large scale PMSG are common to be used for grid integration and wind farms installation [5] and they are efficient at high wind speeds [1]. Small scale generator are suitable for medium wind speed sites [6], also has advantage of running stand alone for residential application and micro grids integration [7], [8]. The control of a PMSG with a diode rectifier followed by a dc chopper is proposed in [9] through variation of the duty cycle and maintains appropriate dc voltage. This arrangement is more practical for small scale PMSG because of its lower cost although with this configuration the control of the generator power factor is not possible and the generator efficiency is affected. Thyristor-based dump-load circuits used in [10] to improve system performance and quality.

Integration of small scale wind turbines with single-phase power supply is introduced in [11] using three-phase PMSG through controlled rectifier and single-phase inverter. Using back-to-back converter is preferred because the control of the machine-side converter can deliver maximum power and increase efficiency of the generation system. This configuration also decouples the wind turbine from grid disturbances.

This paper presents a direct-driven PMSG for variable speed wind turbine system. Back-to-back current controlled converters are controlled utilizing space vector pulse width modulation (SVPWM) to interface the generator and the grid. At the machine-side a novel speed controller is proposed to improve the system performance at wind speed changes. The rotor speed controller uses multi-degree of freedom (MDOF) concept to reduce the changes and duration [12]. This reduces stress at the rotor, while keeping maximum power point tracking (MPPT) with wind speed variation. The grid-side inverter is controlled to keep the dc-link voltage at pre-set value and the current injected to the grid at unity power factor to achieve maximum power delivery to grid as a desired operating condition. Modeling and simulation of the system is developed to insure the enhancement of the performance with the proposed speed controller.

II. SYSTEM DESCRIPTION AND MODELING

A. System Description

In this study, the rotor of the wind turbine is directly coupled to the generator without any gearbox, i.e., through a gearless drive train. A fully controlled back-to-back converter is used as interface between the generator and the grid as shown in Fig.1. SVPWM technique is used for switching both converters. The machine-side converter is controlled so that the generator speed is adjusted to track maximum power operation. Conventional PI controller is used to generate torque reference component, then MDOF controller is used to improve the performance of this control loop at machine-side converter. The dc-link voltage and delivered power to the grid are controlled via PI controllers to achieve unity power factor of the grid injected currents.
B. Turbine Mathematical Modeling
The available wind power can be represented by [13],

\[ P_{\text{wind}} = \left( \frac{1}{2} \rho \right) \times (\pi R^2) \times V_{\text{wind}}^3 \]  

(1)

where \( P_{\text{wind}} \) is the total available wind power, \( \rho \) is the air density (kg/m\(^3\)), \( R \) is the rotor radius (m), and \( V_{\text{wind}} \) is the wind speed (m/sec).

The extracted power from wind energy by the turbine is given by:

\[ P_{\text{mech}} = C_p \times P_{\text{wind}} \]  

(2)

The power coefficient \( (C_p) \) is a function of the tip speed ratio \( (\lambda) \), and the blade pitch angle \( (\beta) \) as shown in Fig. 2.

This relation can be expressed as

\[ C_p = f (\lambda, \beta) \]  

(3)

The tip speed ratio is defined as:

\[ \lambda = \frac{\omega t R}{V_{\text{wind}}} \]  

(4)

where, \( \omega_t \) is the rotational speed (rad/sec) of the wind turbine.

C. Permanent Magnet Synchronous Generator
The mathematical model of the PMSG is considered in per unit quantities. The model equations of the machine are voltages, torque, and mechanical expression [14], [15]. The machine voltage can be expressed in d-q axis as

\[ v_{qs} = -R_s i_{qs} - \frac{\omega_e}{\omega_b} \lambda ds + \frac{\omega_e}{\omega_b} \lambda f - \frac{d \lambda qs}{dt} \]  

(5)

\[ v_{ds} = -R_s i_{ds} + \omega_e L_{ds} i_{ds} + \omega_e L_{qs} i_{qs} - \frac{L_{ds}}{L_{qs}} \frac{d i_{ds}}{dt} \]  

(6)

where \( i_{ds}, i_{qs} \) are the stator direct, quadrature currents and \( R_s \) is the stator resistance. The base electrical angular frequency is \( \omega_b \) and \( \omega_e \) is the actual electrical speed in (rad/sec).

