Simulation and Control of Direct Driven PMSG for Wind Turbine Application based on MPPT in SEQUEL

Anu Nissy Soney
Dept. of Electrical & Electronics Engineering
Manipal University Jaipur
Jaipur, India

Dhanesh P R
External Guide
Power Electronics Group
Centre for Development of Advanced Computing
Thiruvananthapuram, India

Manish kumar Thukral
Internal Guide
Dept. of Electrical & Electronics Engineering
Manipal University Jaipur
Jaipur, India

***Abstract*— As we are aware about the increasing concerns about CO_2 emissions and the depletion of existing fossil fuel deposits, renewable energy becomes more and more attractive. This project aims to study and simulate direct driven permanent magnet synchronous generator for wind energy conversion system to extract maximum power from variable wind speed based on maximum power point tracking algorithm in the SEQUEL simulation platform. The direct driven generator omits gearbox in the wind energy conversion system and thereby increases the operational reliability. Boost converter is controlled to get a fixed DC link voltage. Various constraints like interaction between the wind farm and the grid, operational limits are taken into consideration. We shall deal with the same in detail in this paper.**

Keywords—wind turbine; direct driven permanent magnet synchronous generator (DDPMSG); boost converter; space vector pulse width modulation

I. INTRODUCTION

On earth where survival has become a query, there is an urge for some social and environmental concern as a result of which, electricity is generated from renewable energy resources. Power generation from wind energy has become an advanced technology and plays a major role to overcome the worldwide energy crisis and solves the green house problem to an extent. Nowadays wind generators (WGs) have been widely used to supply power in grid-connected applications.

The wind energy conversion system can control and make use of kinetic energy of the wind. Optimum wind energy extraction is possible, when the wind turbine is operating in variable speed mode. In fixed speed system, the turbine's rotor speed is determined by grid frequency. A wind energy conversion system operating at variable speeds (see Fig. 1) is currently playing a superior role on fixed speed designs. The wind speed, turbine parameters, air density etc, is responsible for power generation at a particular wind velocity.

With the advent of latest technology, permanent magnet synchronous machine is considered as the efficient and simpler ones with no exciter. The direct driven permanent magnet synchronous generator can spin at the speed of wind turbine rotor. So it removes the gearbox problem in the wind power generation system. Therefore, it increases the operating reliability, energy efficiency and reduces system losses. In order to convert wind energy to the grid, various converters are investigated. In this paper, permanent magnet generators with diode rectifiers are used to convert variable output voltage from PMSG to variable DC voltage. Boost converter is used to boost and regulate the output voltage of the diode rectifier to a fixed DC voltage. Voltage Source Inverter (VSI) is used to convert the DC voltage back to AC for electrical utilizations in the grid. And also the reactive power control strategy can be done at the supply side converter. This work is about simulation study of DDPMSG for wind turbine application to extract maximum power from wind.

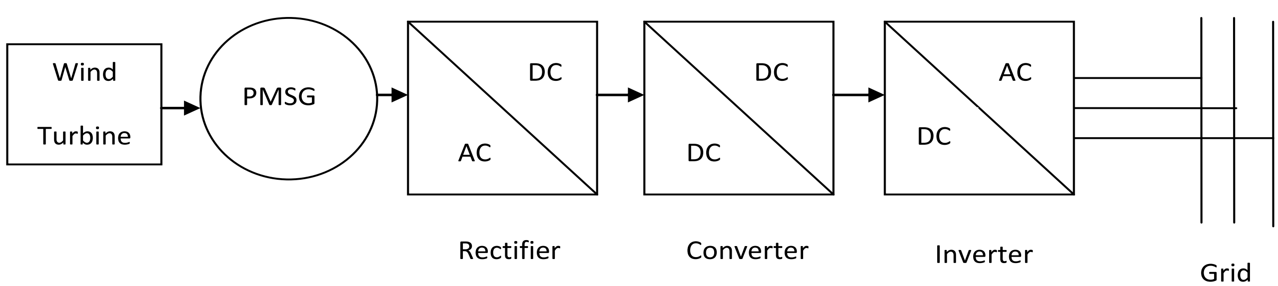

Fig. 1. Block diagram for wind power extraction.

