Modeling and Optimization of Variable Speed Wind Turbine Using Permanent Magnet Synchronous Generator

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Abstract

This paper proposes an optimized model of a Variable Speed Wind Turbine equipped with Permanent Magnet Synchronous Generator (PMSG). This model has the ability to respond to a disturbance or fault of the system from a normal operating condition to return to a state where their operation is normal again. The model has a set of six-IGBT converter-inverter connected through a DC bus. The paper presents a simulation model of a 3MW-level variable speed wind turbine with a permanent magnet synchronous generator and a full-scale converter developed in the simulation tool of PSCAD/EMTDC. Simulation results shows that the proposed model can enhance the stability of power system effectively.

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

1. Introduction

In recent years the risks of shortage of fossil fuels and their effects on the climatic change have indicated the importance of renewable energies. WIND is a promising source of renewable energy. In worldwide there are now many thousands of wind turbines operating, with a total nameplate capacity of 196,630MW [1]. Both induction and synchronous generators can be used for wind turbine [2]. But the PMSG is chosen, because it offers better performance due to higher efficiency and less maintenance since it does not have rotor current and can be used without a gearbox, which also implies a reduction of the weight of the nacelle and a reduction of costs. Using the PMSG the design can be even more simplified. However, the recent advancements in power electronics and control strategies have made it possible to regulate the voltage of the PMSG in many different ways. [3, 4].

The goal of this paper is to optimize the electromagnetic energy conversion from the wind turbine and develop suitable control strategies in one hand and to stabilize the power system from fault on the other hand. Here, PWM (Pulse Width Modulator) is used to control the frequency converters. The instantaneous values of voltages are used as PWM control variables. These values of voltages are obtained from the real and reactive power through PI controllers.

2. Conversion of Wind Energy

Wind energy conversion system is quite complex. It depends on some factors like existence of various fields, (aerodynamic, mechanical and electric fields) and the factors that determine the mechanical power as wind speed, dimension and shape of the turbine. Four components are considered in describing a wind model [5] as follows:

$$V_{wind}=V_{bw}+V_{gw}+V_{rw}+V_{nw} \qquad (1)$$

Where, V_{bw}, V_{gw}, V_{rw} and V_{nw} are the Base wind, Gust Wind, Ramp Wind and Noise wind components respectively (in m/s).

The kinetic energy of the wind (air mass m, wind speed v) is given by the following equations:

$$Ec=\frac{1}{2}mv^2 \qquad (2)$$

Where, $m=\rho v S\Delta t$, (With S: Covered surface of the turbine and ρ: The air density)

The wind power P_w can be expressed as:

$$Pw = \frac{d}{dt}Ec \Rightarrow Pw = \frac{1}{2}\rho S v^3 \quad (3)$$

P_m is the mechanical power that the turbine extracts from the wind, it is inferior to P_W. Because the wind speed after the turbine isn't zero (the air needs to be carried off after the turbine). Therefore, the power coefficient of the turbine C_p is defined as [6]:

$$Cp = \frac{Pm}{Pw}; \quad Cp < 1 \quad (4)$$

Therefore, the recovered power from the wind P_m (i.e. the mechanical power) is given by

$$Pm = \frac{1}{2}\rho\pi R^2 v^3 Cp \quad (5)$$

Where, R is the radius of the rotor. C_p depends on the tip speed ratio λ of the wind turbine and angle of the blades, β

$$Cp = Cp(\lambda, \beta) \qquad \text{with: } \lambda = \frac{R\omega}{v} \quad (6)$$

Where, ω is the rotation speed of the rotor. The maximum theoretical value possible for the of the power coefficient, named limit of Betz [6], is:

$$Cpmax = \frac{16}{27} = 0.593$$

The wind turbine torque on the shaft can be calculated from the power:

$$Tm = \frac{Pm}{\omega} = \frac{1}{2}\rho\pi R^2 \frac{v^3}{\omega} Cp \quad (7)$$

Introducing $\lambda = \frac{R\omega}{v}$, the equation becomes, $Tm = \frac{1}{2}\rho\pi R^3 v^2 \frac{Cp}{\lambda}$ (8)

The torque coefficient C_T is given by, $C_T = \frac{Cp}{\lambda}$

This gives: $Tm = \frac{1}{2}\rho\pi R^3 v^2 C_T$ (9)

3. Modeling of the System

A variable speed wind turbine (VSWT) with PMSG is shown in the figure.

