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Modeling and Controlling of Directly Driven Wind Turbine with Permanent Magnet Synchronous Generator

Zinat Tasneem[1], M.R.I. Sheikh[2]
EEE Department, Rajshahi University of Engineering & Technology, Rajshahi 6204, Bangladesh
Email: tasneemzinat@gmail.com[1], ris_ruet@yahoo.com[2]

Abstract

This paper proposes a dynamic simulation of a directly driven wind turbine generation system having an effective control strategy with permanent magnet synchronous generator (PMSG). This control strategy allows the PMSG to operate for different wind speed in order to optimize the generated power from the wind turbine and also to maintain a constant grid side voltage. For the dynamic analysis of PMSG, two-level IGBT converter-inverter set has been used associated with the Maximum Power Point Tracking (MPPT). All the elements have been modeled and the equations explaining their behavior have been introduced. The simulation model of PMSG and the proposed control strategies are presented by the engineering software PSCAD/EMTDC. The comparative results show that directly driven PMSG perform better performance than Induction Generator (IG).

Keywords: Wind Turbine, Permanent Magnet Synchronous Generator (PMSG), Modeling.

1. Introduction

In recent years the world consumption of energy has increased enormously due to the massive industrialization which has been intensified rapidly in some geographical areas of the world remarkably in the countries of Asia. So renewable energy sources, such as the wind energy has attracted the attention as a clean and non-polluting energy source. Worldwide there are now over two hundred thousand wind turbines operating, with a total nameplate capacity of 282,482 MW as of end 2012 [1]. The realization of a wind turbine may depend on the optimum design of the system and the control strategies of the different possible parameters that can operate efficiently under extreme variations in wind conditions. The general goal of this paper is to model a variable–speed wind turbine and optimize the electromechanical energy conversion of the wind turbines; developing suitable strategies of control [2]. This paper describes the operation and control of such a variable speed wind generator named PMSG.

Megawatt class wind turbines equipped with PMSG have been announced by Siemens Power Generation and GE energy. In this concept, the PMSG can be directly driven (gearless) and is connected to the AC power grid through the power converter [3, 4]. In PMSG, the excitation is provided by permanent magnets instead of field windings. Permanent magnet machines are characterized as having large air gaps, which reduce flux linkage even in machines with multi-magnetic poles [5, 6]. This paper presents an effective control strategy for the operation of a directly-driven permanent-magnet synchronous-generator-based variable-speed wind turbine. This generator is connected to the power network by means of a fully controlled frequency converter, which consists of a pulse width-modulation (PWM) rectifier, an intermediate DC circuit, and a PWM inverter, Phase Locked Loop (PLL) etc. The control strategy for the generator-side converter with maximum power point tracking (MPPT) is also presented here. In this paper, a comparison of some parameters between Induction Generator (IG) without Static Compensator (STATCOM) and PMSG has been introduced. It is shown that the proposed model of PMSG maintains a constant output voltage and power, which, in case of IG is not possible without using STATCOM.

2. Modeling and Description of the system

The model system shown in Fig.1 has been used for the simulation analysis of variable speed wind turbine (VSWT)-PMSG analysis. The proposed model is derived from the analytical representation of the main components: (I)Dynamic wind turbine model, (II) Directly-driven PMSG, (III)AC/DC converter and (IV)the Grid Model.

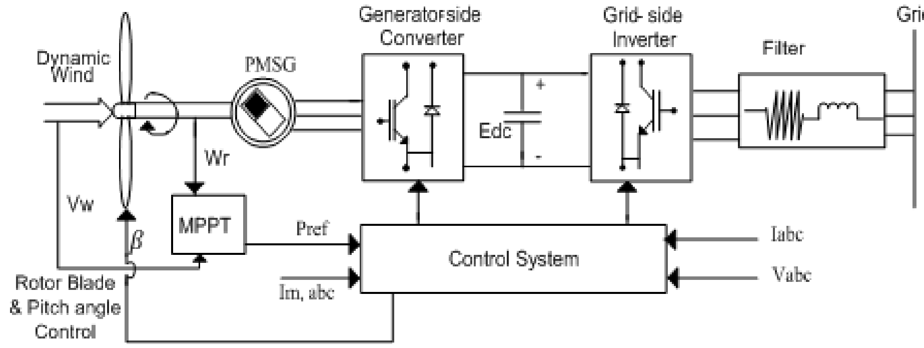

Fig.1 Power system model with direct-drive PMSG

In the fig.1, a VSWT-PMSG system is modeled with a fully controlled frequency converter. The frequency converter consists of a generator side AC/DC converter, a DC link capacitor and a grid side DC/AC inverter. Each of the converter/inverter is a standard three phase two-level unit, composed of six insulated gate bipolar transistor (IGBT) and anti parallel diodes. The control system also consists of MPPT, PLL, pitch controller etc.

