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Control of IPM Synchronous Generator Based Direct Drive Wind Turbine with MTPA Trajectory and Maximum Power Extraction

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***Abstract*—This paper presents an enhanced control scheme for an interior permanent magnet (IPM) synchronous generator based direct drive wind turbine, incorporating maximum torque per ampere trajectory (MTPA) and maximum power extraction (MPE) algorithm. The main advantage of incorporating MTPA trajectory in the control scheme is that it can generate the required torque with a minimum stator current to minimize the stator loss of the IPM synchronous generator. The detail analysis of the control scheme is presented. The control scheme is implemented in *Matlab/SimPowerSystems* environment. Results confirm the effectiveness of the control scheme to control the direct drive variable speed wind turbine with maximum power extraction.**

***Index Terms*—IPM synchronous generator, variable speed wind turbine, MTPA control, maximum power extraction.**

I. INTRODUCTION

Currently, doubly fed induction generator (DFIG) based variable speed wind turbine technology is dominating the world market [1], [2]. The advantage of this technology is that it requires power converter with reduced capacity (30% of full capacity) as the converter connected to the rotor circuit instead of stator circuit [1]. However, the main drawback of this type of wind turbine is the requirement of a gearbox which requires regular maintenance and suffers from faults and malfunctions [1]. Moreover, it increases the overall size of the wind turbine. Recently, the popularity of direct drive, gearless, permanent magnet synchronous generator (PMSG) based variable speed wind turbines is increasing due to their advantages over induction generator based wind turbine with gearbox. The main features of PMSG based wind turbines are gearless operation, enhanced reliability, simple structure, smaller size, reduced cost, low mechanical and electrical losses, higher power factor, increased efficiency, and no requirement for reactive power support [2]-[12]. Most of the previous works related to PMSG based wind turbines are based on surface type permanent magnet synchronous generator for which the *d*-axis and *q*-axis inductances are equal, $L_d=L_q$ [5]-[10]. However, very little attention has been paid to interior permanent magnet (IPM) synchronous generator based variable speed wind turbines. The IPM synchronous generator (for which $L_d \neq L_q$) can produce more power than that of a surface type PMSG by utilizing the saliency of their rotors [11]-[13]. The IPM generator can be operated over a wide speed range by using flux weakening and allows constant power like operation at speeds higher than the rated speed [11], [12]. This work concentrated on the control of IPM synchronous generator based variable speed wind turbines.

Traditionally, a PMSG is controlled using switch-mode boost rectifiers [4], [5], three switch PWM rectifiers [12], vector controlled PWM rectifiers [11], [14]. The switch-mode rectifier has simple structure and lower cost. However, it introduces high harmonic distortion and unable to control the power factor which affects the performance and efficiency of the system [11], [12]. Therefore, vector controlled back to back PWM converter with voltage source converter (VSC) is preferred for IPM synchronous generator based variable speed wind turbines. In a traditional vector control scheme, the *d*-axis current is regulated to zero and the *q*-axis current is controlled to control the torque of the generator in the rotor reference frame. However in an IPM synchronous generator, both *d*- and *q*-axes currents need to be regulated in order to utilize the rotor saliency as well as to enhance the efficiency. In the proposed control scheme, the IPM synchronous generator is controlled using MTPA trajectory and MPE algorithm to enhance system performance with increased energy capture and efficiency. The MTPA control produces a given torque with a minimum stator current which reduces the stator losses of the IPM generator [15]. Results show that the IPM synchronous generator based variable speed wind turbine with MTPA control can regulate the generator speed and extract maximum power under variable wind speeds.

II. SYSTEM STRUCTURE

Fig. 1 shows the system structure of the direct drive IPM synchronous generator based wind turbine using a back to back PWM converter. The system consists of a wind turbine, IPM synchronous generator, and generator side PWM rectifier with MTPA controller, DC link capacitor, load side PWM inverter, filter, coupling transformer, and loads. The control of the wind energy conversion system includes (i) generator side PWM rectifier with MTPA control and MPE to extract maximum/optimum power from the wind turbine under varying wind speeds (ii) load side inverter control with voltage and frequency controllers in stand-alone mode.

