Maximum Power Point tracking in Variable Speed wind Turbine based on Permanent Magnet Synchronous Generator using Maximum Torque Sliding Mode Control Strategy

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ABSTRACT: *The present study was carried out in order to track the maximum power point in a variable speed turbine by minimizing electromechanical torque changes using sliding mode control strategy. In this strategy, first, the rotor speed is set at an optimal point for different wind speeds, as a results of which, the tip speed ratio reaches an optimal point, mechanical power coefficient maximizes, and wind turbine produces its maximum power and mechanical torque. Then, the maximum mechanical torque is tracked using electromechanical torque. In this technique, tracking error integral of maximum mechanical torque, error, and derivative of error are used as state variables. During changes in wind speed, sliding mode control is designed to absorb the maximum energy from the wind and minimize the response time of maximum power point tracking (MPPT). In this method, the actual control input signal is formed from a second order integral operation of the original sliding mode control input signal. The result of the second order integral in this model includes, control signal integrity, full chattering attenuation, and prevention from large fluctuations in the power generator output. Simulation results, calculated using MATLAB software, have shown the effectiveness of the proposed control strategy for wind energy systems based on the PMSG.*

Keywords: Wind Turbine, Permanent Magnet Synchronous Generator, Maximum Power Point Tracking, Sliding Mode Control

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1. Introduction

Nowadays, due to a decrease in fossil fuel resources and thus an increase in pollution, there is an increasing willingness to use renewable non-fossil resources to produce electricity. In this regard, various renewable resources like wind, solar, and geothermal energies have been introduced. At present, wind energy has the highest significance.

Once the idea of using wind turbines to generate electricity was proposed, different models were suggested, which are still developing and becoming more complicated. Early models had limited control ability which were improved as a result of advances in technology and the use of new methods, and electricity was generated with a better quality. Turbines utilized in wind power plants are used in two group: fixed speed and variable speed.

In the first group, the speed of the generator is kept almost fixed via mechanical equipment, and there is no electric control over it. In such turbines, generating maximum power is only possible if wind blows at a certain speed. Using mechanical controls in such turbines causes them to become slow and decreases their life.

The second group includes wind turbines with variable speed. They have remarkable advantages including absorbing maximum power point for allowed changes in wind speed, efficiency improvement, less mechanical stress, and decreased power fluctuations. In such a system, Permanent Magnet Synchronous Generator (PMSG) is more often used due to removal of gearbox, higher efficiency, smaller size, and usability in different wind speeds. Variable speed wind turbine systems are nonlinear systems whose parameters are usually uncertain. In order to increase accuracy in maximum power point tracking, advanced control strategies are required. Different control techniques like Fuzzy Logic Controller (FLC) [1, 2], Adaptive Control (AC) [3, 4], Particle Swarm Optimization (PSO) [5, 6], RST control [7], Tip Speed Ratio (TSR) [8], and Sliding Model Control (SMC) [9, 10], have evolved for application in MPPT control. Among these, sliding mode control method has received more attention because of its high resistance against changes in parameters. In the present study, sliding mode control was proposed to reach MPPT in the variable speed wind turbine system. In this strategy, first, the rotor speed is set at an optimal point for different wind speeds, as a results of which, the tip speed ratio reaches an optimal point and power coefficient maximizes, which in turn result in maximum power and mechanical torque. The controller aims to track the maximum mechanical torque for changes in allowed wind speed via electromagnetic torque. In order to design the proposed controller, tracking error integral of maximum mechanical torque, error, and derivative of error are used as state variables, and MPPT is completely carried out when tracking error tends toward zero. The weakness of sliding mode control method is chattering phenomenon which is created by discontinuous control rule. In this regard, in the present study, the actual control input signal is formed from a second order integral operation of the original sliding mode control input signal, which leads to complete continuity of control signal and complete removal of chattering phenomenon.

In order to examine the efficiency of sliding mode control strategy, the proposed controller was compared with classic PI controller, and simulation results were presented for the PMSG-equipped wind turbine.

2. The System Model and Statement of the Problem

2.1 Aerodynamic Model

A wind turbine is a system with a number of blades through which wind energy is obtained and converted into mechanical energy. The mechanical power received from a wind turbine is calculated using the following equation.

$$P_m = \frac{1}{2} \pi \rho C_p (\lambda, \beta) R^2 V^3 \tag{1}$$

Where ρ is air density, $C_p (\lambda, \beta)$ is mechanical power coefficient, R is turbine radius, V is wind speed, λ is tip speed ratio, and β is blade pitch angle. Power coefficient is a function of λ and β, and is obtained from the following equation.

$$C_p (\lambda, \beta) = C_1 \left[C_2 \frac{1}{\lambda_i} - C_3 \beta - C_4 \right] e^{-C_5 \frac{1}{\lambda_i}} + C_6 \lambda \tag{2}$$

$$\frac{1}{\lambda_i} = \frac{1}{\lambda + 0.08 \beta} - \frac{0.035}{1 + \beta^3} \tag{3}$$

The equation of tip speed ratio is defined as follow:

$$\lambda = R \frac{\omega}{V} \tag{4}$$

Where ω is the wind turbine rotor angular speed.

