Analysis of Vector Controlled Variable Speed DFIG for Wind Turbines

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Abstract. Double Fed Induction Generators (DFIG) has been widely used for the past two decades in large wind farms. This paper presents control and analysis of the doubly fed induction generator (DFIG) connected to variable speed horizontal axis wind turbine (HAWT). The detailed wind turbine (WT) model, DFIG dynamic model in d-q -synchronous reference frame, power electronic converters, and controllers are presented. The reactive and active power of the DFIG can be precisely decoupled by controlling the rotor side converter (RSC). The field-oriented control (FOC) strategy and the proportional-integral (PI) controllers were used to control the RSC of the DFIG. Furthermore, a space vector pulse width modulation (SVPWM) was utilized to generate pulsing signals required to drive three phases DC-AC converter (inverter). The proposed control method of DFIG based on HAWT was verified by simulation in MATLAB-SIMULINK software. The obtained simulation results showed the capability and effectiveness of the proposed control method.

Keywords: WT, DFIG, SVPWM, Vector Control.

1. Introduction

For the previous period, the demands of energy have been increasing gradually, electrical power and environmental issues especially and this has become a challenging problem for the world. Besides, pollution is gradually growing parallel with the energy request while sources of conventional energy such as fossil fuels are rapidly depleting. Over the last few decades, scholars have been directing studies to improve the energy efficiency. This has led to the finding of many alternatives as renewable energies to generate electricity [1].
It is well known that clean energy can be generated by various environmental sources such as solar radiation, wind movement, water flow and biological wastes. However, such energy is almost unexpansive and handy with no clear environmental pollutants. The power generated by wind being soundly alternative of those produced by classic fuels and also has no impacts on global warming. Furthermore, such energy is produced by transferring kinetic power to electric form by using well designed turbines [2]. Obviously, wind power was applied in mill circulation and ship navigation particularly in case of absence of classic energy [1]. It is a replacement of fossil fuels because of minor influence upon the environment and free to use.

Figure 1: The topology of the entire wind power converting system.

Figure 1 describes topology of the entire wind power converting system. WECS generates electric energy via applying the wind intensity to operate electricity generators. The transforming of incoming air power in to the electric power occurs at two stages: the extraction device where the wind turbine rotor hunts the wind power speed by aerodynamically blades resulting into rotating mechanical energy to operate the generator rotor [3]. The electricity generator transfers the rotating mechanical energy into electric. A gearbox can be used for controlling the speed of rotation of the turbine rotor matching a generator. Electric power is transmitted to the grid by a transformer. The linking of the turbine to the grid is probable at different voltage levels with a known level rate of 600 - 700 V. Where the first stage consists of extracting tool, power electronics converters can also be used for better power extraction and variable speed working of the wind turbine [3]. The wind generator converts mechanical energy rotating inputs into electrical energy outputs.

The doubly feed induction generator (DFIG) presented in Figure 2, shows that DFIG, or WRIG are the common terms to be used in defining the electric machine with a stator in a cylindrical shape with a number of slots(typically36–48) in the inner face which contains 3-phase windings, producing an air gap magnetic field in the with either 2 or 3 pole pairs. The magnetic field generated via the rotor and stator windings necessity is turn at the identical speed nevertheless with shifting to some degrees to create the torque by a machine. By means of the revolving portion of the machine(rotor) to provide it, it should have a slip ring (three-slip rings). Slip rings are needed to maintenance, cost, as well as efficiency [4].
DFIG is applied for linking towards the network by means of a variable-pace wind generator. DFIG has a sum of rewards associated with fixed speed generators, consisting that the machine can work in sub-synchronous, synchronous, and super-synchronous mode, control of active power in the same time with the reactive power control, improved energy detection and mechanical stress decreasing with low cost by the advance of the power converters. The bi-directional buck-boost DC-DC converter is mediated between the fixed DC Link voltages. Rotor side converter (RSC) is linked to rotor to control active power in addition to reactive power of DFIG’s stator. While, grid side converter (GSC) is linked with network for controlling the DC Link voltage [5].