III. CONTROL OF IPM SYNCHRONOUS GENERATOR WITH MTPA TRAJECTORY AND MPE

Fig. 2 shows the control structure of the generator side PWM rectifier with MTPA control and MPE under varying wind speeds. The main purpose of the generator side converter controllers is to extract maximum power under variable wind speeds and to limit the peak absorbed power for the safe operation of the wind turbine under varying wind speeds.

A. Algorithm for Maximum Power Extraction

The proposed control algorithm for the generator side PWM rectifier with maximum power extraction involves following steps and inputs:

- Measure wind speed v_w
- Determine the reference speed of the generator. The expression for optimum power is given by

$$P_{m\_opt} = 0.5\rho\, A C_{p\_opt}\left(\frac{\omega_{m\_opt}\times R}{\lambda_{opt}}\right)^3 = K_{opt}(\omega_{m\_opt})^3 \quad (5)$$

where λ_{opt} = Optimum tip speed ratio, R= radius of the turbine blade (m), C_{p_opt} = optimum power coefficient, ρ= air density (kg/m^3), A= swept area (m^2), v_ω = wind speed (m/s).

$$K_{opt} = 0.5\rho A C_{p\_opt}\left(\frac{R}{\lambda_{opt}}\right)^3 \text{ and } \omega_{m\_opt} = \frac{\lambda_{opt}}{R}v_w = K_w v_w$$

Therefore, the reference speed is

$$\omega_m^* = \frac{\lambda_{opt}}{R}v_w = K_w v_w \quad (6)$$

- Measure the generator speed using speed sensor.
- The error between reference generator speed and measured speed is, $e_\omega = \omega_m^* - \omega_m$.

This error is the input to the PI controller and the PI controller output will give the reference torque, T_g^*. The generator is controlled by controlling *d-* and *q-axes* currents using MTPA which is discussed in the following sub-section.

B. The MTPA Control of IPM Synchronous Generator

The IPM synchronous generator torque is given by [15],

$$T_g = \frac{2}{3}P_n\left(\lambda_d i_q - \lambda_q i_d\right) = -\frac{2}{3}P_n\left[\lambda_M i_q + \left(L_d - L_q\right)i_d i_q\right]$$
$$= \frac{2}{3}P_n\left[\lambda_M i_q + \left(L_d - L_q\right)\left(\sqrt{i_s^2 - i_q^2}\right)i_q\right] \quad (11)$$

where λ_d and λ_q are *d-* and *q-* axes stator flux linkages; i_d, i_q, L_d, and L_q are the *d-* and *q-* axes stator currents and inductances, respectively; λ_M is the permanent magnet flux linkage; ω_r is the electrical rotor speed in rad/sec; p is the operator *d/dt*; and P_n is number of pole pairs.

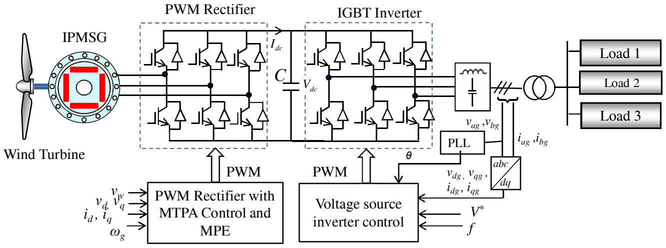


Fig. 1. A direct drive IPM synchronous generator based variable speed wind turbine.

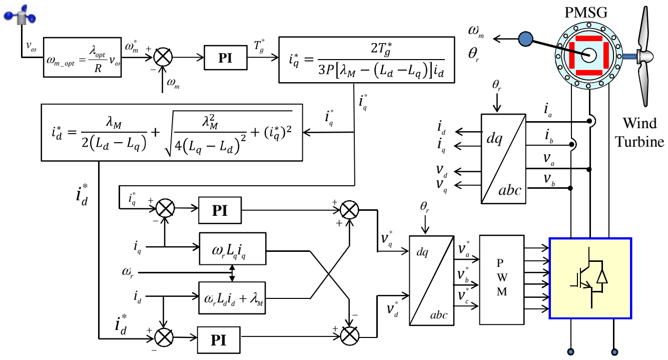


Fig. 2. Control scheme of IPM synchronous generator with MTPA control trajectory and MPE.

