Robust Maximum Power Point Tracking Control of Permanent Magnet Synchronous Generator for Grid Connected Wind Turbines

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Abstract— **In this paper a class of PI-sliding mode controller is presented in order to implement maximum power point tracking (MPPT) algorithm for permanent magnet synchronous generator (PMSG) based wind turbines. The principles of sliding mode and linear PI controller are combined to ensure high performance operation. The proposed method provides a robust, fast and accurate speed tracking without penalty of high chattering which guarantees maximum power point tracking in a wind turbine. Comparative results demonstrate best performance of transient and steady state operation of proposed technique. The simulation results verify that the presented control strategy is accurate, quick and strongly robust.**

Keywords-Permanent magnet synchronous drive – Sliding mode controller – MPPT – variable speed wind turbine

I. INTRODUCTION

Due to reduction of fossil fuels and environmental pollutions, renewable energies are currently raising a great attention for obtaining electric power [1]. Wind energy is the most economical and promising resource in the world, it is renewable, infinite and environmentally clean [2].

There are mainly two types of wind turbines: fixed speed operation and variable speed operation [3]. Variable speed concept is more attractive because of its ability of operation at its maximum power coefficient, which results in larger energy capture from the wind.

There are mainly two kinds of generators, used in variable speed wind turbines: Doubly fed induction generator (DFIG) and permanent magnet synchronous generator (PMSG).

At present DFIG [4] is the most used generator in variable speed wind turbines. The advantage of DFIG is that the rated power of converter is only about 30% of rated turbine power. In this method variable speed operation is limited in only $\pm$ 30% of synchronous speed.

In comparison with DFIG, PMSG has several advantages such as the ability of operation over full range of generator speed, less weight, small in size, gearless drive, lowering maintenance expenses and improving low voltage ride through (LVRT) capability [5]. Based on these reasons the usage of PMSG based direct driven wind turbines are increasing widely in power systems. The power converter used in this method is fully rated converter (FRC), causes more expenses and more switching losses.

Various converter configurations have been proposed in [6]-[8]. References [6], [7] present a configuration, that using combination of a diode rectifier and a boost chopper in generator side converter. With this configuration, generator power factor is uncontrollable, which reduces generator efficiency as well as existence of high harmonic distortion currents.

In [8], control of a variable speed permanent magnet generator with a back to back inverter is discussed. In this method both active and reactive power are controllable, which makes it an attractive choice. Several control strategies have been proposed for generator side converter in order to track the reference of generator speed. In [8] a conventional PI controller is discussed. This method is simple but doesn't have a satisfactory robustness because of nonlinearity of the system, specially, with respect to stochastic inherent of wind that increases uncertainties. In sliding mode approach robustness to uncertainties is improved but it has the drawback of chattering effect, which might be harmful for the system.

The present paper deals with design of a PI-sliding mode controller for PMSG driven by a back to back converter. The proposed method provides a robust, fast and accurate speed tracking without penalty of high chattering which guarantees maximum power point tracking in a wind turbine. The whole system including wind turbine, permanent magnet synchronous generator, back to back converter, AC grid and control system of each converter has been simulated in MATLAB/SIMULINK to validate the proposed control strategy.

II. SYSTEM MODELLING

The variable speed wind turbine is a complex electromechanical system, consists of wind turbine, permanent magnet synchronous generator and back to back converter [2]. (See Fig. 1)

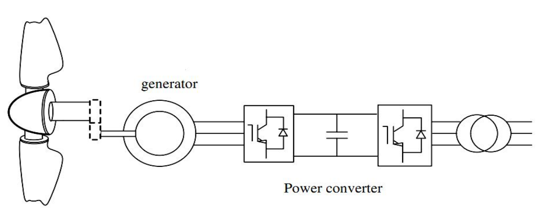


Figure 1. Wind power system components

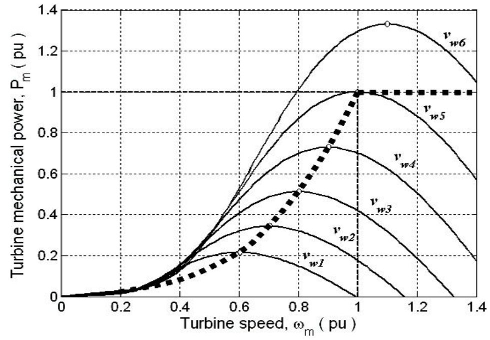


Figure 2. Power curves when pitch angle is zero

A. Aerodynamic Model

The mechanical power extracted from the wind is given below [9]