II. WIND TURBINE

The kinetic energy contained in the wind can be converted into mechanical energy by using wind turbines. The kinetic energy of wind with a mass flow $\dot{m}$ and density ρ (kg/m^3), moving at a velocity v (m/s) through the area A (m^2) is

$$P_{wind} = \frac{1}{2}\dot{m}v^2 \qquad (1)$$

and the mass flow is

$$\dot{m} = \rho A v \qquad (2)$$

(2)

The power available in the wind is

$$P_{wind} = \frac{1}{2}\rho A v^3 \qquad (3)$$

The power captured is some fraction of the available power. Aerodynamic efficiency represents the power extracted from the wind to the available power which is defined by the coefficient of performance, Cp. According to Betz theory, the amount of extractable energy from an air stream is limited. The maximum extractable power is, 16/27 of available wind power which is called Betz factor. The mechanical power, P_m which we can extract from the wind,

$$P_m = \frac{1}{2}\rho\pi R^2 v^3 C_p(\theta,\lambda) \qquad (4)$$

where R is the blade radius (m) and C_p is the power coefficient which is related with pitch angle θ (deg) and tip speed ratio λ. The tip speed ratio depends on wind velocity and wind turbine speed, W_w is defined as

$$\lambda = \frac{W_w R}{v} \qquad (5)$$

Fig. 2, shows Power coefficient versus tip speed ratio curve of a wind turbine. The wind turbine power

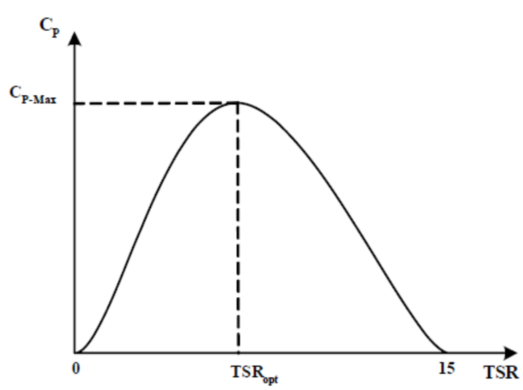

Fig. 2. Power coefficient versus tip speed ratio.

coefficient becomes the maximum value at a particular tip-speed ratio, λ_{opt}. Cp based on the modeling turbine characteristics can be written as

$$C_P(\lambda,\beta) = C_1(C_2/\lambda_i - C_3\beta - C_4)e^{-\frac{C_6}{\lambda_i}} + C_6\lambda \qquad (6)$$

Where,

$$\frac{1}{\lambda_i} = \frac{1}{\lambda+0.8\beta} - \frac{0.035}{1+\beta^3} \qquad (7)$$

III. MPPT STRATEGY

Wind power varies continuously with changes in the wind speed throughout the day. The wind turbine can deliver Maximum Power when rotor speed changes with respect to the variation in wind speeds. So extracting maximum possible power from the available wind power is very important. The technique used for this purpose is known as Maximum Power Point Tracking (MPPT). Based on the measured wind speed, a maximum power tracking algorithm calculates the speed command $W*$, the reference value for generator speed, in which, output power is maximized, can be obtained as below.

$$W* = \frac{\lambda_{opt}\ v}{R} \qquad (8)$$

For various Wind speeds, the rotational speed is controlled to follow the maximum power point trajectory. The maximum mechanical output power of the wind turbine is given as follows,

$$P_{m\_max} = \frac{1}{2}\rho A C_{Pmax}\frac{RW^*}{\lambda_{opt}} \qquad (9)$$

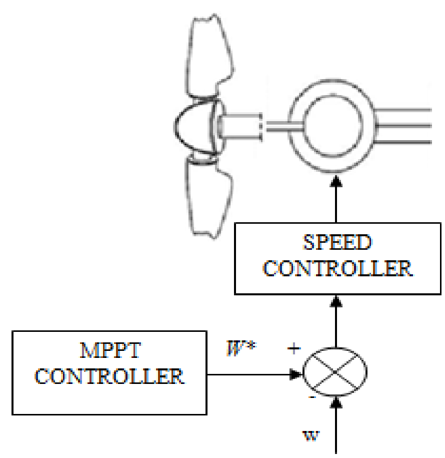

Fig. 3. MPPT control system.

Consequently, we can get the maximum power by regulating the PMSG speed in different wind speed conditions. Depending on the wind speed, the MPPT control adjusts the turbine reference speed, bringing the turbine operating points onto the maximum power curve.

