



MODELING AND CONTROL OF VARIABLE SPEED WIND TURBINE EQUIPPED WITH PMSG

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Abstract: This paper presents the dynamic model and control schemes of a wind turbine Generator system equipped with permanent magnet synchronous generator (PMSG). Along with the PMSG, wind turbine have been modeled and the equations that explain their behaviour have been introduced. The PMSG model is established in the dq-synchronous rotating reference frame. The concept of the Maximum Power Point Tracking (MPPT) has been presented in terms of the adjustment of the generator rotor speed according to instantaneous wind Speed. The wind turbine generator is connected to the grid through a frequency converter comprising of a diode rectifier and six pulse pwm inverter. The dc link voltage has been controlled in such away such that the grid power factor maintains nearly unity. The current controller has been proposed to generate reference voltage signal and corresponding control signal for grid side inverter. In order to verify, the proposed model has been implemented in the MATLAB/SIMULINK using Simpower system library. Simulation results prove the validity of the model and the control schemes

Keywords: Modeling, PMSG, WECS, MPPT, Grid Side Converter, Active and Reactive power

I. Introduction

Wind energy is one of the most promising renewable energy resources for generating electricity due to its cost competitiveness compared to other conventional types of energy resources. Only some specific locations with adequate wind energy resources can be described as being suitable for wind energy electricity generation. Wind energy is not harmful to the environment and it is naturally an abundant resource. Hence, wind power could be utilized by mechanically converting it to electrical power using wind turbine (WT). Various WT concepts have been developed into wind power technologies and led to significant growth of wind power capacity during the last two decade. By the end of 2003, the total installed capacity of the wind turbines has reached as much as 39.234GW and will exceed 110GW by the year of 2012 [1]-[16]. In depth understanding and investigation of wind energy related technologies, such as wind power generators, wind farm integration, grid code and etc., is very meaningful. In terms of the generators for wind-power application, there are different concepts in use today. The major distinction among them is made between fixed speed and variable speed wind turbine generator concepts. In the early stage of wind power development, fixed-speed wind turbines and induction generators were often used in wind farms. But the limitations of such generators, e.g. low efficiency and poor power quality, adversely influence their further application. With large-scale exploration and integration of wind sources, variable speed wind turbine generators, such as doubly fed induction generators (DFIGs) and permanent magnet synchronous generators (PMSGs) are emerging as the preferred technology [2]. In contrast to their fixed-speed counterparts, the variable speed generators allow operating wind turbines at the optimum tip-speed ratio and hence at the optimum power efficient for a wide wind speed range. However, the variable-speed directly-driven multi-pole permanent magnet synchronous generator (PMSG) wind architecture is chosen for this purpose and it is going to be modeled: it offers better performance due to higher efficiency and less maintenance because it does not have rotor current. What is more, PMSG can be used without a gearbox, which implies a reduction of the weight of the nacelle and reduction of costs. Optimum wind energy extraction is achieved by running the Wind Turbine Generator (WTG) invariable speed because of the higher energy gain and the reduced stresses. Using the Permanent Magnet Synchronous Generator (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. This paper proposes a control strategy of direct-drive permanent magnet wind power system, and discusses back to-back PWM converter control method. The PMSG wind architecture is chosen. We present a complete detailed modeling and a control scheme of a three-phase grid connected WECS [6]. Moreover, the concept of the maximum power point tracking has been presented in terms of the adjustment of the generator rotor speed according to instantaneous wind speed. The WECS model includes a wind turbine, a PMSG, diode rectifier in generator-side, intermediate DC circuit, and PWM inverter in grid-side. PMSG is coupled to wind turbine without gearbox. Inverter is used to sustain the DC bus voltage and regulate the grid-side power factor. Thus, active and reactive powers are controlled respectively by the inverter in grid-side [7]. Validation of models and control schemes is fulfilled out through simulations by using the MATLAB/ Simulink environment.

This paper is structured as follows. In Sections II the models of the wind turbine generator and PMSG are developed. In Section III, control of system will be presented. The simulations results are given in Section IV and finally, some conclusions are given in Section.