$$P_{wind} = 0.5\rho A C_p(\lambda,\beta)v^3 \quad (1)$$

Where ρ is air density (kg/m^3), A is blades swept area (m^2), C_p is the power coefficient, β is pitch angle (deg) (in this paper $\beta = 0°$), v is wind speed (m/s) and λ is tip speed ratio, defined as follows

$$\lambda = \frac{\omega_r R}{v} \quad (2)$$

Where ω_r is turbine rotor speed (rad/s) and R is blade radius (m). The wind turbine power curves for various wind speeds when $\beta = 0°$ are shown in Fig. 2. It is observed that, for each wind speed, there exists a specific point in the wind turbine output power versus rotating-speed, where the output power is maximized. At these points $\lambda = \lambda_{opt}$ where λ_{opt} is a constant value for each turbine. So the reference value for generator speed, in which, output power is maximized, can be obtained as below. [See Fig. 3]

$$\omega_r^* = \frac{\lambda_{opt} v}{R} \quad (3)$$

B. Permanent Magnet Synchronous Generator Model

In order to get a dynamical model for generator that would be useful to design the generator control system, the equations of the generator are transformed to synchronous reference frame.

The dynamic model of the surface-mounted permanent magnet generator in synchronous reference frame could be stated as follows [9]

$$\frac{di_{sd}}{dt} = \frac{1}{L_s}u_{sd} - \frac{R_s}{L_s}i_{sd} + P\omega_g i_{sq} \quad (4)$$

$$\frac{di_{sq}}{dt} = \frac{1}{L_s}u_{sq} - \frac{R_s}{L_s}i_{sq} - P\omega_g i_{sd} - \frac{1}{L_S}P\omega_g\psi \quad (5)$$

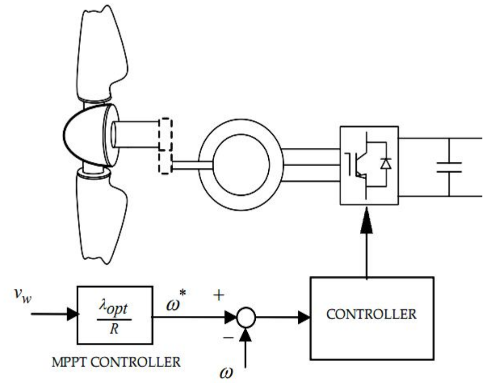


Figure 3. MPPT control system

Where u_{sd} and u_{sq} are respectively d axis and q axis voltages, i_{sd} and i_{sq} are respectively d axis and q axis currents, L_s, R_s are respectively generator inductance and resistance, ψ is the magnet flux and ω_g is generator speed. The electromagnetic torque is given by

$$T_e = 1.5P\psi i_{sq} \quad (6)$$

Where P is the pole pair number. "Equation (6)" shows that electrical torque can be directly control by quadrature current component.

The mechanical dynamic equation is given below

$$T_e - T_l = B\omega_g + J\frac{d\omega_g}{dt} \quad (7)$$

Where J is rotor inertia, B is friction constant and T_l is the torque produced by wind turbine.

III. Control Strategy

A. Linear and Variable Structure Control

A block diagram of linear and variable Structure control (LVSC) method that implemented on generator side converter is shown in Fig. 4.a. The controller includes a switching part and a linear one, and has dual behaviour. This is a flexible control scheme that takes advantage of the best features of linear control, smooth and chattering free operation, and of sliding mode controller, robustness to uncertainties. An SVM unit is used to produce switching signals based on voltage references [10].

The sliding surface defines as below:

$$S_w = e_\omega(t) + c_w\int_{-\infty}^{t} e_\omega(\tau)d\tau \quad (8)$$

Where $e_\omega(t) = \omega_g^{ref} - \omega_g$ is the generator speed control error. Design constant, c_ω is selected to achieve the desired sliding dynamic.