2. Wind Turbine Aerodynamic Model

Wind turbines generate electric energy by extracting the wind energy in order to move an electrical generator. The swept area of the blades extracts the kinetic energy from the WT according to equation (1), and produces the moving air power (Pair) according to equation (3).

\[ E = \frac{1}{2} m v^2 \]  

(1)

Where \( m = \rho V \) and \( \rho \) is density of air particles (nearly 1.225 kg/m³), \( V \) is the volume with \( = Ax \), and \( A \) is the blades swept area equals to:

\[ A = \pi R^2 \]  

(2)

The moving air power is equal to

\[ Pair = \frac{dE}{dt} \]

\[ = \frac{1}{2} \rho \pi R^2 v^2 \frac{dx}{dt} \]

\[ = \frac{1}{2} \rho \pi R^2 v^3 \]  

(3)
$P_{\text{air}}$ indicates the existing energy in the wind but the energy actually moved to the rotor of the wind turbine ($P_{\text{wind turbine}}$) is decreased by $C_p$ according to equations 4 and 5. Where $C_p$ is the wind power coefficient and according to Betz limit

$$C_p = \frac{P_{\text{wind turbine}}}{\text{Pair}} \tag{4}$$

$$P_{\text{wind turbine}} = \frac{1}{2} \rho \pi R^2 v^3 C_p \tag{5}$$

The torque and power coefficient can be represented via analytical terms related to tip speed ratio ($\lambda$) and the pitch or blade angle ($\beta$). The frequently expression applied and improved to various WTs, are given by equation below:

$$C_p(\lambda, \beta) = c_1 (c_2 / \lambda_i - c_3 \beta - c_4) e^{-(c_5/\lambda_i)} + c_6 \lambda \tag{6}$$

Where $c_1$ to $c_6$ are equal to 0.517, 116, 0.4, 5, 21 and 0.0068 respectively for HAWT with a variable speed of wind [6]. And ($\lambda_i$) is given via the following equation:

$$\lambda_i = \frac{1}{\lambda + 0.08\beta^{0.35}/\beta^{5+1}} \tag{7}$$

The ratio of tip speed is calculated by the following equation:

$$\lambda = \frac{wR}{v} \tag{8}$$

$C_p$ and $\lambda$ are dimensionless and applied for defining the action of the rotor of wind turbine at different sizes $C_p$ which depend on geothermal parameters and manufacturer, typically $C_p$ is introduced being related with two limits ratio of tip speed ($\lambda$) and bitch angle ($\beta$) such as shown in Figure 3 [7] [8].

Finally, the rotor of WT produces a torque according to the following equation:

$$T_w = \frac{P_{\text{wind turbine}}}{w} \tag{9}$$

The block scheme for wind turbine calculations is shown in Figure 4:
3. Dynamic Model Of DFIG

DFIG is a predictable induction generator with wound-rotor. Generator stator is linked to network directly through a transformer, and the rotor is linked to AC-DC-AC voltage source convertor. AC-DC-AC converters includes the rotor side converter (RSC) and the grid side converter (GSC) which linked via DC link. Representation of DFIG is shown in Figure 5[9].
In an AC machine, rotor windings move regarding the stator windings because of this, the dynamic action of an AC machine is much hard [9].

Then the Park’s and Clarke’s transformation will be used to transform three phase signals (abc) to a (αβ0) stationary reference frame according to the following matrices [10]. And shown in Figure 6:

\[
[f_{dqo}] = T_{dqo}(\theta)[f_{abc}]
\]  

\[f\] denotes to the voltages, magnetic flux linkages, electric currents or electric charges and the transformation matrix is shown below

\[
T_{dq0}(\theta) = \frac{2}{3}
\begin{bmatrix}
\cos\theta & \cos(\theta - 120^\circ) & \cos(\theta + 120^\circ) \\
\sin\theta & \sin(\theta - 120^\circ) & \sin(\theta + 120^\circ) \\
\frac{1}{2} & \frac{1}{2} & \frac{1}{2}
\end{bmatrix}
\]

\[\begin{bmatrix} f_{\alpha} \\ f_{\beta} \\ 0 \end{bmatrix} = T_{\alpha\beta0}[f_{abc}]
\]

The transformation matrix is shown below:

\[
T_{\alpha\beta0} = \frac{2}{3}
\begin{bmatrix}
1 & -1/2 & -1/2 \\
0 & \sqrt{3}/2 & -\sqrt{3}/2 \\
1/2 & 1/2 & 1/2
\end{bmatrix}
\]