IV. PMSG SPEED CONTROLLER

The PMSG speed controller requires a reference speed $W*$, and an actual generator speed w, and the speed error set the q axis current command i_{qref}, required by the current controller. The d axis current command i_{dref} , is zero. The current controllers generate voltages and this is used for the real dq current generation of the machine, which in turn are used to calculate electrical torque T_e, inside the mechanical subsystem. The T_e, produced by the PMSG along with the mechanical torque T_m, produced by the turbine determines w, which is finally fed to the speed controller. The dq rotating reference frame is used to analyze PMSG. Park and inverse park transformation is used to transform three phase system to dq rotating frame and vice versa respectively for speed control of PMSG.

The dynamic equations of PMSG is

$$\frac{di_d}{dt} = -\frac{R_s i_d}{L} + w_e i_q + \frac{V_d}{L} \qquad (10)$$

$$\frac{di_q}{dt} = -\frac{R_s i_q}{L} + w_e \left(i_d + \frac{\lambda_0}{L}\right) + \frac{V_q}{L} \qquad (11)$$

R_s is the stator resistance (Ω), i_d and i_q are the d and q axis currents (A), L is the inductances of generator (H), λ_0 is the permanent magnet flux (Wb), w_e is the electrical rotating speed ($rads^{-1}$) and V_d and V_q are the d and q axis voltages (V).

V. BOOST VOLTAGE CONTROLLER

It consists of an input voltage source E_s, boost inductance RL, controlled switch S, diode D, boost capacitance C and load resistance R. The operation of this converter is achieved by the periodic opening and closing of the switch S. It is called as a boost converter because the output voltage is greater than the input voltage.

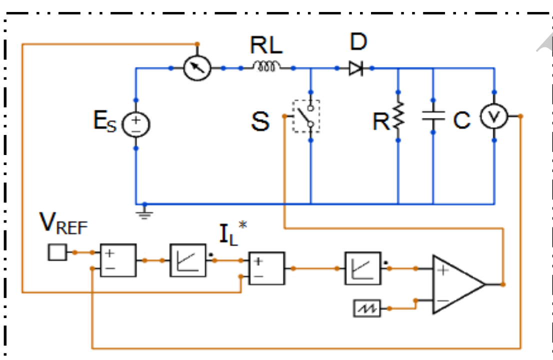

Fig. 4. Boost converter control strategy diagram.

The boost converter controller diagram is shown in fig. 4. Here, the boost converter has been controlled to produce constant output DC voltage level U_{dc}, same as that of reference voltage V_{REF}, by varying the duty ratio D, in response to variations in rectifier output voltage. The relation between the input and output voltage and currents of the boost converter is written as.

$$V_{out} = V_{in} \frac{1}{1-D} \qquad (12)$$

$$I_{out} = I_{in}(1-D) \qquad (13)$$

(3.12)

The boost converter adopts double control loops. The inductor current i_L, is controlled in the inside loop, and DC-link voltage U_{dc}, is controlled in the outside loop, which makes sure the DC-link voltage constant.

VI. INVERTER CONTROL STRATEGY

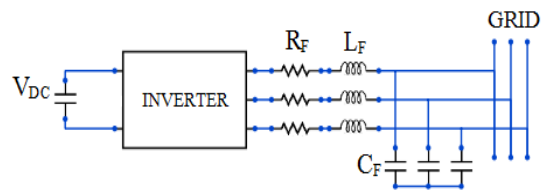

Fig. 5. Supply-side converter arrangement.

Fig. 5 shows a schematic representation of grid connected inverter. It consists of a dc-side capacitor, a 3-phase inverter, and a filter which connects the inverter output to the grid. The output DC voltage of boost circuit is fed to an inverter. According to Kirchhoff's Voltage Law the voltage equations can be written as

$$e_A = R_F i_A + L_F \frac{di_A}{dt} + V_A \qquad (14)$$

$$e_B = R_F i_B + L_F \frac{di_B}{dt} + V_B \qquad (15)$$

$$e_C = R_F i_C + L_F \frac{di_C}{dt} + V_C \qquad (16)$$

Where e_A, e_B, e_C are grid voltages and V_A, V_B, V_C are inverter voltages, i_A, i_B, i_C are inverter currents, R_F and L_F are filter resistance and inductance. In rotating frame we can write the above equations as

$$V_d = R_F i_d + L_F \left[\frac{d}{dt}(i_d) - w(i_q)\right] + e_d \qquad (17)$$

$$V_q = R_F i_q + L_F \left[\frac{d}{dt}(i_q) + w(i_d)\right] + e_q \qquad (18)$$

where, i_d and i_q are d-axis and q-axis component of inverter current, e_d and e_q are d-axis and q-axis component of grid voltage. The rotating reference frame is chosen in such a way that: e_q=0 and e_d=|V|, so the simplified equation of active power P, and reactive power Q, in the rotating reference frame is

$$P = \frac{3}{2}(|V| i_d) \qquad (19)$$

$$Q = \frac{3}{2}(|V| i_q) \qquad (20)$$

(3.25)

So by controlling d and q currents, active and reactive powers can be controlled respectively. To transfer all the captured power from the wind to grid instantaneously active power controller is implemented. For unit power factor, reactive power control reference is fixed to zero. The current controllers generate a voltage reference for the inverter that can be implemented by space vector PWM switching technique.