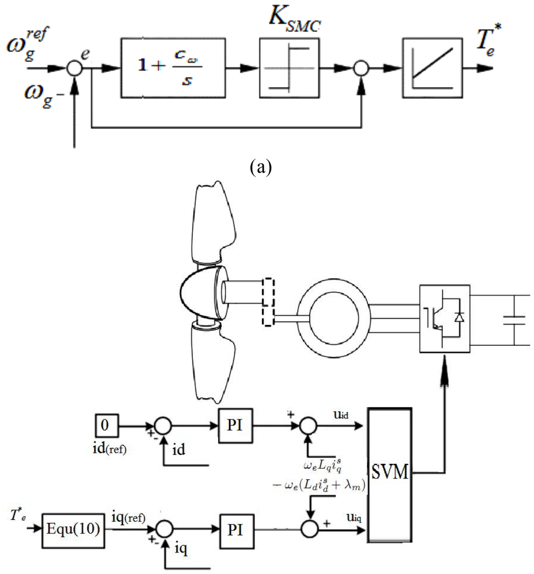


Figure 4. a) PI-Sliding mode controller b) Field oriented current loops

The control law that produces the reference value of torque can be stated as

$$T_e^* = (K_{P\omega} + \frac{K_{I\omega}}{s})(e_\omega + \frac{K_{SMC}}{s}\mathrm{sgn}(S_\omega)) \qquad (9)$$

Where s is Laplace operator and $K_{P\omega}$ and $K_{I\omega}$ are the PI controller gains and K_{SMC} is the sliding mode control (SMC) gain. Adequate balance between the linear PI controller and switching behaviour of the SMC can be achieved by proper gains selection of both controllers. For the transient responses, the linear component is dominant, and the PI gains are selected so as the linear control achieves the desired dynamic response. In the steady state operation, the sliding mode component is dominated and the ripple magnitude depends on the K_{SMC} gains. It can be proved that large enough values for K_{SMC} will fulfill the stability condition $S_w \dot{S}_w < 0$.

The sliding mode controller gain K_{SMC} is selected as large as enough to obtain the desired performance in terms of steady-state robustness and chattering free operation.

With respect to "Equation (6)", the reference value of i_{sq} can be directly obtained by reference value of electromagnetic torque as:

$$i^*_{sq} = \frac{T^*_e}{1.5P\psi} \qquad (10)$$

The reference value of direct-axis current component can be set to zero to minimize current for a given toque and therefore minimize resistive losses [11].

In order to track current references Field oriented control strategy is used. This is a common control strategy in PMSG control systems (See Fig. 4.b). A deeper study of this control strategy may be found in [12].

B. Grid side inverter Control design

The dynamic model of the grid connection when selecting a reference frame rotating synchronously with the grid frequency is given below:

$$u_d = u_{id} - Ri_d - L\frac{di_d}{dt} + L\omega i_q \qquad (11)$$

$$u_q = u_{iq} - Ri_q - L\frac{di_q}{dt} - L\omega i_d \qquad (12)$$

Where L and R are the grid inductance and resistance, respectively and u_{id} and u_{iq} are inverter voltage components. If the reference frame is oriented along the supply voltage, the grid voltage vector is

$$u = u_d + j0 \qquad (13)$$

Then active and reactive power may be expressed as

$$P = \frac{3}{2}u_d i_d \qquad Q = \frac{3}{2}u_d i_q \qquad (14)$$

Active and reactive power are controllable by controlling direct and quadrature current components respectively. The control of this converter is quite similar to generator side one.

Fig. 5 shows the block diagram of grid side converter control. There are two control loops, are used to control the active and reactive power into the grid. An outer dc voltage control loop is used to assure that all of the power coming from the generator is instantaneously injected to the grid by the inverter. The reactive power can be directly control by regulating q-axis current component. The current controllers make a voltage reference for the inverter that can be implemented by SVM switching technique.

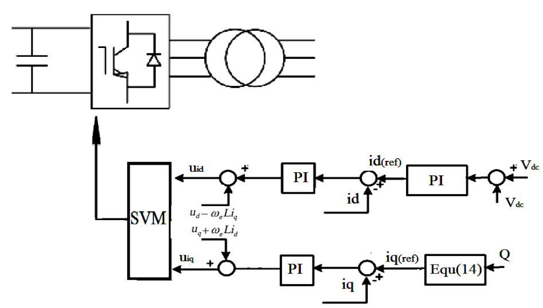


Figure 5. Field oriented control of grid side inverter

IV. Simulation Results

The performance of proposed control strategy is evaluated with the simulation study using MATLAB/SIMULINK. The performance of linear and sliding mode control system is compared with conventional PI controller and Sliding Mode controller. Table 1 shows the wind turbine and generator parameters.