II. MATHEMATICAL MODELING OF WECS

A. Modelling of wind turbine with Pmsg

Wind turbines cannot fully capture wind energy. The components of wind turbine have been modeled by the following equations. Output aerodynamic power of the wind-turbine is expressed as

$$P_{Turbine} = \frac{1}{2} C_p(\lambda, \beta) \rho A V^3 \quad (1)$$

Where ρ is the air density (typically 1.225 kg/m^3), A is the area swept by the rotor blades (in m^2), C_p is the coefficient of power conversion and V is the wind speed (in m/s). The tip-speed ratio is defined as

$$\lambda = \frac{W_{mR}}{V} \quad (2)$$

Where W_m and R are the rotor angular velocity (in rad/sec) and rotor radius (in m), respectively. The wind turbine mechanical torque output T_m given as

$$T_m = \frac{1}{2} \rho A C_p(\lambda, \beta) \frac{V^3}{W_m} \quad (3)$$

The power coefficient is a nonlinear function of the tip speed ratio λ and the blade pitch angle β (in degrees). If the swept area of the blade and the air density are constant, the value of C_p is a function of λ and it is maximum at the particular λ_{opt} . Hence, to fully utilize the wind energy, λ should be maintained at λ_{opt} , which is determined from the blade design. Then

$$P_{Turbine} = \frac{1}{2} \rho A C_{p \max} V^3 \quad (4)$$

A generic equation is used to model the power coefficient $C_p(\lambda, \beta)$ based on the modeling turbine characteristics described in and. In order to simulate the wind generation system, an empirical expression of $C_p(\lambda, \beta)$ has been considered in, such that

$$C_p = [0.5 - 0.00167(\beta - 2)] \sin \frac{\pi(\lambda + 0.1)}{12 - 0.3(\beta - 2)} - 0.00184(\beta - 2)(\lambda - 3) \quad (5)$$

In this, the pitch angle β is set to zero. The rotational speed is calculated by considering the followings:

$$J \frac{dW}{dt} = T_m - T_{em} - F_w \quad (6)$$

Where J is Inertia moment of the turbine, axle and generator F Axle friction T_{em} Electromagnet torque. The characteristic function $C_p(\lambda, \beta)$ Vs λ for various values of the pitch angle β & mechanical power Vs rotor speed is illustrated in Fig.4.&5. The maximum value of $C_p = 0.593$ [17] which means that the power extracted from the wind is always less than 59.3% (Betz 's limit), because of various aerodynamic losses depend on the rotor construction (number and shape of blades, weight, stiffness, etc.). This is the well known low efficiency to produce electricity from the wind. This particular value λ_{opt} results in the point wind speed, there exists a specific point in the wind generator power characteristic, MPPT, where the output power is maximized. Thus, the control of the WECS load results in a variable-speed operation of the turbine rotor, so the maximum power is extracted continuously from the wind.