By combining Equations 1 and 4, the generated mechanical torque in the wind turbine is calculated.

$$T_m = \frac{P_m}{\omega} = \frac{1}{2\lambda^3} \pi \rho C_p (\lambda, \beta) R^5 \omega^2 \tag{5}$$

2.2 Permanent Magnet Synchronous Generator (PMSG) Model

Voltage and generator torque equations in the rotor reference system are expressed as follows [11].

$$u_d = -R_s i_d - L_d \frac{di_d}{d_t} + L_q n_p \omega i_q \tag{6}$$

$$u_q = -R_s i_q - L_q \frac{di_q}{d_t} - L_d n_p \omega i_d + n_p \omega \psi_f \tag{7}$$

$$T_e = \frac{3}{2} n_p [\psi_f i_q + (L_d - L_q) i_q i_d] \tag{8}$$

In Equations 6 to 8, i_q and i_d are the stator current components, u_q and u_q are machine terminal voltage components, R_S is ohmic stator resistance, L_d and L_q are stator inductance components, n_p is the number of the generator's poles, ψ_f is excitation field flux, and T_e is the generator's electromagnetic torque. In permanent magnet synchronous generators, L_d and L_q stator inductance components can be considered equal ($L_d = L_q$). Therefore, electromagnetic torque is defined as follow:

$$T_e = \frac{3}{2} n_p \psi_f i_q \tag{9}$$

2.3 The Mechanical Model of Wind Turbine

The mechanical equation of the wind turbine motion is calculated based on the following equation:

$$\frac{d\omega}{dt} = \frac{1}{j} \left[T_m - \frac{3}{2} n_p \psi_f i_q - T_o \right] \tag{10}$$

Where J is the system's moment of inertia, T_m is mechanical torque, and T_o is no-load torque that is equal to:

$$T_o = B\omega \tag{11}$$

Where B is the friction coefficient.

3. Description of the problem

According to Equation 1, power coefficient C_p (λ, β) is the most important parameter of wind turbine to achieve maximum power point, such that the maximum mechanical power of a turbine occurs when C_p is maximum. Given the constant value of β (usually, $\beta_{opt=0}$), this optimal amount of C_p occurs in a certain tip speed ratio (λ), which is indicated with λ_{opt} (optimal value of tip speed ratio).

For a certain wind turbine, C_{pmax} and λ_{opt} are constant values (C_{pmax} = 0.48 and λ_{opt} = 8.1). By placing λ_{opt} in Equation 2, the value of C_{pmax} is obtained.

$$C_p = (\lambda_{opt}, \beta_{opt}) = C_p (\lambda_{opt}, 0) = C_{pmax} \tag{12}$$

For certain wind speeds, there is an optimal rotor speed (ω_{opt}) which maximizes the power obtained from the wind. This optimal

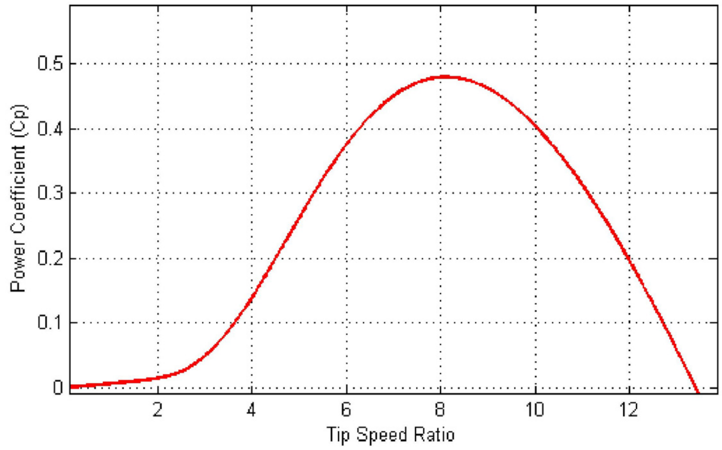

Figure 1. Curve of $C_p - \lambda$

speed is related to the value of λ_{opt}.

$$\lambda_{opt} = \omega_{opt} \frac{R}{V} \tag{13}$$

Therefore, if wind speed is considered constant, the value of $C_p(\lambda)$ depends only on the speed of the turbine's rotor. As a result, during changes in wind speed, the mechanical power obtained from the wind turbine maximizes by keeping rotor speed at an optimal value.