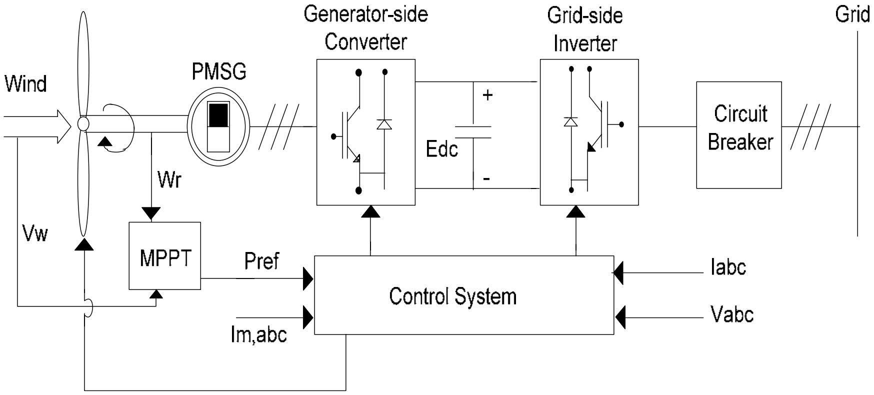

Fig.1 Electrical Scheme of VSWT-PMSG

As shown 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 IGBTs and anti parallel diodes.

Generator Model

The generator is based on PARK transformation. In order to get a dynamic model for the generator that easily allows us to define the generator control system, the equations of the generator are projected on a reference coordinate system rotating synchronously with the magnetic flux as shown in fig. 2.

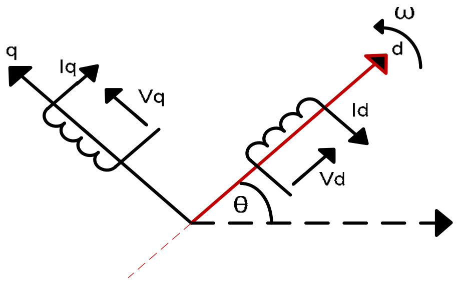

Fig.2 PARK Model for PMSG

With sinusoidal distribution of conductors and flux are linear functions of currents Id and Iq situated on the rotor. They are given by the equations [7]:

$$\begin{cases} \psi d = LdId + \psi f & (10) \\ \psi q = LqIq & (11) \end{cases}$$

Where, Ld: Stator inductance in d-axis;

Lq: Stator inductance in q-axis;

Ld and Lq are supposed independent of θ

ψf : Magnetic flux;

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

$$Id = \sqrt{\frac{2}{3}} \begin{bmatrix} \cos\theta & \cos\left(\theta - \frac{2\pi}{3}\right) & \cos\left(\theta + \frac{2\pi}{3}\right) \end{bmatrix} \begin{bmatrix} Ia \\ Ib \\ Ic \end{bmatrix} \tag{12}$$

$$Iq = \sqrt{\frac{2}{3}} \begin{bmatrix} -\sin(\theta) & -\sin\left(\theta - \frac{2\pi}{3}\right) & -\sin\left(\theta + \frac{2\pi}{3}\right) \end{bmatrix} \begin{bmatrix} Ia \\ Ib \\ Ic \end{bmatrix} \tag{13}$$

The equations of voltage are:

$$Va = \sqrt{\frac{2}{3}} [Vd\ cos(\theta) - Vq\ sin(\theta)] \tag{14}$$

$$Vb = \sqrt{\frac{2}{3}} \left[Vd\ cos\left(\theta - \frac{2\pi}{3}\right) - Vq\ sin\left(\theta - \frac{2\pi}{3}\right)\right] \tag{15}$$

$$Vc = \sqrt{\frac{2}{3}} \left[Vd\ cos\left(\theta + \frac{2\pi}{3}\right) - Vq\ sin(\theta + \frac{2\pi}{3})\right] \tag{16}$$