To find the maximum torque per ampere, equation (11) can be differentiated and set the derivative equal to zero which implies

$$i_d = \frac{\lambda_M}{2\left(L_d - L_q\right)} \pm \sqrt{\frac{\lambda_M^2}{4\left(L_q - L_d\right)^2} + i_q^2} \quad \text{where } L_d \neq L_q \quad (12)$$

For a given generator torque and magnetic flux linkage, the *d-* and *q*-axes currents for the MTPA control can be found by solving (11) and (12). Therefore, for an IPM synchronous generator, the *d-* and *q*-axes current references are given by

$$i_q^* = \frac{2T_g^*}{3P_n[\lambda_M - (L_d - L_q)]i_d} \quad (13)$$

$$i_d^* = \frac{\lambda_M}{2\left(L_d - L_q\right)} \pm \sqrt{\frac{\lambda_M^2}{4\left(L_q - L_d\right)^2} + (i_q^*)^2} \quad (14)$$

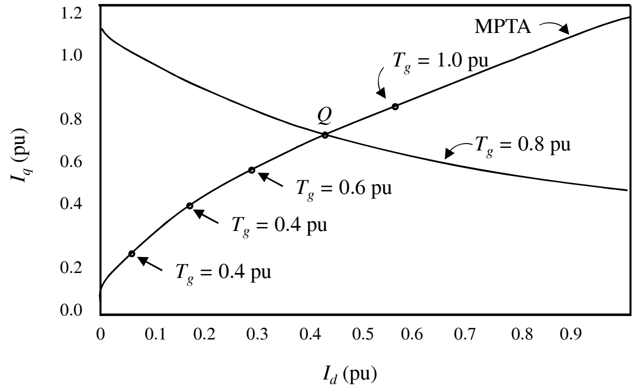


Fig. 3. Trajectory of MTPA control.

The MTPA controller produces a required torque with a minimum stator current [15]. The generator torque given by (11) is a function of generator *d*- and *q*-axes currents. This means that the IPM generator can generate the required torque with different values of i_d and i_q. Therefore, it is possible to generate a torque with minimum current by adjusting the ratio of i_d and i_q [15].

Fig. 3 shows the trajectory of the IPM synchronous generator torque produced by the MTPA control scheme. The MTPA trajectory intersects with the 0.8 pu torque at point *Q* where the torque is produced with a minimum stator current [15]. The MTPA control technique reduces the stator losses of the IPM synchronous generator and ensures the maximum utilization of the stator current.

IV. CONTROL OF LOAD SIDE INVERTER

The function of the load side inverter is to interface the wind turbine generator with the load and control the voltage/frequency for a stand-alone system. In stand-alone mode, the function of the load side inverter is to regulate the inverter output voltage and frequency as there is no grid connection. Fig. 4 shows the control structure of the load side inverter in stand-alone mode. The angular speed of the rotating reference frame is set at $\omega=2\pi f$ in the controller which is the electrical frequency of the inverter output voltage (load voltage) and current. The outer loop is the voltage controller and the inner loop is the current controller. The decoupled current controllers are implemented by adding the compensation terms to compensate for the cross coupling due to the output filter inductance. Normally, battery energy storages and dump loads are used to maintain the DC link voltage under varying wind speeds.

V. SIMULATION RESULTS AND DISCUSSION

The wind energy conversion system as shown in Fig. 1 is implemented using *Matlab/SimPowerSystems.* The generator side converter with MTPA control and MPE as shown in Fig. 2, is implemented. The sampling times for the inner and outer control loops are 20 µs and 100 µs, respectively. The input to the wind turbine model is wind speed and the output is torque.