Figure 6: presented Park’s and Clarke’s transformation reference frames

In the dynamic modeling of DFIG, the instantaneous stator and rotor voltages are presented in equations below[11]:

\[
V_{as}(t) = R_s i_{as}(t) + \frac{d\psi_{as}(t)}{dt}
\]  

\[
V_{bs}(t) = R_s i_{bs}(t) + \frac{d\psi_{bs}(t)}{dt}
\]  

\[
V_{cs}(t) = R_s i_{cs}(t) + \frac{d\psi_{cs}(t)}{dt}
\]
\[ V_{ar}(t) = R_r i_{ar}(t) + \frac{d\psi_{ar}(t)}{dt} \quad (15) \]
\[ V_{br}(t) = R_r i_{br}(t) + \frac{d\psi_{br}(t)}{dt} \quad (16) \]
\[ V_{cr}(t) = R_r i_{cr}(t) + \frac{d\psi_{cr}(t)}{dt} \quad (17) \]

The currents of the stator and rotor can be represented in \( \alpha\beta \) components such as follows:

\[
\frac{d}{dt} \begin{bmatrix}
i_{\alpha s} \\
i_{\beta s} \\
i_{\alpha r} \\
i_{\beta r}
\end{bmatrix} = \left(\frac{1}{\sigma L_s L_r}\right) M \cdot \begin{bmatrix}
i_{\alpha s} \\
i_{\beta s} \\
i_{\alpha r} \\
i_{\beta r}
\end{bmatrix} + \left(\frac{1}{\sigma L_s L_r}\right) N \cdot \begin{bmatrix}
v_{\alpha s} \\
v_{\beta s} \\
v_{\alpha r} \\
v_{\beta r}
\end{bmatrix} \quad (18)
\]

Where

\[
M = \begin{bmatrix}
-R_s L_r & \omega m L_m^2 & R_r L_m & \omega m L_m L_r \\
-\omega m L_m^2 & -R_s L_r & -\omega m L_m L_r & R_r L_m \\
R_s L_m & -\omega m L_s L_m & -R_r L_s & -\omega m L_r L_s \\
\omega m L_s L_m & R_s L_m & \omega m L_r L_s & -R_r L_s
\end{bmatrix}
\]
\[
N = \begin{bmatrix}
L_r & 0 & -L_m & 0 \\
0 & L_r & 0 & -L_m \\
-L_m & 0 & L_s & 0 \\
0 & -L_m & 0 & L_s
\end{bmatrix}
\]

After finding \( i_{\alpha s}, i_{\beta s}, i_{\alpha r}, i_{\beta r} \), the fluxes expanded in \( \alpha\beta \) components are obtained according to the following expressions:

\[
\frac{d}{dt} \begin{bmatrix}
\psi_{\alpha s} \\
\psi_{\beta s} \\
\psi_{\alpha r} \\
\psi_{\beta r}
\end{bmatrix} = \begin{bmatrix}
-\frac{R_s}{\alpha L_s} & 0 & \frac{R_s L_m}{\alpha L_s L_r} & 0 \\
0 & -\frac{R_r}{\alpha L_r} & 0 & \frac{R_s L_m}{\alpha L_s L_r} \\
\frac{R_l L_m}{\alpha L_s L_r} & 0 & -\frac{R_r}{\alpha L_r} & -\omega m \\
0 & \frac{R_l L_m}{\alpha L_s L_r} & \omega m & -\frac{R_r}{\alpha L_r}
\end{bmatrix} \cdot \begin{bmatrix}
\psi_{\alpha s} \\
\psi_{\beta s} \\
\psi_{\alpha r} \\
\psi_{\beta r}
\end{bmatrix} + \begin{bmatrix}
v_{\alpha s} \\
v_{\beta s} \\
v_{\alpha r} \\
v_{\beta r}
\end{bmatrix} \quad (19)
\]

Where \( \sigma \) is the leakage coefficient, which can be obtained from

\[
\sigma = 1 - \frac{L_m^2}{L_s L_r} \quad (20)
\]

The electromagnetic torque calculation according to the following equation:

\[
Tem = \frac{3}{2} P L_m L_m \{i_{\alpha} \cdot \overline{i_{\beta}}\} = \frac{3}{2} P L_m (i_{\alpha r} \cdot i_{\beta s} - \alpha s \cdot i_{\beta r}) \quad (21)
\]
Finally, to obtain the dynamic and responsive powers of the stator and rotor and torque via αβ model, the following expressions will be used [12]:

\[
Ps = \frac{3}{2} \text{Re} \left\{ \vec{v}_s \cdot \vec{i}_{s*} \right\} = \frac{3}{2} (v_{as} \cdot i_{as} + v_{bs} \cdot i_{bs})
\]  
(22)