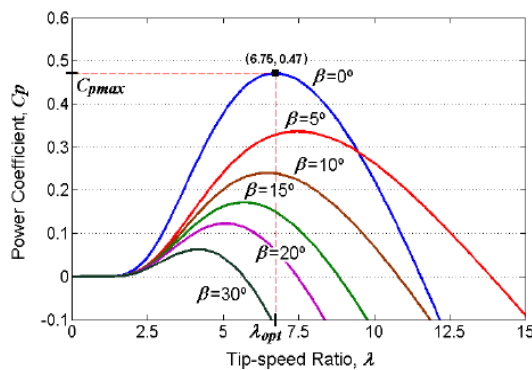


Fig.1. Typical TSR Vs λ curve

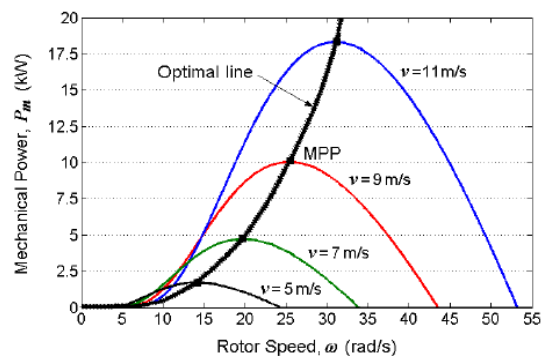


Fig. 2. Typical Pm Vs W curve

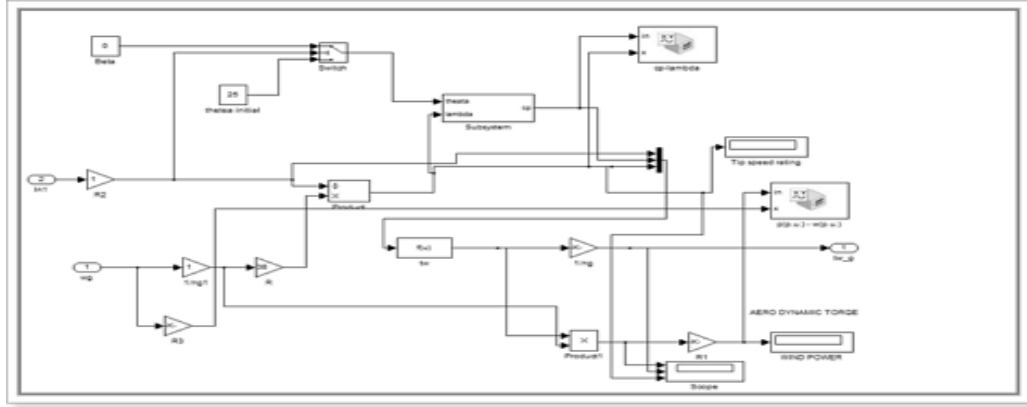


Fig.3. Wind Turbine model with Simulink

B. PMSG Model

The dynamic model of the PMSG is derived from the two phase synchronous reference frame, 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 phase locked loop (PLL) [10]. Fig. 9 shows the d-q reference frame used in a salient-pole synchronous machine (which is the same reference as the one used in a PMSG), where θ is the mechanical angle, which is the angle between the rotor d-axis and the stator axis. The mathematical model of the PMSG for power system and converter system analysis is usually based on the following assumptions. [10].

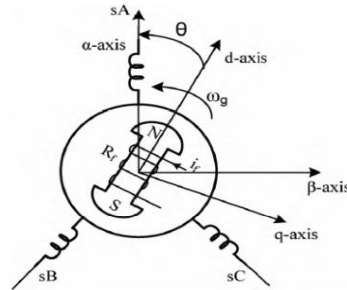


Fig. 4. d-q and α - β axis of a typical salient-pole synchronous machine

The stator windings are positioned sinusoidal along the air-gap as far as the mutual effect with the rotor is concerned; the stator slots cause no appreciable variations of the rotor inductances with rotor position; magnetic hysteresis and saturation effects are negligible; the stator winding is symmetrical; damping windings are not considered; the capacitance of all the windings can be neglected and the resistances are constant (this means that power losses are considered constant). The mathematical model of the PMSG in the synchronous reference frame (in the state equation form) is given by [10]

$$\frac{di_d}{dt} = \frac{1}{L_{ds} + L_{qs}} R_s i_d + W_e (L_{qs} + L_{is}) i_q + u_d \quad (7)$$

$$\frac{di_q}{dt} = \frac{1}{L_{qs} + L_{is}} (R_s i_q + W_e (L_{ds} + L_{is}) i_d + u_q) \quad (8)$$

where subscripts 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 in ohm, L_d and L_q are the inductances in henry of the generator on the d and q axis, L_{id} and L_{iq} are the leakage inductances in henry of the generator on the d and q axis, respectively, ψ is the permanent magnetic flux in wb and W_e is the electrical rotating speed in rad/s of the generator, defined by

$$W_e = p w_g \quad (9)$$

where p is the number of pole pairs of the generator. In order to complete the mathematical model of the PMSG, the mechanical equation is needed, and it is described by the following electromagnetic torque equation given by [10].

$$\tau_e = 1.5p((L_{ds} - L_{is})i_d i_q + i_q \psi_f) \quad (10)$$

developing current regulator .the developed current regulator has been used to develop reference voltage signal for the grid side inverter. The simplest and effective controller is used for proposed model is PI controller. The current regulator stabilizes the DC voltage to the reference value. PI controllers are used to regulate the output currents and voltage in the inner control loops and the DC voltage controller in the second loop. In order to compensate the cross-coupling effect due to the output filter in the rotating synchronously reference frame, the decoupling voltages are added to the current controller outputs. The vector control scheme used is based on a rotating synchronously reference frame. PWM is used to produce the control signal to control the grid-side converter.