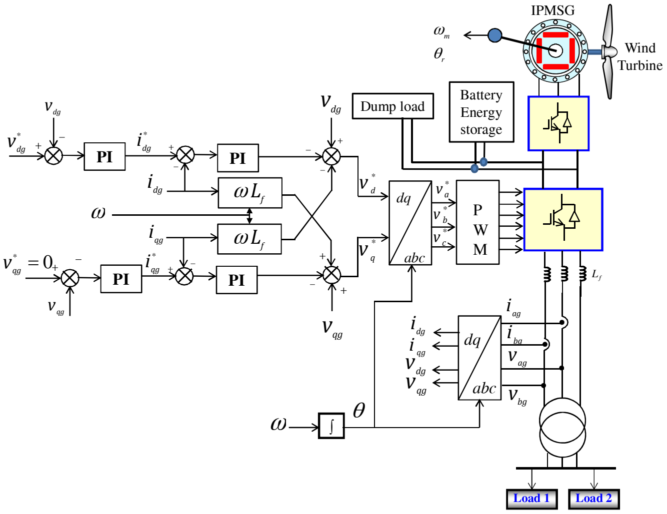
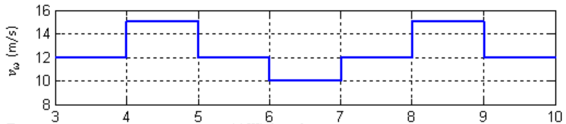


Fig. 4. Control of load side inverter in stand-alone mode.

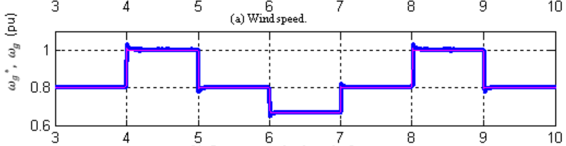
Fig. 5(b) to (e) show the performance of the proposed MTPA controller for generator side PWM rectifier with MPE under varying wind speed, as shown in Fig. 5(a). The reference speed and actual speed are shown in Fig. 5(b) from where it can be seen that the generator speed follows its reference quite well and allow the generator to extract maximum power under varying wind speeds. The *d*- and *q*-axes currents together with their references are shown in Fig. 5(c) and Fig. 5(d), respectively. It is observed that *d-s* and *q*-axes currents follow their respective references well and regulate the generator current under varying wind speeds. The modulation index of the PWM rectifier is shown in Fig. 5(e). Fig. 6 (a) to (c) show the generator electromagnetic torques, turbine mechanical torque, and generator power responses; respectively. Fig. 7 shows the locus of generator stator current vector under MTPA control and it is observed that the stator current vector moves along the MTPA trajectory to extract maximum power at variable wind speeds.

Fig. 8(a) shows the transient responses of generator speed and power whereas Fig. 8(b) shows the generator electromagnetic torque and turbine mechanical torque, respectively. During $3.99<t<4.0$ sec, the wind turbine generator operates in steady-state. At t = 4 sec., the wind speed is increased to the rated value. The turbine mechanical torque increased to the rated value instantly, however, the generator speed increases to rated value gradually due to rotor inertia. The positive difference between the turbine mechanical torque (T_m) and the generator torque (T_g) makes the generator to accelerate and the generator speed increases as well. Finally, the wind turbine generator reaches to its steady-state rated value.

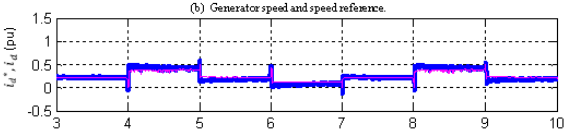
Fig. 9 shows a comparison of torque responses between vector control with MTPA trajectory using PWM rectifier and switch-mode rectifier. The switch mode rectifier consists of diode rectifiers and a boost DC to DC converter. Fig. 9(a) clearly shows that torque ripple is less with vector control with MTPA trajectory than that of the switch-mode rectifier as shown in Fig. 9(b).



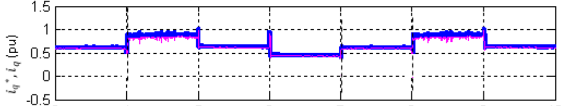
(a) Wind speed.



