Modeling and Investigation Performance of Small-Scale PMSG based HAWT with FOC

Talib Z. Farge  
Ali. H. Numan  
Zaineb Tahir

Electromechanical Engineering Department, University of Technology, Baghdad, Iraq

Correspondence Author Ali H. Numan: 50059@uotechnology.edu.iq

Abstract. This paper focused on modeling and simulation of small-scale horizontal axis wind turbine (HAWT) based on permanent magnetic synchronous generator (PMSG) with filed oriented control (FOC) circuit connected to 3-phase full bridge rectifier by MATLAB software. FOC system developed for generator side converter to regulate mechanical speed and electromagnetic torque at variable wind speed. Space vector pulse width modulation (SVPWM) had been implanted in FOC system to turn on six-IGBT switches and validate pure and steady-state of output voltage. Results showed optimum performance coefficient was 0.48 and tip speed ratio 8.1 at zero pitch angle, also when pitch angle increase by 5° coefficient performance decreased to 0.35. The simulated waveforms of the mechanical speed, and electromagnetic torque were contained two case, before and after applied FOC. With FOC, the results shown faster and smooth response to the faster change in wind speed.

Keywords: HAWT, PMSG, FOC, and SVPWM.

1. Introduction

Variable speed wind turbine system has many features as compared with fixed speed wind turbine system such as low cost, small size, high efficiency, high power production, high power quality and, maximum power can be extracted at variable wind speed. There are many types of generators use in wind turbine systems. Permanent Magnet Synchronous Generator (PMSG) its common applied in modern wind turbines because of low weight, small size, high pole number, gear-less, less maintenance and, compact structure. Therefore it is an excellent applicant for this purpose. Power delivered to grid by variable speed wind turbines depend on wind speed and rotor speed of generator [1]. In the generating side, there are many control strategies used to regulate speed and extract maximum power of variable speed wind turbines. Felid oriented control (FOC) is a popular and modern control method because archive optimal utilization of wind energy [2].
A literature review represent ideas and researchers efforts in dealing with theoretical (simulation) and experimental of wind energy conversion system based on PMSG. P. Thayumanavan et al. [3] presented maximum power point tracking (MPPT) method based on sensor-less FOC to control speed and torque of PMSG. Electromagnetic torque had been control by set $i_d$ to zero and control by $i_q$. B. Lahfaoui et al. [4] modeling and simulation of MPPT based on PMSG. MPPT connected DC boost convertor. Perturb and observe algorithm used in MPPT. B. Jain et al. [5] reviewed control methods of PMSG based wind energy conversion system connected to grid. Control methods included direct and vector methods. Direct torque and field oriented control method used to control speed and torque in machine side, while direct power control and voltage oriented control used in grid side. This paper focused as follows, section 2 presents modeling aerodynamic HAWT. In section 3, presents modeling of PMSG, MPPT based FOC and, VOC.

2. Aerodynamic Modeling of HAWT

The kinetic energy available from wind energy for x distance [6]:

$$U = \frac{1}{2} mu^2 = \frac{1}{2}(\rho_aAx)u^2 \quad (1)$$

Wind power is derivative of kinetic energy:

$$P_w = \frac{dU}{dt} = \frac{1}{2} \rho_a u^2 A \frac{dx}{dt} = \frac{1}{2} \rho_a A u^3 \quad (2)$$

$$\rho_a = 3.485 \frac{T_a}{T} \quad (3)$$

Air density $\rho_a$ equal 1.225 kg/m$^3$ at stander conditions (101.3kPa, 288K).

$$P_m = C_p \left( \frac{1}{2} \rho_a A u^3 \right) = C_p P_w \quad (4)$$

Betz coefficient ($C_p$) is factor prove that ideal turbine can’t extract more than 0.593 from the wind power.