The flux linkages of the machine are

\[ \lambda_{ds} = L_{ds} i_{ds} \]  

(7)

\[ \lambda_{qs} = L_{qs} i_{qs} \]  

(8)

Substituting \( \lambda_{ds} \) and \( \lambda_{qs} \) in the machine voltage equations

\[ v_{qs} = -R_s i_{qs} - \frac{\omega_e}{\omega_b} L_{ds} i_{ds} + \frac{\omega_e}{\omega_b} \lambda f - L_{qs} \frac{d i_{qs}}{dt} \]  

(9)

\[ v_{ds} = -R_s i_{ds} + \omega_e L_{qs} i_{qs} - L_{ds} \frac{d i_{ds}}{dt} \]  

(10)

The electromechanical torque can be expressed as

\[ T_e = (\lambda f i_{qs} + i_{qs} i_{ds} (L_{ds} - L_{qs})) \]  

(11)

The system mechanical equation is expressed as follows,

\[ T_e - T_m = 2H \frac{d(\omega_e)}{dt} \]  

(12)

Where \( H \) is the system inertia constant \( = \frac{1}{2} J \omega_{bm}^2 / S_b \) and \( J \) is the system moment of inertia and \( \omega_{bm} \) is the base mechanical speed in rad/sec and \( S_b \) is the base power.

D. Voltage Source Converter
Fully controlled voltage source converter, back-to-back connected configuration, is used in this study. The generator-side converter rectifies the generator output voltage to dc voltage and the grid-side converter converts the dc voltage to ac three-phase grid voltage. The converter switches are IGBT type. For modeling we will consider switch state either on or off and switching losses will be neglected.

The applied voltage at the machine terminal may be expressed as a function of the dc-link voltage and the switches status (Fig. 3).

Therefore the converter can be modeled as follows [16]:

\[
\begin{bmatrix}
    v_{an} \\
    v_{bn} \\
    v_{cn}
\end{bmatrix} = \frac{1}{3} V_{dc} \begin{bmatrix}
    2 & -1 & -1 \\
    -1 & 2 & -1 \\
    -1 & -1 & 2
\end{bmatrix} \begin{bmatrix}
    S_a \\
    S_b \\
    S_c
\end{bmatrix}
\]  

(13)
where \( S_a, S_b, S_c, \overline{S_a}, \overline{S_b}, \overline{S_c} \) are the converter switches status.

The current of the dc-link is defined as:

\[
i_{dc} = [S_a S_b S_c] \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} \tag{14}
\]

The previous equations can be applied on the machine-side and the grid-side converter.

The dc-link voltage is given as:

\[
V_{dc} = \frac{1}{C} \int i_c dt = \frac{1}{C} \int (i_R - i_f) dt \tag{15}
\]

where \( V_{dc} \) and \( C \) are the dc-link voltage and capacitance of the capacitor respectively, \( i_R \) is the output rectifier current and \( i_f \) is the input current to the inverter.

### E. Grid Model

Considering the grid-side converter (inverter) voltage is expressed as follows:

\[
\begin{align*}
V_{g_a} &= V_g \cos \omega_g t \\
V_{g_b} &= V_g \cos (\omega_g t - \frac{2\pi}{3}) \\
V_{g_c} &= V_g \cos (\omega_g t + \frac{2\pi}{3})
\end{align*} \tag{16-18}
\]

where \( V_g \) is the peak grid phase voltage and \( \omega_g \) is the angular frequency.