\[
Pr = \frac{3}{2} \text{Re} \left\{ \vec{v}_r \cdot \vec{i}_{r*} \right\} = \frac{3}{2} (v_{ar} \cdot i_{ar} + v_{br} \cdot i_{br})
\]  
(23)

\[
Qs = \frac{3}{2} \text{Im} \left\{ \vec{v}_s \cdot \vec{i}_{s*} \right\} = \frac{3}{2} (v_{bs} \cdot i_{as} - v_{as} \cdot i_{bs})
\]  
(24)

\[
Qr = \frac{3}{2} \text{Im} \left\{ \vec{v}_r \cdot \vec{i}_{r*} \right\} = \frac{3}{2} (v_{br} \cdot i_{ar} - v_{ar} \cdot i_{br})
\]  
(25)

The detailed block scheme for DFIG calculations is shown in the Figure 7:

Figure 7: The detailed block scheme of DFIG calculation

4. Field Oriented Control (FOC)

The main impartial of FOC or vector control (VC) is for finding and keeping an angular association between the space vector current of the stator and one internal field vector [13].

The first and the standard selection for controlling DFIM is the flux orientation. It summarizes approximating of the flux of the machine and then aligning the d axis reference frame to it [14].
The modeling of FOC contains the external loop of the rotor speed of the generator which is the slower loop for comparison between the rotor generator speed and the reference speed which is needed as a constant value. The internal loop is the dq rotor currents which is the fastest loop where the two loops enter to proportional-integral controller (PI) for controlling them via the PI parameters ($K_p$ & $K_i$). And the outer loop, the comparator block measures the error value between the desired value $\omega_r$ and the variable value of the rotor speed from generator contentiously. In case of the turbine speed is higher or lower than the rated speed, the comparator measures the error and sends it to PI controller to adjust it via reset of the value of $K_p$ and $K_i$ to keep the rotor speed at speed level which produces maximum $C_P$ in order to increase the efficiency of WT [15]. Figure 8 which represents the two control loops and their controllers.

![Figure 8: The representation PI controller loops](image)

To obtain the values of $K_p$ and $K_i$, the following equations were used.

$$K_p = \frac{2I_{qr}}{\omega_{ref} - \omega_r}$$

$$K_i = \frac{(1/ \omega_{ref} - \omega_r) * (2I_{qr} / (\omega_{ref} - \omega_r) - K_p) * (d\Delta \omega / dt)}{\tau I_{qr} + 1}$$

Figure 9 represents the FOC modeling and PI controllers.

![Figure 9: The representation of FOC and PI controller](image)
5. SVPWM Model

The variable speed of wind turbine and constant frequency technology are widespread in wind power generation system where the space vector control technology is presented in DFIG system for decoupling controller of active power in addition to reactive power by using IGBT as the switching element together with SVPWM [16].

PWM of 3-phase (VSI) voltage source inverter is presented in Figure 10. For formation the output using six switches of power from S1 to S6, controlling on it via switching variables a, a', b, b', c and c'.

In case of the upper transistor is switched on that means that a, b or c is 1, then the matching lower transistor is switched off and this means that a', b' or c' is 0. So, the cases of the upper transistors (on and off) S1, S3 and S5 are applied to regulate the voltage output [17] [18].

![3-phase PWM-VSI](image)

Figure 10: 3-phase PWM-VSI

6. Simulation Model

Figure 11 shows the aerodynamic modeling of wind turbine. The wind profile generated by signal builder and enters to the wind turbine as a variable wind speed simulation to rotate wind blades. The pitch angle of the blades enters the mask as a constant block. Inside the wind turbine mask, the representation of all equations of aerodynamic of wind which used to generate the torque of wind turbine which required to operate the DFIG, then the sub-system block of DFIG which contains the simulation of the equations of doubly fed induction generator to generate required electrical power. The outputs of this sub-system are the currents, fluxes, active and reactive powers of both stator and rotor of the generator and the electrical angular speed and the electromagnetic torque.

To control on the speed of DFIG, the PI controller block used as three loops where the outer loop was the speed controlling and the other two loops was to rotor current control. Also, the SVPWM block was presented to generate the pulses to operate the inverters of the RSC.
This simulation model was built by using DFIG with the parameters which presents in following table at variable speed of wind for 4sec operation time.