$$\lambda = \frac{r_m \omega_m}{u} \quad (5)$$

$$C_p = b_1 \left(\frac{b_2}{\lambda_i} - b_3 \beta - b_4\right) \exp\left(-\frac{b_5}{\lambda_i}\right) + b_6 \lambda \quad (6)$$

$$\lambda_i = \left(\frac{1}{\lambda + 0.08\beta} - \frac{0.035}{\beta^3 + 1}\right)^{-1} \quad (7)$$

For variable wind speed, $b_1 = 0.5176, b_2 = 116, b_3 = 0.4, b_4 = 5, b_5 = 21, b_6 = 0.0068$

Modeling shaft of wind turbine described in the following equation:

$$J_m \frac{d}{dt} \omega_m + B_m \omega_m = T_e - T_m \quad (8)$$
3. Electrical Modeling

3.1. PMSG modeling

PMSG rotor contained poles of permanent magnet (PM) generate magnetic field. Figure 2 shows equivalent circuit of 3-phase PMSG has 2-poles with $abc$-axis of stator. Current induced by rotor divide into two quadrature, $q$-axis and $d$-axis. Rotor position angle $\theta_r$ is angle made angle between $d$-axis and $a$-axis [7]. Following basic equations of PMSG modeling:

\[
\begin{align*}
\omega_r L_{q} i_q &= v_{q} \\
\omega_r L_{d} i_d &= v_{d} \\
\end{align*}
\]

Figure 2: Equivalent circuit of PMSG.

Table 1: Parameters of wind turbine

| Parameters           | Values    |
|----------------------|-----------|
| Rated power          | 220W      |
| Rated wind speed     | 11.5m/s   |
| Blade diameter       | 1.3m      |
| Rated R.P.M          | 600 r.p.m |

Figure 1: Simulation of HAWT.
Active power \( P_{dq} \) and reactive power \( Q_{dq} \) in \( dq \)-frame

\[
P_{dq} = \frac{3}{2} (v_{ds}i_{ds} + v_{qs}i_{qs})
\]

\[
Q_{dq} = \frac{3}{2} (v_{qs}i_{ds} - v_{ds}i_{qs})
\]

Electromagnetic torque:

\[
T_e = \frac{3P_2}{2} (\psi_{ds}i_{qs} - \psi_{qs}i_{ds}) = \frac{3P_2}{2} (\psi_r i_{qs} - (L_{ds} - L_{qs})i_{qs}i_{ds})
\]

Figure 3: Modeling of PMSG.

### 3.2. Modeling of field oriented control

Because of fluctuation of wind speed that effect on speed of generator and power production field oriented control (FOC) use in generator side. By set \( i_{ds}^* = 0 \), maximum electromagnetic torque can be achieve. By quadrature current \( i_{qs}^* \) can be controlled by electromagnetic torque [8].
4. Results and Discussions

Wind turbine based on PMSG system was simulated by MATLAB/Simulink 2017b. Figure 5 shows the coefficient performance with tip speed ratio, optimum performance coefficient was 0.48 at tip speed ratio 8.1 while pitch angle was $0^\circ$. It is clear from the figure when pitch angle increase by $5^\circ$, coefficient performance decreased to 0.35 at tip speed ratio 9.3. Mechanical torque effected mainly by pitch angle, when pitch angle fixed at $0^\circ$, maximum torque was 3.85N.m at mechanical speed 600r.p.m. When pitch angle increased by $5^\circ$, mechanical torque drop to 2.64N.m at mechanical speed 320.3r.p.m.

Figure 5: Performance coefficient vs. tip speed ratio.
Figure 6: Mechanical torque vs. mechanical speed.

Three air speeds (11.5, 8 and, 3 m/s) were selected for operation simulation of wind turbine system for 1sec as shown in figure (7). Output current is directly proportional to the air speed. At 11.5, 8 and, 3m/s the output current was 4.81, 3.15, 1.6 A, respectively as figure 8. Mechanical rotational speed effected mainly by wind speed fluctuation, this is clearly shown by the figure 9. With FOC we could get the curve without fluctuation and stable speed. Also, electromagnetic torque effected mainly fluctuation of wind speed, FOC system cancelled these fluctuations and get stable electromagnetic torque as shown figure 10.