The electromagnetic torque can be expressed as:

$$\tau = \frac{3}{2} P\ [\ (L_q - L_d)\, I_q I_d + I_q \Psi_f\ ] \tag{17}$$

4. Control Strategies

Frequency converter and PLL

The control structure of the frequency converter at the grid side is shown in the fig. 3. Here the well known cascade control scheme with independent control of the active and reactive currents was used for the IGBT (Insulated Gate Bipolar Transistor) 2-level converter. The voltages obtained from the grid side inverter E_a, E_b, E_c, are used to calculate the Phase Locked Loop (PLL) angle for the dq/abc and abc/dq transformation. Effective firing pulses are produced in order to control the currents for IGBT which in turn control the converter-inverter set of the system. The grid side converter maintains the DC link voltage to 1.0pu.

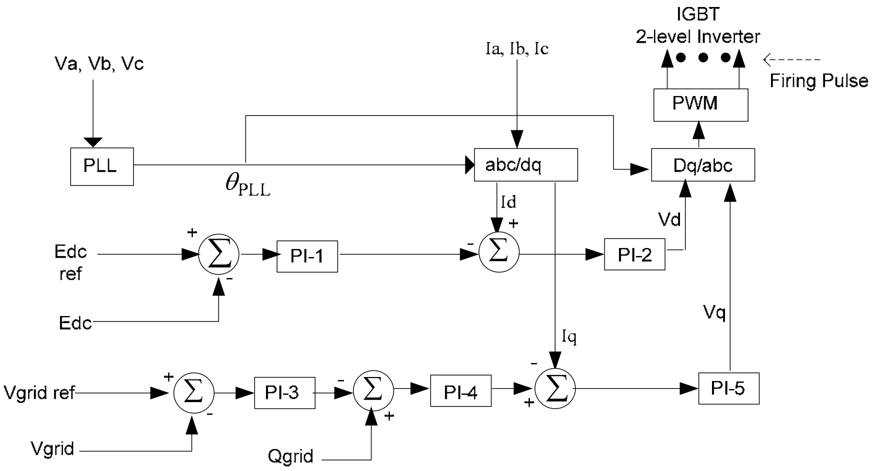

Fig.3 Control structure for the frequency converter

MPPT

The characteristic of the optimum power of a wind is strongly non linear and in the shape of "bell" [6]. For every speed of wind, the system must find the maximum power which is equivalent to the optimum rotational speed. Fig. 4 shows the characteristic curves of the wind. Every dotted line curve corresponds to a speed of wind.

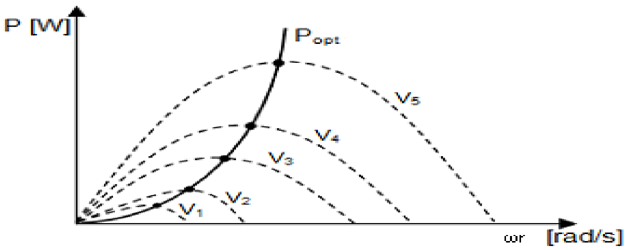

Fig.4 Characteristic curves of wind in plan power, rotational speed

An ideal wind turbine requires a perfect follow-up of this curve. To achieve this, a specific control strategy is used named Maximum Power Point Tracking (MPPT). 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 [8].

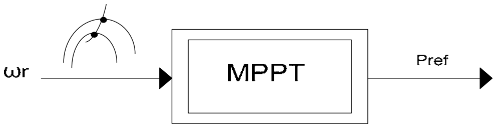

Fig.5 MPPT Searching methodology block

Circuit Breaker

The model has a circuit breaker, which responds when the fault occurs on the line that is, it isolates the faulty section from the healthy section.

5. Result and Analysis

Simulations have been done by using Power System Computer Aided Design/Electromagnetic Transient including DC (PSCAD/EMTDC) program, for 80 seconds, where a fault occurs at 35 second and clears within 0.05 second. The timing step of the simulation is chosen to be 0.001 sec. The simulation results are shown below.

Figure 6 shows the rotor speed (ω_r) variation of PMSG. It can be observed that the rotor speed fluctuates during fault, but it returns to the normal state as soon as the fault is cleared.

Figure 7 is the response of the DC link voltage after the generator side AC/DC converter. The converter maintains the DC link voltage at 1.0 pu as shown in the fig.7. Here, also, the DC bus voltage E_{DC} returns back to the normal operating condition after the fluctuations caused by the fault.