Assuming grid currents \((i_{ga}, i_{gb}, i_{gc})\) flow from the inverter to the grid [17].

\[
\begin{bmatrix}
\frac{d}{dt} i_{ga} \\
\frac{d}{dt} i_{gb} \\
\frac{d}{dt} i_{gc}
\end{bmatrix} = \begin{bmatrix}
-R_g & 1 & 0 & 0 \\
0 & 1 & 0 & 0 \\
0 & 0 & 1 & 0
\end{bmatrix} \begin{bmatrix}
i_{ga} \\
i_{gb} \\
i_{gc}
\end{bmatrix} + \begin{bmatrix}
V_{ia} - V_{ga} \\
V_{ib} - V_{gb} \\
V_{ic} - V_{gc}
\end{bmatrix} \tag{19}
\]

where \((V_{ia}, V_{ib}, V_{ic}), R_g \) and \( L_g \) are the inverter output voltage, line resistance and inductance connecting inverter to the grid respectively.

The output voltage of the inverter can be expressed in d-q axis as follows [17]:

\[
[V_{dt}] = L_g \frac{d}{dt} [i_{dg}] + R [i_{dg}] + \omega_g L_g [-i_{qg}] + [V_{dg}] \tag{20}
\]

### III. SYSTEM CONTROL

#### A. Machine-side Converter Control

The control of the machine side converter is performed through rotational frame direct and quadrature current controllers as illustrated in Fig. 4. The controllers deliver the reference voltages \( V_{ds}^* \) and \( V_{qs}^* \) for switching drivers. Switching signals are generated using SVPWM [18].

The speed reference is calculated using MPPT methodology and compared with the generator rotor actual speed which result in the input to conventional PI controller or MDOF controller. The torque reference signal is generated as the output of the controller. Using MDOF controller improves the dynamic performance and reduces system transients with changes in wind turbine speed. The q-axis current reference component \((i_{qs}^*)\) is obtained using gain \( K \) and the direct axis reference current \((i_{ds}^*)\) is set to zero hence the generator is providing the maximum torque at field orientation control (FOC) condition as illustrated in Fig. 4.

To improve current controller performance compensation voltages

\[
\Delta V_{ds} = \omega_e L_{ds} i_{qs} \tag{21}
\]

and

\[
\Delta V_{qs} = \omega_e \lambda_f - \omega_e L_{ds} i_{qs} \tag{22}
\]

are added to their output to generate reference switching voltages.

---

Fig. 3. Star connected PMSG with converter.

Fig. 4. Speed and currents control loops of PMSG.
MDOF controller as illustrated in Fig. 5 depends on two sub-controllers, one is used for wide-range of error and the other sub-controller is considered for fine tuning of the output. This controller was introduced for fuzzy control improvement in [12], but it is proven to be applicable to PI as used in this work.

Comparing the actual turbine speed and the estimated optimal reference speed, activates the controller to ensure maximum power capture.

C. Grid-side Converter Control

The grid reference currents $i_{d}^{*}$ and $i_{q}^{*}$ have been set according to the desired dc-link voltage and the reactive power values, then the reference voltage components are generated by PI current controllers [17] as shown in Fig. 7. The driving signals for grid-side IGBT switches are generated using SVPWM similar to the machine-side converter (subsection 3.1) in order to maximize the range of the inverter output voltage. To ensure unity power factor at the connection to grid, $i_{q}^{*}$ is set to zero. Direct current component $i_{d}^{*}$ has been generated to keep the dc-link voltage constant at preset reference value. The grid angular frequency $\omega_{g}$ is determined using phase locked loop (PLL). Compensation components $\Delta V_{d}$ and $\Delta V_{q}$ are added to current controller output as illustrated in Fig. 7, where

$$\Delta V_{d} = V_{d} - \omega_{g} L_{g} i_{q}$$

(24)

and

$$\Delta V_{q} = \omega_{g} L_{g} i_{d}$$

(25)
IV. Simulation Results

Simulation is carried out using Simulink for small wind turbine system that has parameters as given in the appendix. The system has been modeled and simulated under different operating conditions, starting at rated wind speed (9 m/sec). At time 0.6 sec from the starting the simulation wind speed has been changed from 9 m/sec to 8 m/sec, then at 1 sec time the wind speed has been increased to 9.5 as shown in Fig. 8.