Figure 7: Input wind speed.
Figure 8: Output current of PMSG

Figure 9: Mechanical speed with and without FOC

Figure 10: Electromagnetic torque with and without FOC
5. Conclusions

This paper presented modeling and simulation of HAWT based on PMSG with field oriented control system had been simulated by MATLAB/Simulation. Wind turbine system has rated 220W. To achieve stable operation of PMSG at variable wind speed the field oriented control system was applied. Maximum mechanical torque and optimum performance coefficient were obtained at fixed pitch angle (0°). Steady-state of electromagnetic torque and mechanical speed had been achieved under variable wind speed when used field oriented control.

Nomenclature

\[ \begin{align*}
A & \quad \text{Cross-section area} \quad \text{m}^2 \\
b, b_2, b_3 & \quad \text{Constants of solution aerodynamic differential equations} \\
b_{b}, b_{p}, b_{f} & \\
B_m & \quad \text{Viscous friction} \quad \text{N.m.s} \\
C_p & \quad \text{Performance coefficient} \\
g & \quad \text{Standard acceleration of gravity} \quad \text{m/s}^2 \\
i_{abc}, i_{bdc} & \quad \text{Machine phase abc stator voltage} \quad \text{A} \\
i_{d}, i_{q} & \quad \text{PMSG stator currents in } dq\text{-frame} \quad \text{A} \\
J_m & \quad \text{Momentum inertia of rotor shaft} \quad \text{Kg.m}^2 \\
L_{dq}, L_{d} & \quad \text{PMSG rotor inductance in } dq\text{-frame} \quad \text{H} \\
u_{a}, u & \quad \text{Armature inductance} \quad \text{Wb} \\
m & \quad \text{Air mass} \quad \text{Kg} \\
P_w & \quad \text{Wind power} \quad \text{W} \\
P_m & \quad \text{Mechanical power} \quad \text{W} \\
P_p & \quad \text{Pair poles} \\
P_{dq} & \quad \text{Active power of PMSG in synchronous } dq\text{-reference frame} \quad \text{W} \\
P_{dq} & \quad \text{Reactive power of PMSG in synchronous } dq\text{-reference frame} \quad \text{VA} \\
r_m & \quad \text{Maximum radius blade of wind turbine} \quad \text{m} \\
r_s & \quad \text{Resistance of PMSG stator windings} \quad \text{Ω} \\
T_m & \quad \text{Mechanical torque} \quad \text{N.m} \\
T_e & \quad \text{Electromagnetic torque} \quad \text{N.m} \\
T_a & \quad \text{Air temperature} \quad \text{°C} \\
t & \quad \text{Time} \quad \text{sec} \\
v_{abc}, v_{bdc} & \quad \text{Machine phase abc stator voltages} \quad \text{V} \\
v_{d}, v_{q} & \quad \text{Machine stator voltages in } dq\text{ frame} \quad \text{V} \\
U & \quad \text{Kinetic wind energy} \quad \text{J} \\
u & \quad \text{Wind velocity} \quad \text{m/s} \\
x & \quad \text{thickness of air parcel in x-direction} \quad \text{m} \\
\rho_a & \quad \text{Air density} \quad \text{Kg/m}^3 \\
\lambda & \quad \text{Tip speed ratio} \\
\beta & \quad \text{Pitch angle} \quad \text{degree} \\
\omega_r & \quad \text{Electrical angular speed} \quad \text{rad/s} \\
\omega_m & \quad \text{Mechanical angular speed} \quad \text{rad/s} \\
\omega_e & \quad \text{Angular electrical frequency} \quad \text{rad/s} \\
\psi_r & \quad \text{Peak flux linkage of permanent magnetic} \quad \text{Wb} \\
\psi_{d}, \psi_{q} & \quad \text{Machine stator flux linkages in } dq\text{-frame} \quad \text{Wb}
\end{align*} \]
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