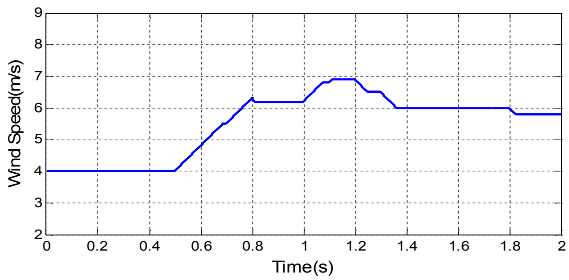
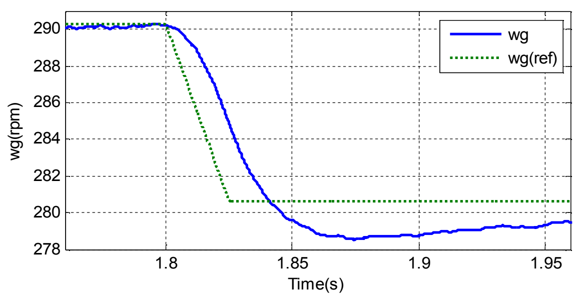
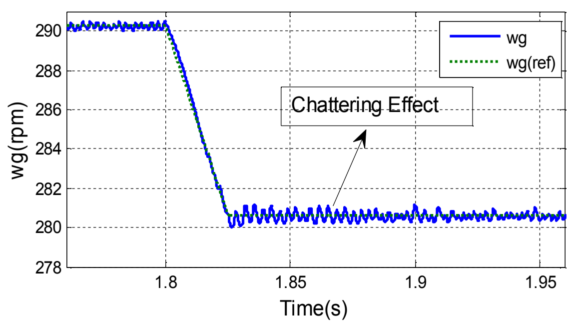


Figure 6. Wind speed



(a)



(b)

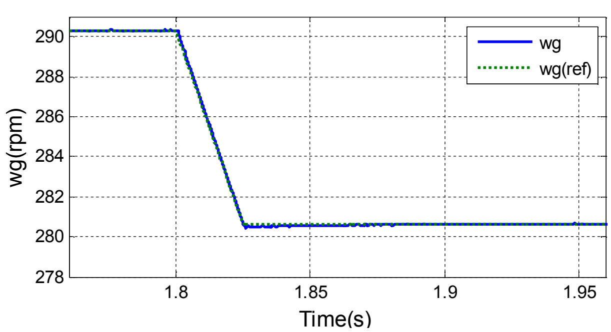


Figure 7. Speed tracking in a) PI controller b) Sliding mode controller c) Variable strcture controller

Table 1. Generator and wind turbine parameters

PERMANENT MAGNET SYNCHRONOUS GENERATOR	
Rated Power = 3KW	Pole Pairs = 11
Rated voltage = 220V	Stator flux = 0.5
L_s = 55 mH	R_s = 2.8 Ohm
WIND TURBINE	
Blade Radius = 3.3 m	$C_{p\ max}$ = 0.436
Gear Ratio = 2.09	Rated Wind Speed = 6 m/s

The results are given for a wind speed, shown in Fig. 6. A comparison of three control strategies of generator converter is shown in Fig. 7. Fig 7.a shows performance of a conventional PI speed controller, Fig 7.b shows performance of the sliding mode speed controller. The operation of speed tracker improved but the chattering effect exists that might be harmful. Finally Fig 7.c shows proper performance of PI-Sliding mode controller proposed in this paper. This comparison is obtained under uncertainties of generator parameters and the inherent fluctuations of wind conditions, which results in torque perturbation on the shaft.

Finally simulation results of a proposed variable structure controller are shown in Fig. 8 -13.