IV. SIMULATION RESULT

The system is built using Matlab/Simulink. The complete Simulink model & control system is shown in fig.7. The simulated responses of the WECS are presented in this section under variable wind speeds. The parameters of the turbine and PMSG used are given in Table I and Table II. The power converter and the control algorithm are also implemented in the model. Fig.8. shows the simulation result of DC link voltage that remains a constant value. Fig.9 shows the output current of PMSG. Fig.10. shows the aerodynamic and electromagnetic torque and rotor speed of PMSG. Fig.11 shows all three phase Inverter voltage. Fig.12 shows the waveforms of phase current and voltage of GRID, and fig.13 shows the waveform of three phase voltage and current. It is obvious that unity power factor is achieved approximately.

V. CONCLUSION

The modeling and optimum control method of PMSG for wind generation system has been proposed in this paper. The concept of the Maximum Power Point Tracking (MPPT) has been presented in terms of the adjustment of the generator rotor speed according to instantaneous wind Speed. The proposed model has been implemented using Matlab/ Simulink. The proposed control algorithm successfully implemented and result obtained for various parameters. The grid side PWM inverter is controlled by controlling the dc link voltage and the simulation result shows that the grid voltage and current possesses approximately unity power factor.

APENDIX

TABLE 1 WIND TURBINE PARAMETERS

Parameter	Symbol	Value and Units
Air density	ρ	1.205kg/ m ³
Rotor radius	R	38m
Rated wind speed	V _w rated	11.8m/s
Maximum Cp	Cp max	0.4412

TABLE II GENERATOR PARAMETERS

Parameter	Symbol	Value
Rated generated power	P _g rated	2MW
Rated mechanical Speed	W _g rated	2.18
Stator resistance	R _s	0.08Ω
Stator d-axis inductance	L _{ds}	0.334 H
Stator q- axis inductance	L _{qs}	0.217 H
Stator leakage inductance	L _{ls}	0.0334 H
Permanent magnet flux	f	0.4832 Wb
Pole pairs	P	3