2.1 Wind Turbine Model

The model of wind turbine rotor is complicated. According to the blade element theory [7], modeling of blade and shaft needs complicated and lengthy computations. Moreover, it also needs detailed and accurate information about rotor geometry. Therefore, considering only the electrical behavior of the system, a simplified method of modeling of the wind turbine blade and shaft is normally used [8]. The mathematical relation for the mechanical power extraction from the wind can be expressed as follows [7]:

$$Pm = \frac{1}{2}\rho\pi R^2 Vw^3 Cp(\lambda, \beta) \quad (1)$$

Where, P_m is the mechanical power that the turbine extracts from the wind, ρ is the air density (Kg/m^3), R is the blade radius (m) and C_P is the power coefficient which is a function of both, tip speed ratio, λ, and blade pitch angle, β(deg). λ and C_P are expressed as[9]:

$$\lambda = \frac{\omega R}{Vw} \quad (2)$$

Where, ω is the wind turbine angular speed (rad/s), V_W is the wind speed (m/s).

The power coefficient, C_P is, [9]

$$C_P = \frac{1}{2}(\Gamma - 0.022\beta^2 - 5.6)e^{-0.17\Gamma} \quad (3)$$

Since, C_P is expressed in feet and mile, Γ is corrected as,

$$\Gamma = \frac{R}{\lambda} \cdot \frac{3600}{1609} \quad (4)$$

The torque coefficient, C_T, is given by,

$$C_T = \frac{Cp(\lambda)}{\lambda} \quad (5)$$

The wind turbine torque is expressed as,

$$Tm = \frac{1}{2}\rho\pi R^3 Vw^2 C_T(\lambda) \quad (6)$$

2.2 Generator Model

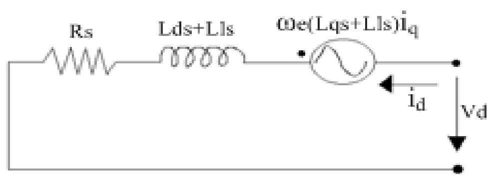

Fig.2 d-axis equivalent circuit of PMSG

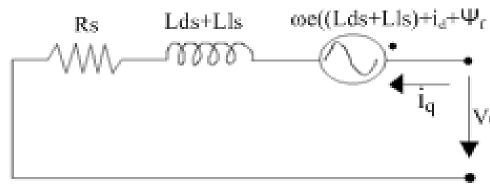

Fig.3 q-axis equivalent circuit of PMSG

Fig.2 and fig.3 shows the d-axis and q-axis equivalent circuit of PMSG. It has been considered that the PMSG is a system which produces electricity from the mechanical energy obtained from the wind. The dynamic model of PMSG is derived from the two-phase synchronous reference frame, in which, the q-axis is 90° ahead of the d-axis with respect to the direction of rotation. The synchronization between the d-q rotating reference frame and the abc three phase frame is maintained by utilizing a PLL.
The equations required to model the PMSG are:

$$\frac{did}{dt} = \frac{1}{Lds+Lls}(-Rs\ id + \omega e(Lqs + Lls)iq + Vd) \quad (7)$$

$$\frac{diq}{dt} = \frac{1}{Lqs+Lls}(-Rs\ iq + \omega e((Lds + Lls)id + \psi f) + Vq) \quad (8)$$

The wind turbine driven PMSG can be represented in the rotor reference frame as:

$$V_d = -R_S i_d - L_d \frac{did}{dt} + \omega L_q i_q \quad (9)$$

$$V_q = -R_S i_q - L_q \frac{diq}{dt} - \omega L_d i_d + \omega \psi_f \quad (10)$$

Where, d and q refer to the physical quantities that have been transformed into the d-q synchronous rotating reference frame, R_S is the stator resistance, L_d and L_q are the inductances of the generator on the d and q axis, ωe is the electrical rotating speed of the generator, Ψ_f is the magnetic flux.