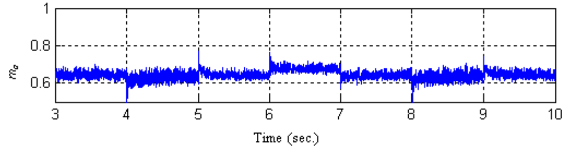
(b) Generator speed and speed reference.



(c) Stator d-axis current and reference.



(d) Stator q-axis current and reference.



(e) Modulation index.

Fig. 5. Performance of MTPA controller with maximum power extraction under varying wind speed

Fig. 10 shows the maximum power extraction under varying wind speed. The negative difference between the turbine torque T_m and generator torque T_g determines the deceleration of the wind turbine generator. Consider Fig. 10, the wind turbine generator is operating at point ‘a’ and the wind speed is increased from v_{w3} to v_{w4} (point b). The difference in torque between T_m and T_g causes the wind turbine generator to accelerate. Finally, the generator reaches the operating point ‘c’ where the accelerating torque is zero. A similar situation occurs when the wind speed is reduced to a lower value. Therefore, the wind turbine generator will extract maximum power by regulating the generator speed at varying wind speeds.

Fig. 11 shows the performance of the load side inverter controller in stand-alone mode. Fig. 11(a) shows the d-axis voltage follows its reference and regulates the voltage at varying wind speeds. The d- and q-axes currents are shown in Fig. 11(b) and (c) together with their references, respectively. The d- and q-axes currents follow their references and regulate the power flow to the load. As the q-axis reference voltage is set to zero, the q-axis current is zero. Fig.11(d) shows the modulation index of the inverter which changes with changes in wind speeds and power supplied to the load.

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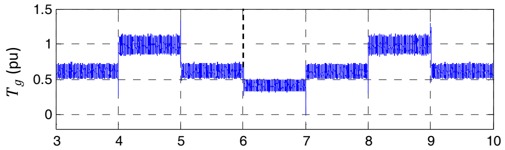
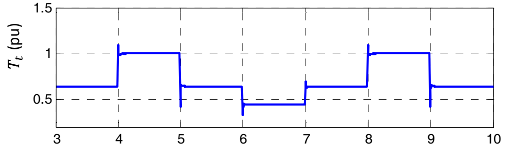
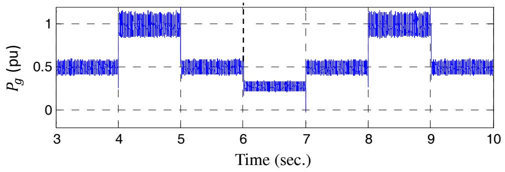


(a) Generator electromagnetic torque.



(b) Turbine mechanical torque.



(c) Generator power.

Fig. 6. Generator electromagnetic torque, turbine mechanical torque and generator power responses under varying wind speed.

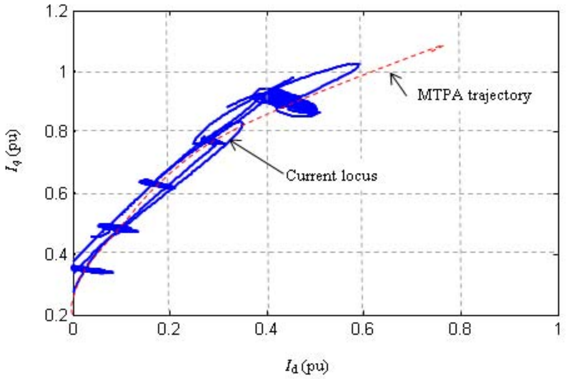
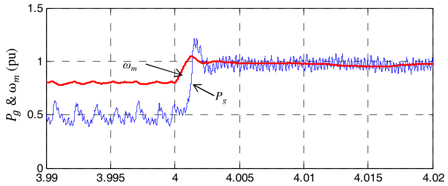
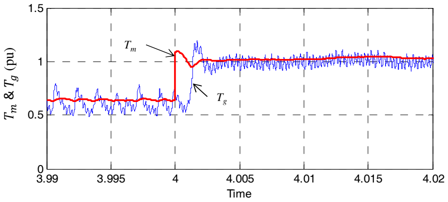


Fig. 7. Locus of generator stator current vector under MTPA control.