At starting turbine mechanical torque has increased to reach its rated value, and it follows the wind speed profile at .6 and 1 sec consequently as shown in Fig. 9.

The performance of the conventional PI controller and MDOF controller is shown in Fig. 10. Notice that error value and duration have been decreased with MDOF control strategy. The total efficiency and the system dynamic performance are improved keeping MPPT through modified MDOF controller at changes of wind speed. The effect of the wind gust and torque transients will result in a reduced influence on the system stability using MDOF controller.

The following simulation results for voltage, speed, and current are obtained using modified MDOF controller. Stator terminal voltage is shown in Fig. 11, where the voltage depends on the electrical speed which started from zero and increased with the turbine mechanical speed and torque and continues to follow the wind speed changes as illustrated in Fig. 12.
Generator output current is controlled utilizing PI controllers in the rotating frame. The output three-phase current of the generator is shown in Fig. 13.

The dc-link voltage is kept constant at its reference set value using conventional PI controller as illustrated in Fig. 14. The transients of the system appear at dc-link during speed variations, but the controller tracks the reference value which insures system stability. Space vector pulse width modulation strategy is applied at the grid-side converter to deliver maximum power to the grid. Fig. 15 gives the produced voltage at the inverter output under SVPWM strategy. Unity power factor operation of grid-side inverter is clear as shown in Fig. 16, while the actual reactive component current ($i_{qg}$) is controlled to be around zero.

V. CONCLUSION

A novel speed controller is presented to improve the DDPMSG system performance at wind speed changes. The rotor speed controller uses MDOF concept to reduce the changes and duration of transients. This reduces stress at the rotor, while keeping maximum power point tracking (MPPT) with wind speed variation. The grid-side inverter has been controlled to keep the dc-link voltage at pre-set value and the current injected to the grid at unity power factor to achieve maximum power delivery to grid as a desired operating condition. The system has been modeled and simulated to realize the proposed controller effect on the performance improvement.
The used wind turbine and generator parameters are shown in table 1 and 2.

Table 1. Wind turbine parameters [20].

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rated Power (W)</td>
<td>1000</td>
</tr>
<tr>
<td>Maximum output power (W)</td>
<td>1500</td>
</tr>
<tr>
<td>Start-up wind speed (m/s)</td>
<td>3</td>
</tr>
<tr>
<td>Rated wind speed (m/s)</td>
<td>9</td>
</tr>
<tr>
<td>Wind speed range (m/s)</td>
<td>3-25</td>
</tr>
<tr>
<td>Wind energy utilizing ratio ($C_p$)</td>
<td>0.45</td>
</tr>
<tr>
<td>Blade diameter (m)</td>
<td>3</td>
</tr>
</tbody>
</table>

Table 2. PMSG Parameters [21].

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power (W)</td>
<td>1000</td>
</tr>
<tr>
<td>Speed (rpm)</td>
<td>420</td>
</tr>
<tr>
<td>$\omega_m$ (rad/sec)</td>
<td>44</td>
</tr>
<tr>
<td>$\omega_e$ (rad/sec)</td>
<td>264</td>
</tr>
<tr>
<td>$T_m$ (N.m)</td>
<td>22.7</td>
</tr>
<tr>
<td>Voltage L-L (V)</td>
<td>220</td>
</tr>
<tr>
<td>$p$ (pair poles)</td>
<td>6</td>
</tr>
<tr>
<td>Flux (Wb)</td>
<td>0.74</td>
</tr>
<tr>
<td>Rs (ohm)</td>
<td>12.6</td>
</tr>
<tr>
<td>Inductance L-L (mH)</td>
<td>92.5</td>
</tr>
<tr>
<td>$L_d-L_q$ (mH)</td>
<td>61.67</td>
</tr>
<tr>
<td>J rotor inertia (m$^2$)</td>
<td>0.026</td>
</tr>
<tr>
<td>Frequency (Hz)</td>
<td>42</td>
</tr>
</tbody>
</table>

REFERENCES