VII. SIMULATION RESULTS

In order to evaluate the responses of the proposed model and control algorithms of the PMSG based wind energy conversion system, simulations were implemented using the SEQUEL circuit simulator.

The electrical parameters of the circuit are as follows. Stator resistance is 2.875Ω, Inductance is 8.5mH, Permanent magnet flux is 0.175Wb, Pole pairs are 2, Moment of inertia is 0.0008Kgm^2, Boost inductor is 1.8mH, Boost Capacitor is 312.81μF, Filter inductance is 5.45mH, Filter resistance is 0.3Ω, and Filter capacitance is 18.6mF. Grid voltage is 415V, 50Hz.

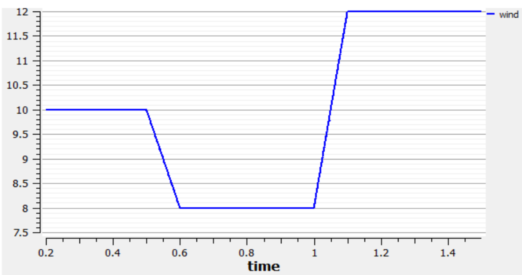

Fig. 6. Wind variation (m/s).

A rectangular speed profile with a maximum of 12 m/s and a minimum of 8 m/s as shown in Fig. 6 is applied to the WECS. The wind speed, reference speed, rotor speed, active power output, boost output voltage and inverter output voltages are shown below.

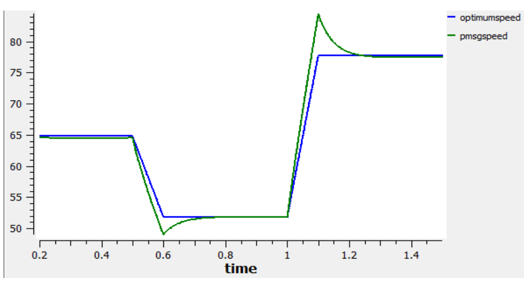

Fig. 7. Reference speed and PMSG speed.

The MPPT controller generates the reference speed command of 65rpm corresponding to the wind speed of 10m/s related to the maximum output power of 2kW. In 0.6s it is assumed that the wind speed decreases to 8m/s; therefore, the control system changes the required turbine speed by using the maximum power tracking algorithm to capture the maximum power from the wind in this speed.

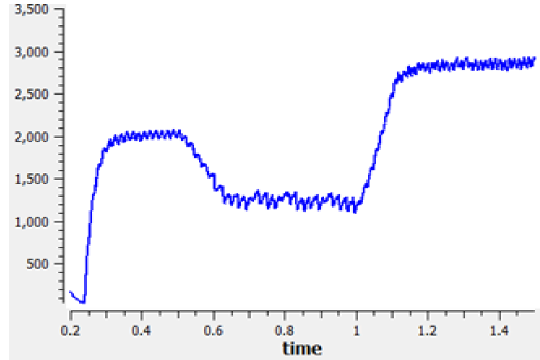

Fig. 8. Output electrical power.

As can be seen from Fig. 7 the speed of PMSG is adjusted to 52 rpm that generates 1.1kW power. After 1.5s from the beginning the wind speed increases to 12m/s from 8m/s. Consequently, the reference turbine speed will be increased by the control system. Then the speed of the PMSG is adjusted to 78 rpm rapidly. As a result, the output power of the turbine is 3kW as seen in Fig. 8.

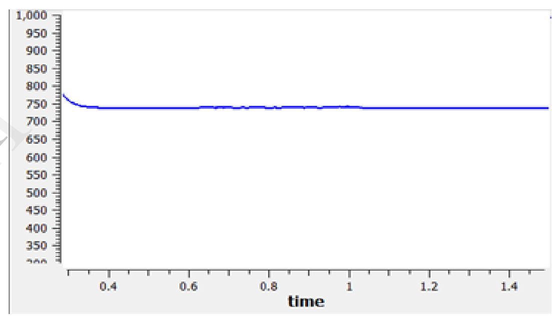

Fig. 9. Boost converter output voltage.