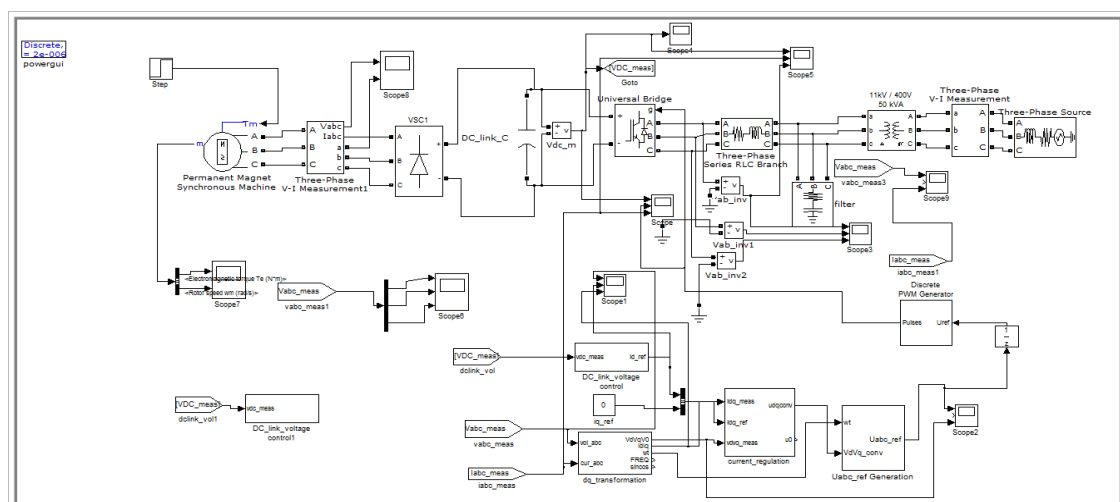


Fig.7.Complete Proposed Wind Turbine model with Simulink

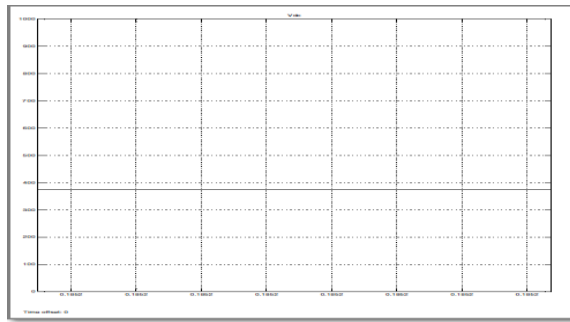


Fig. 8 DC link Voltage

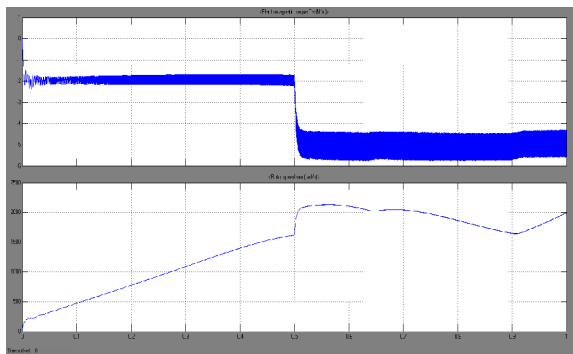


Fig.10 Electromagnetic torque and Rotor speed

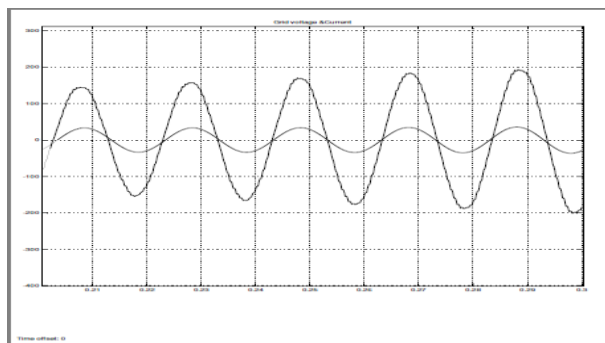


Fig.12 Grid voltage and grid current

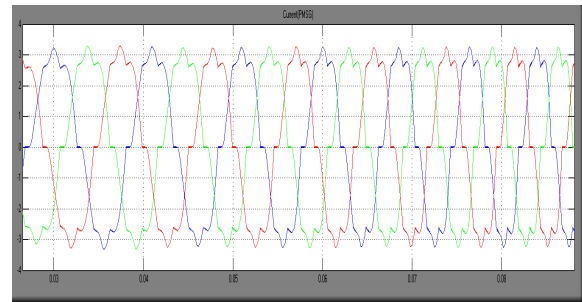
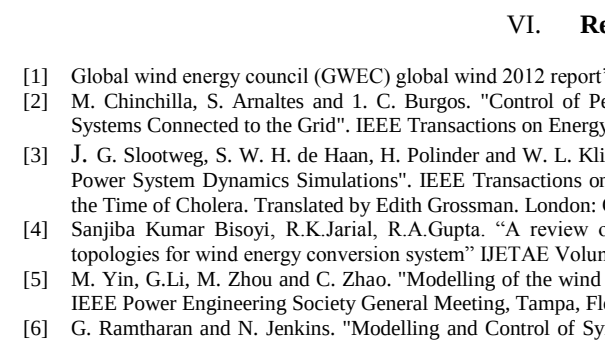


Fig. 9 Output current of PMSG

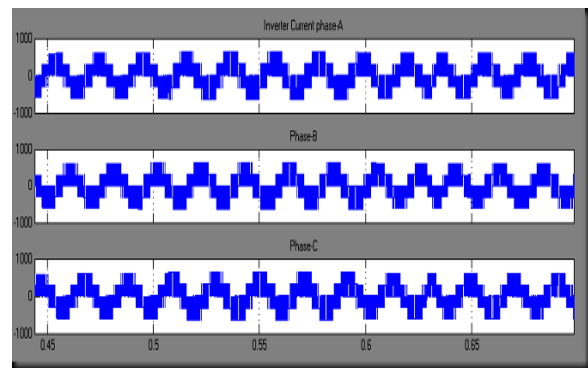


Fig.11 Inverter Voltage phase a phase band phase c

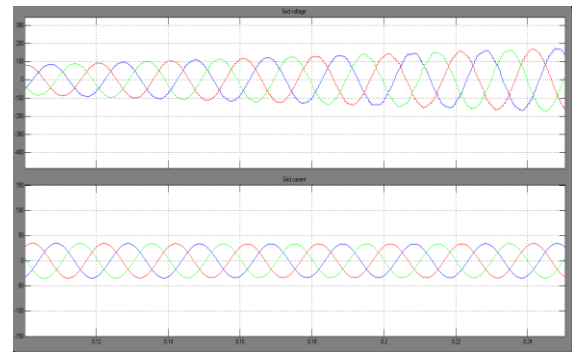


Fig.13 Three phase source voltage and current

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