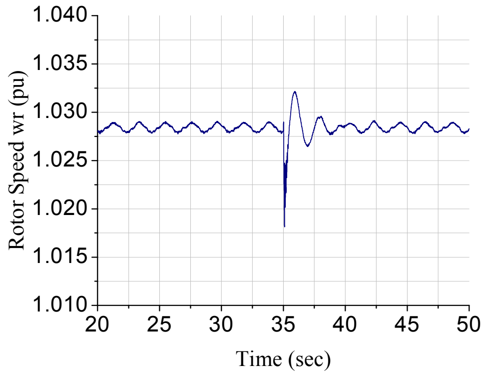

Fig.6 Rotor speed of PMSG

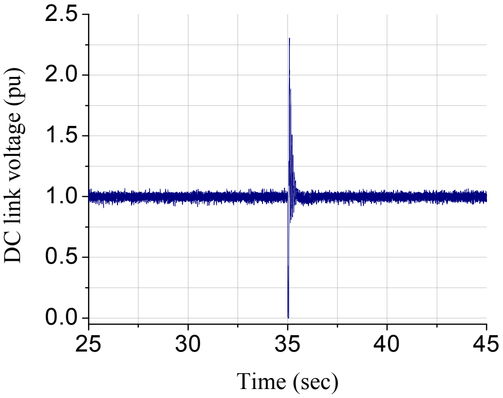

Fig.7 DC bus voltage

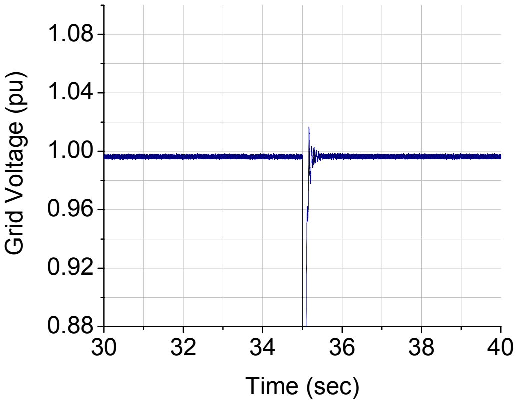

Fig.8 Voltage at the grid

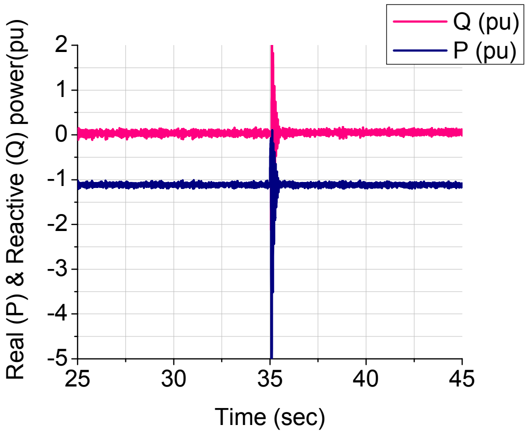

Fig.9 Real and reactive power at the grid

The grid side voltage Vg_{rid} is shown in the fig 8. As can be seen that a constant voltage is supplied to the grid by the model, again the grid voltage overcomes the fluctuations caused by the faults and went back to the normal operating condition. Similarly in fig 9, the real and reactive powers at the grid are shown. Here again the system not only supplies a constant power to the grid but also resumes to the normal sate after the occurrence of fault.

So, from all the simulation results it can be seen that the system maintains a constant voltage and power at the grid side and also it is capable of clearing faults on the line and returning back to the normal operating condition.

6. Conclusion

The paper presented a model of a VSWT driven by a PMSG. The modeling and controlling strategies for the generator rotor side frequency converter are presented. These control topologies are suitable for improving the transient analysis of the VSWT driven by PMSG, to be able to generate a constant voltage and power at the grid side and also to respond to a fault, which occurs on the system, to return back to the normal operating condition as soon as possible.

The graphs shown here proves the transient stability of the system. The model is capable of not only controlling a constant voltage and power at the grid but also resuming to the normal sate after the fault occurs, so the model is stable. Therefore the system has proved its better quality and improved reliability.

7. References

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