$$\omega e = p \times \omega g \quad (11)$$

Where, p is the number of pole pairs of the generator. The electromagnetic torque equation is given by,

$$Te = 1.5p(Lds - Lls)idiq + iq\psi_f \quad (12)$$

2.3 Pitch Controller

The range of rotor speed variation is, in general, approximately 5 to 16 rpm [9]. If the reference optimum power, P_{opt}, is greater than the rated power of the PMSG, then a specific controller is used to control the rotational speed, named pitch controller. Therefore, the reference optimum power will not exceed the rated power of the PMSG. The pitch servo is modeled with a first order delay system with a time constant, Td, of 2.0 sec. Because the pitch actuation system cannot, in general, respond instantly, a rate limiter with the value of 10°/s is added. The minimum and maximum blade pitch settings are 0° and 90° respectively [10].

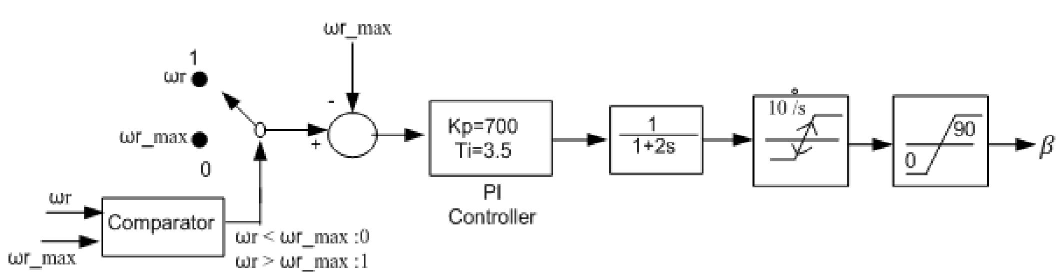

Fig.4 Pitch controller

3. Control Strategies

3.1 Grid side frequency inverter

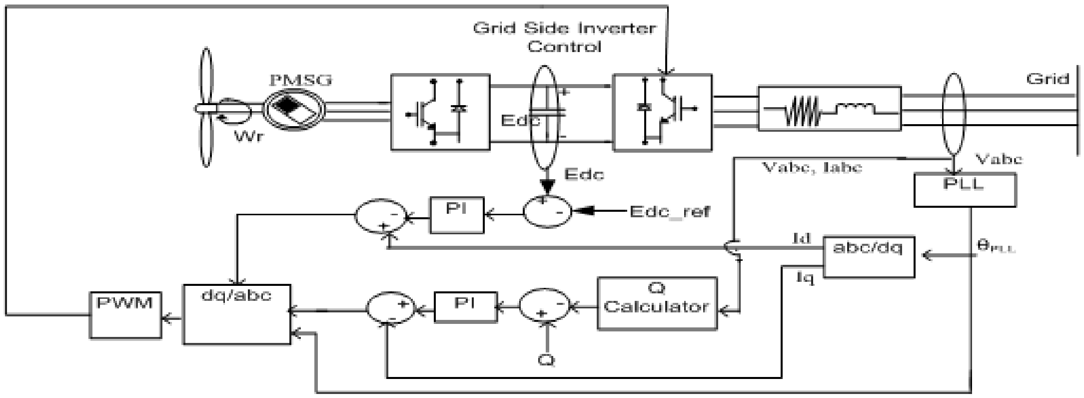

Fig.5 Control structure for the grid side frequency inverter

In this model, the back to back converter-inverter set is composed of six IGBT connected with a common DC link. An advantage of this system is that, the DC link capacitor decouples the converter and inverter and a separate control on each of them can be used. The control structure for the grid side frequency inverter is shown in the fig.5. The voltage obtained from the grid is used as the input of PLL. The output of PLL, i.e. θ_{PLL} is used for dq/abc and abc/dq transformations. The d-q components of currents and voltages are used by the PWM, which produces effective firing pulses in order to control the IGBT two-level converter-inverter set. Similar control topology has been used for the generator side converter.

3.2 MPPT

In order to obtain the maximum amount of energy from the wind, the wind turbine must have a specific rotation speed to maintain the optimum tip-speed ratio. The purpose of the MPPT is to maintain the tip-speed ratio of the wind turbine as close as possible to the optimal tip-speed ratio. Fig. 6 shows the characteristic curves of the wind. Every dotted line curve corresponds to a speed of wind.