Table 1: The Input Parameters of DFIG

| Parameter                  | Value       |
|----------------------------|-------------|
| Stator voltage             | 208 V       |
| Rotor voltage              | 104 V       |
| Supply frequency           | 50 Hz       |
| Pole pair                  | 2           |
| No. of stator winding      | 516 turns   |
| No. of rotor winding       | 264 turns   |
| Stator resistance          | 12.6 ohm    |
| Rotor resistance           | 16.7 ohm    |
| Stator inductance          | 0.376 H     |
| Rotor inductance           | 0.38 H      |
| Magnetizing inductance     | 0.352 H     |
| Moment of inertia          | 0.0016 kg.m²|
| Bitch angle                | 0°          |
7. Results and Discussions

The velocities of the wind as step signal which vary from 5m/sec for time from 0 to 1 sec., 11.25m/sec for time from 1 to 2 sec., 17.5m/sec for time from 2 to 3 sec. and 8m/sec for time from 3 sec. to 4 sec. As shown in Figure 12, they were used as an input data to the modeling.

Inside the DFIG model, Figure 13 represents the 3-phases instantaneous voltages of the stator with respect to time as a sine wave signal with phase shifting by 120° and varying according to the velocity of the wind which is transformed to αβ components.

Figures 13 & 14 shows the 3-phases instantaneous voltages of the stator and rotor with respect to time as a sine wave signal with phase shifting by 120° and varying also according to the velocity of the wind which is transformed to αβ components.

Figures 15 & 16 indicate that the voltages of the stator in αβ components with respect to time after being transformed it via Clarke mask to facilitate the simulation it by computing program.

Figures 17 & 18 represent the voltages of the rotor in αβ components with respect to time after being transformed to dq components via Park mask and then transformed to αβ with angular position wt of the stationary and rotating reference frame.

Figures 19 & 20 represent the currents of the stator in αβ components, which varied according to wind velocity, increasing with wind velocity and decreasing with it.

Figures 21 & 22 represent the currents of the rotor in αβ components, which also increased and decreased with wind velocity.

Figures 23 & 24 show that the three phase currents of the stator and rotor respectively.

Figures 25 & 26 represent the fluxes of the stator and rotor in αβ components respectively, which increased by increased in wind velocity.

Figure 27 indicates that the electrical angular frequency of generator which increases with wind velocity by enhancing the rotation speed of the shaft.

Figure 28 represents the electromagnetic torque of the generator which was decreased with increasing of the wind speed.

Figures 29 & 30 represent an active and reactive power of the stator, which increasing after the speed of the wind reaches its rated value.

Figures 31 & 32 indicate that an active and reactive power of the rotor, which were increased after the speed of the wind reaches the rated value.

Figure 33 represents the torque of wind and torque of generator where torque of wind had a constant value while the generator torque varied with wind velocity.

![Figure 12: The wind velocity profile](image)
Figure 13: The 3-phases instantaneous voltages of the stator

Figure 14: The 3-phases instantaneous voltages of the rotor

Figure 15: The voltages of the stator in α component
Figure 16: The voltages of the stator in β component

Figure 17: The voltages of the rotor in α component

Figure 18: The voltages of the rotor in β components
Figure 19: The currents of the stator in $\alpha$ components

Figure 20: The currents of the stator in $\beta$ components

Figure 21: The currents of the rotor in $\alpha$ components
Figure 22: The currents of the rotor in $\beta$ components

Figure 23: Three-phase stator currents

Figure 24: Three-phase rotor currents
Figure 25: αβ stator flux

Figure 26: αβ rotor flux

Figure 27: The mechanical shaft speed of the generator

Figure 28: Electromagnetic torque of the generator
Figure 29: Stator active power

Figure 30: Stator reactive power

Figure 31: Rotor active power

Figure 32: Rotor reactive power
8. Conclusions

In this modeling, control and analysis of doubly fed induction generator (DFIG) connected to variable speed horizontal axis wind turbine (HAWT) was analyzed and several remark conclusions was obtained from the simulation results as summarized follows:

1) By using of the MATLAB/Simulink, the aerodynamic model of WT under different wind speed values over time was obtained and give accurate results.

2) By using of the MATLAB/Simulink, the steady state and dynamic performance of the DFIG was modeled, simulated and decoupled controlled on the reactive and active powers by controlling rotor side converter (RSC) by various control methods such as FOC and SVPWM.

3) By using of the MATLAB/Simulink, the modeling of AC-DC and DC-AC power electronics converters was implemented and generating pulsing of the inverters by using SVPWM.

4) Field oriented control was applied and investigated and efficient result as one of the power control strategies was used in induction machines.

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