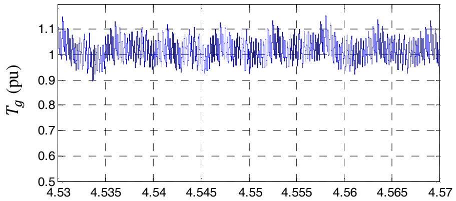


(a) Transient response of generator speed and power.

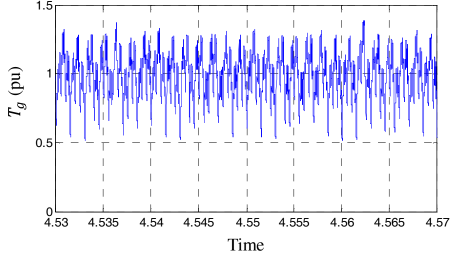


(b) Transient response of turbine mechanical torque and generator electromagnetic torque.

Fig. 8. Transient responses of generate speed, generate power, turbine torque and generator torque when wind speed increased to rated value at t = 4s.



(a) Torque response under Vector control with MTPA using PWM rectifier.



(b) Torque response with switch-mode rectifier.

Fig. 9. Comparison of torque responses under vector control with PWM rectifier and switch-mode rectifier.

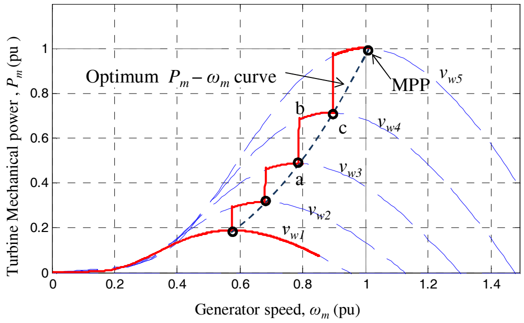
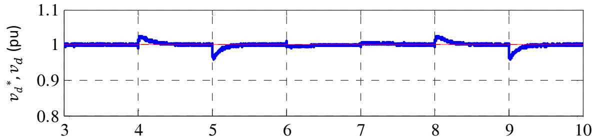
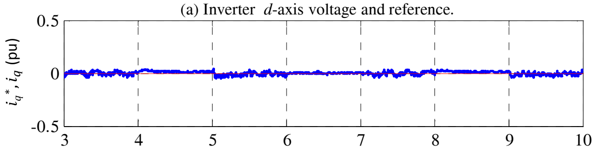


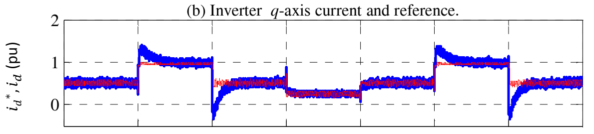
Fig. 10. Maximum power extraction under varying wind speed (mechanical power vs generator speed).



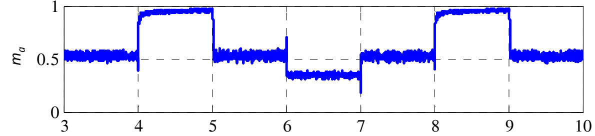
(a) Inverter d-axis voltage and reference.



(b) Inverter q-axis current and reference.



(c) Inverter d-axis current and reference.



(d) Modulation index.
Time (sec.)

Fig. 11. Performance of the load side inverter controller in stand-alone mode.

VI. CONCLUSION

In this paper, an enhanced control technique for a direct drive variable speed wind turbine with an IPM synchronous generator is presented. The MTPA control trajectory and maximum power extraction algorithm are incorporated with the control scheme of generator side PWM rectifier to enhance the performance and efficiency of the system. The main advantage of incorporating MTPA trajectory in the control scheme is that it can generate the required torque with a minimum stator current which reduces the stator copper losses which in turn increases the overall efficiency. The MTPA control scheme ensures the maximum utilization of the stator current. The simulations results confirm the effectiveness of the proposed control scheme and show very good dynamic and steady-state performance. The control scheme can perform well and able to extract maximum/optimum power under varying wind speeds.

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