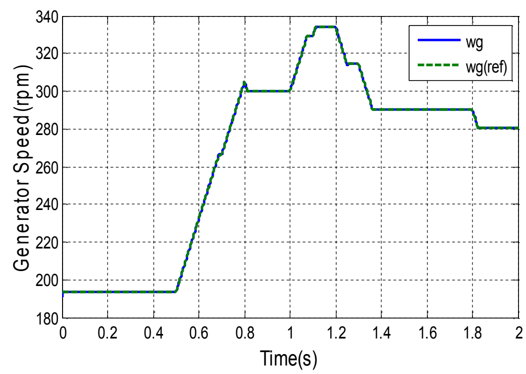


Figure 8. Speed tracking in whole range

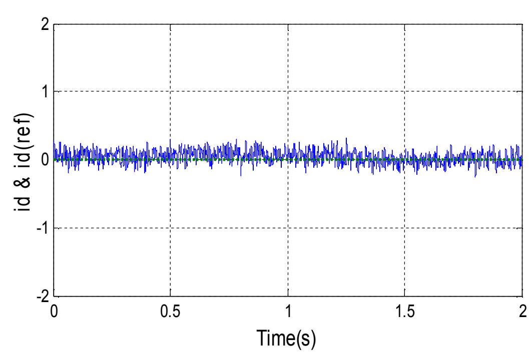


Figure 9. Direct-axis current control performance

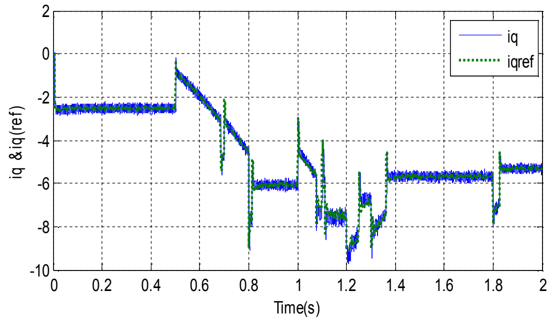


Figure 10. Quadrature-axis current control performance

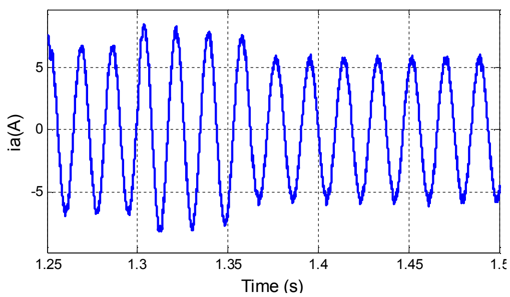


Figure 11. Phase current (i_a) in time range 1.25 - 1.5

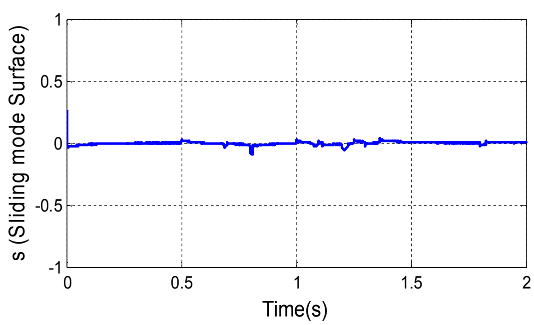


Figure 12. Sliding surface

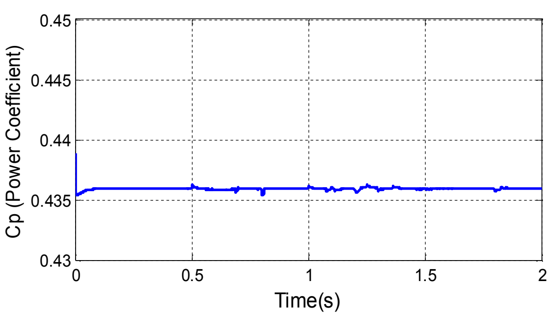


Figure 13. Maximum power point tracking performance

V. Conclusion

A robust PI-sliding mode technique for maximum power point tracking control of PMSG based wind turbine was proposed and evaluated. The control strategy combines sliding mode controller and linear PI principles to achieve a simple and robust high performance drive. In the steady state, sliding mode controller is dominated. During transient operation the proposed approach shows good dynamic response and strong robustness with respect to inherent fluctuations of wind. This simple, quick, accurate and robust control strategy guarantees proper performance of MPPT algorithm implementation and therefore best energy capturing from wind turbine.

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