Fig. 9 shows boost converter output. Here the capacitor voltage is maintained at 750V approximately.

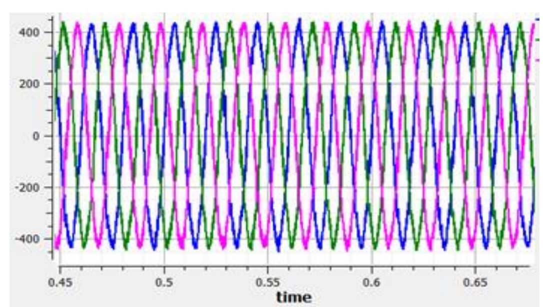

Fig. 10. Inverter output voltage.

Fig. 10 shows the inverter output voltage with filter. Grid voltage is maintained at 415V and 50Hz. The simulation results have shown satisfactory results using the proposed design procedure.

VIII. CONCLUSION

Variable speed direct driven PMSG WTG system has studied and modeled in this paper. In addition, control schemes are designed for maximum power extraction, constant DC link voltage, active and reactive power control. Simulation results show the effectiveness of the proposed control systems for the wind energy conversion system. The control strategy can implement MPPT strategy in terms of adjustment of PMSGs rotor speeds under varying wind conditions. It ensures a maximum energy extracted from the available wind. Boost converter is controlled to get a fixed dc link voltage. Control strategy for a three-phase inverter has been studied and simulated to provide high output power quality. The active and reactive power current decoupled control is achieved. The inverter output voltage and frequency are synchronized with grid voltage and frequency. The simulation results of the work provide satisfactory results.

ACKNOWLEDGMENT

The authors would like to thank Mr. Sreenath S, Dept. of Electrical & Electronics Engineering, Manipal University Jaipur, Mr. Soney Varghese, Mrs. Mini Soney, and Ms. Anju Nissy Soney for their assistance in this work.

REFERENCES

[1] Amei K, Takayasu Y, and Ohji T, “A maximum power control of wind generator system using a permanent magnet synchronous generator and a boost chopper circuit,” Proceedings of the Power Conversion Conference, Osaka, Japan, vol. 3, pp. 1447-1452, April 2002.

[2] Chen Z and Spooner E, “A DC to AC converter with thyristor inverter and active compensation,” The 6th International Conference on Power Electronics and Variable Speed Drives, Bristol, UK, vol. 1, pp 1-6, September 1996.

[3] E. Muljadi, S. Drouilhet, R. Holz, and V. Gevorgian, “Analysis of permanent magnet generator for wind power battery charging,” Proceedings of the 1996 IEEE International Conference on Industry Applications Conference, San Diego, CA, pp. 541 – 548, 6-10 Oct 1996.

[4] Koutroulis E and Kalaitzakis K, “Design of a maximum power tracking system for wind energy conversion applications,” IEEE Transactions on Industrial Electronics, vol. 53, pp. 486-494, August 2006.

[5] Menniti D, Picardi C and Pinnarelli A, “Grid-connected inverters for alternative energy sources with a combined voltage and current control strategy,” International Conference on Clean Electrical Power, Capri, Italy, vol. 1, pp. 223-228, May 2007.

[6] R. Datta and V. T. Ranganathan, “A method of tracking the peak power points for a variable speed wind energy conversion system,” IEEE Transactions on Energy Conversion, vol. 18, Mar. 2003, pp.163 – 168.

[7] Slootweg, J. G and de Haan S.W.H, “General model for representing variable speed wind turbines in power system dynamics simulations,” IEEE Transactions on Power System, vol. 18, pp. 144–151, February 2003.

[8] Wang Q C and Chen C L, “An intelligent maximum power extraction algorithm for inverter-based variable speed wind turbine systems,” IEEE Transactions on Power Electronics, vol. 19, pp. 1242- 1249, May 2004.

[9] Y. Tang and L. Xu, “Flexible active and reactive power control strategy for a variable speed constant frequency generating system,” IEEE Transactions on Power Electronics, Vol. 10, pp. 472 – 478, Jul 1995.

[10] Yicheng Chen and Pragasen Pillay, “PM wind generator topologies”, IEEE Transaction on Industry Applications, Vol. 41, pp. 1619-1626, December 2005.