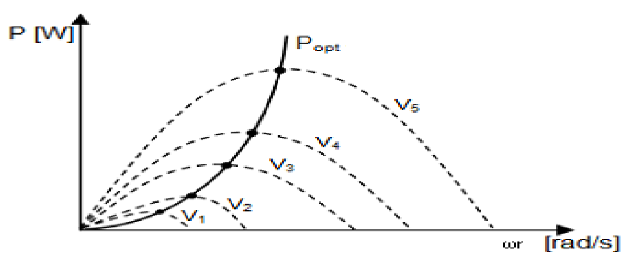

Fig.6 Characteristic curves of wind in plan power, rotational speed

An ideal wind turbine requires a perfect follow-up of this curve. For the MPPT operation, rotor speed is used as the controller input instead of wind speed, because the rotor speed can be measured more precisely and more easily than the wind speed. For a VSWT, generated active power depends on the power coefficient, C_p, which is related to the proportion of power extracted from the wind hitting the wind turbine blades. For each instantaneous wind speed of a VSWT, there is a specific turbine rotational speed, which corresponds to the maximum active power from the wind generator. In this way the MPPT for each wind speed, increases the energy generation in a VSWT [9].

4. Simulation result and comparison to IG without STATCOM

Simulations have been done by using Power System Computer Aided Design/Electromagnetic Transient including DC (PSCAD/EMTDC) program [11], for 80 seconds. The timing step of the simulation is chosen to be 0.001 sec. The rotor speed, grid side voltage and output power for PMSG are compared with that of the IG without STATCOM. The simulation results are shown below.

Fig 8 shows the variable wind speed data used in the simulation of both PMSG and IG without STATCOM. It appears from fig.9 that IG has apparently a better response of rotor speed than that of PMSG. But actually IG rotor has no control over the output power and voltage, since it cannot change its speed, which PMSG can. So the PMSG provides a control of output power and voltage as shown in the next figures.

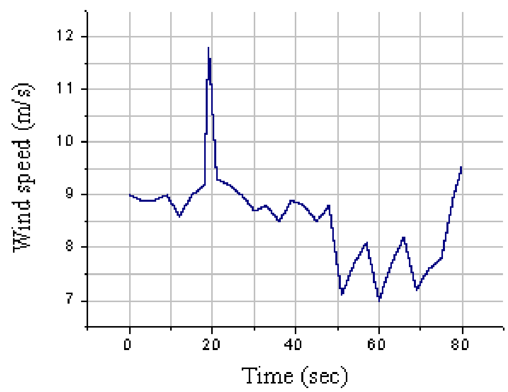

Fig.8 Wind speed data

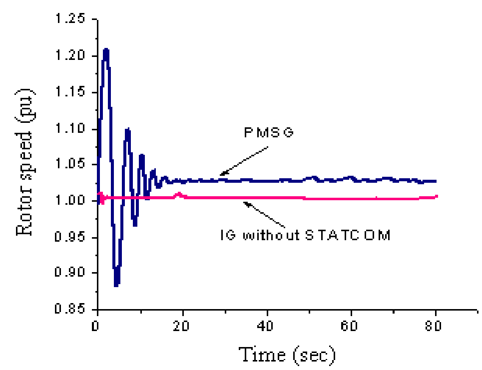

Fig.9 Rotor speed of VSWT-PMSG

Fig.10 shows the real power, P, available at the grid side. For PMSG, in spite of varying wind speed, the real power at the grid maintains a constant value, whereas, in case of IG without STATCOM, the power at the grid side fluctuates with the wind speed, as stated above. Similar result can be observed in fig.11, in case of reactive power, Q, at the grid side. It shows, though the wind speed is dynamic, but the proposed control strategy allows a constant grid-side reactive power, which can not be obtained with an IG without STATCOM.

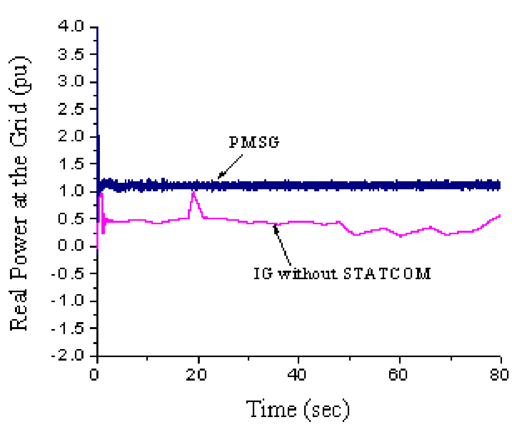

Fig.10 Real power at the grid side

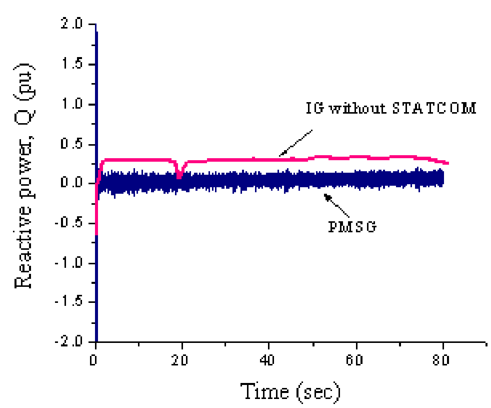

Fig.11 Reactive power at the grid side

Fig.12 shows the grid side voltage. For an IG without STATCOM, the grid side voltage is fluctuating in nature, whereas, the proposed model of PMSG is able to maintain a constant voltage at the grid side in spite of the dynamic nature of wind.

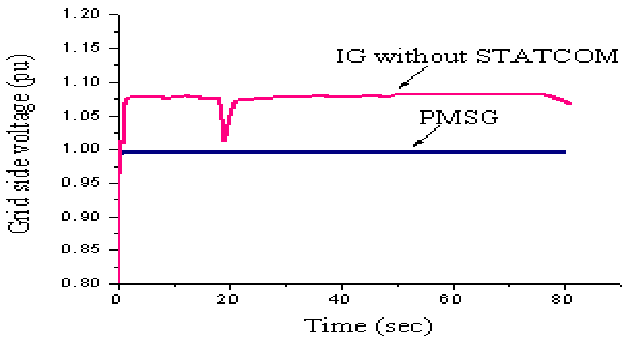

Fig.12 Grid Side Voltage

Fig.10, 11 and 12 indicates the stated parameters for both IG and PMSG, simulated for the same wind speed. For IG the output powers (real and reactive) and the grid side voltage fluctuate with the wind speed. If it is to be controlled, i.e. to supply a constant voltage and power at the grid with the IG, then some special control systems like STATCOM must be used. But it can be observed from these figures that the proposed model with PMSG is able to supply constant power and voltage at the grid side without using STATCOM.

5. Conclusion

This paper presented the model of a VSWT driven by a PMSG. The modeling and control strategies for the generator and grid side frequency inverter are presented. These control topologies are suitable for improving the dynamic analysis of the VSWT driven by PMSG.

Since wind is fluctuating in nature; the output power and terminal voltage of wind generator also fluctuate randomly, as seen from the figures in case of IG without STATCOM. The proposed control system can smooth the wind generator output power. Moreover, it can also maintain constant voltage magnitude at wind farm terminal. The graphs shown here proves the dynamic stability of the system. Therefore the proposed system has better quality and improved reliability.

6. References

[1] "Global Wind Report Annual market updates 2012". Global Wind Energy Council. Retrieved 23 April 2013.

[2] H. STIESDAL; The wind turbine, components and operation; 1999.

[3] Ackermann, T. 2005. *Wind Power in Power Systems*. John Wiley and Sons, Ltd. London, UK.

[4] Kim, Hong-Woo, Kim, Sung-Soo, and Ko, Hee-Sang. 2010. “Modeling and control of PMSG based Variable-speed Wind Turbine”. *Electric Power Systems Research*. 80:46-52.

[5] Vas, Peter. 1992. *Electrical Machines and Drives-A Space Vector Theory Approach*. Oxford University Press. New York, NY.

[6] Miller, T.J.E 1989. ***Brushless Permanent-Magnet and Reluctance Motor Drives.*** Oxford University Press. New York, NY.

[7] S. Heier, Grid Integration of Wind Energy Conversion System, John Wiley & Sons Ltd., (1998).

[8] M. R. I. Sheikh, S. M. Muyeen, R. Takahashi, T. Murata, and J. Tamura, International Review of Automatic Control (IREACO) 1(3), 311 (2008).

[9] Muyeen, S.M, J. Tamura, and T. Murata. 2009. *Stability Augmentation of a Grid-connected Wind Farm.* 1st edition. Springer-Verlag: London, UK.

[10] J. Jonkman, S. Butterfield, W. Musial, and G. Scott. “Definition of a 5-MW Reference Wind Turbine for Offshore System Development”. s.l. : NREL, February 2009.
[11] PSCAD/EMTDC Manual.1994. Manitoba HVDC Research Center.