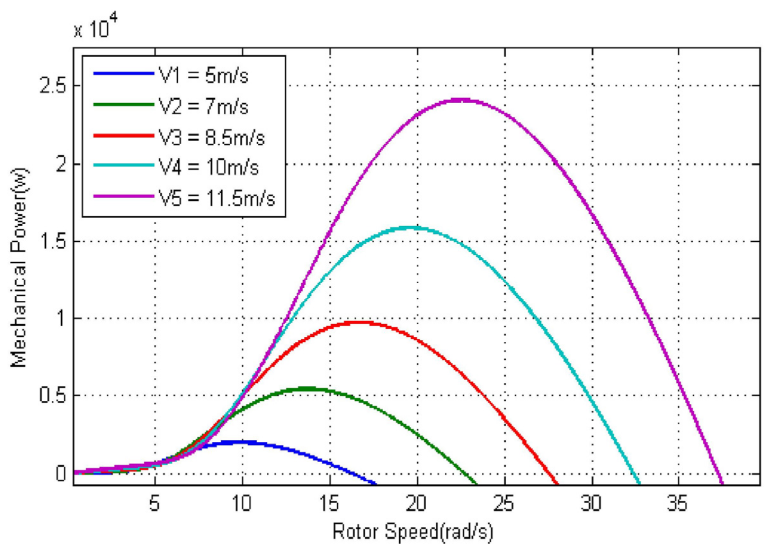

Figure 2. Power-speed curve of wind turbine

Rotor speed of wind turbine is set at an optimal point for all different values of wind speed by using sliding mode control strategy. According to Equations 12 and 13, tip speed ratio and mechanical power coefficient maximize and remain the same with changes in wind speed. By placing Equations 12 and 13 in Equations 1 and 5, maximum mechanical power and maximum mechanical torque of the wind turbine are obtained.

$$P_{Mmax} = \frac{1}{2\lambda_{opt}^{\ 3}} \pi\rho C_{pmax} R^5 \omega^3 = K_{opt}\, \omega^3 \tag{14}$$

$$T_{Mmax} = \frac{P_{Mmax}}{\omega} = K_{opt}\,\omega^2 \tag{15}$$

Where K_{opt} is maximum power coefficient which can be calculated using the following equation.

$$K_{opt} = \frac{1}{2\lambda_{opt}^{\;3}}\pi\rho C_{pmax} R^5 \tag{16}$$

Different sliding mode control strategies including maximum torque control, fast terminal [12], direct torque [13], and extremum seek [14] are usually used for maximum power point tracking. Controlling maximum torque for wind turbine system is appropriate with great inertia, because it has a limited effect on electromechanical system, and measuring torque in no-load state is easy. Therefore, maximum torque control strategy is widely considered in practice.

MPPT methods are normally applied when wind speed is less than its nominal level. In this case, pitch angle is considered a constant value. During winds with speeds over the nominal level, the PMSG's output power is controlled using the pitch angle system [15, 16].

Maximum mechanical torque tracking via electromagnetic torque is the general rule of torque control in reaching maximum power point in a wind turbine, and it is necessary that its motion dynamic feature be according to Equation 10.

4. Designing Sliding Mode Control

In this study, designing the sliding mode control is carried out in two phases in order to obtain MPPT. The first phase includes designing an auxiliary controller through which the optimal speed of rotor is tracked. According to Equation 13, tip speed ratio is placed at the optimal point and power coefficient, and maximum mechanical torque are obtained. And the second phase includes designing the main sliding mode control through which maximum mechanical torque is tracked via electromagnetic torque, and tracking error tends toward zero.

4.1 Designing Auxiliary Sliding Mode Controller

The aim of this section is designing an auxiliary controller through which the optimal speed of rotor is tracked for different values of wind speed, as a results of which, the tip speed ratio reaches an optimal point and mechanical power coefficient maximizes, while these values remain the same with changes in wind speed. By using maximum mechanical power coefficient, maximum mechanical power and torque of the wind turbine can be obtained.

In order to design this controller, the equation of wind turbine motion mechanical is used.

$$\dot{\omega} = \frac{1}{j}\left[T_m - \frac{3}{2}n_p\psi_f i_q - T_o\right] + h = \frac{1}{j}\left[k_{opt}\omega^2 - \frac{3}{2}n_p\psi_f i_q - B\omega\right] + h \tag{17}$$

In order to simplify the equations, can be written as follows:

$$\dot{\omega} = \frac{1}{j}\left[k_{opt}\,\omega^2 - B\omega\right] + \left[-\frac{3}{2j}n_p\psi_f\right]i_q + h \rightarrow \begin{cases} f(\omega) = \frac{1}{j}\left[k_{opt}\,\omega^2 - B\omega\right] \\ g(\omega) = -\frac{3}{2j}n_p\psi_f \\ u = i_q \end{cases} \rightarrow \dot{\omega} = f(\omega) + g(\omega)\,u + h \tag{18}$$

Where h is Uncertainties or system disturbances which does not exist information about it and in best situation, it is known only as upper bound.

In this equation, stator current component (i_q) is used as the auxiliary control input(u).

In the first step of designing, assuming that the control target, is optimum rotor speed tracking error to zero, sliding surface equation is defined as follow:

$$s=\left[\frac{d}{dt}+\zeta\right]^{n-1}e \tag{19}$$

In this equation, n is the system's order (n = 1), ζ is a positive constant, and e is the tracking error of the rotor optimal speed which equals to:

$$e=\omega-\omega_{opt} \tag{20}$$

In the second step, to create sliding variable dynamic, the derivative of sliding surface equation is obtained, and Equations 13 and 18 are placed in it.

$$\begin{cases}\dot{s}=\dot{\omega}-\dot{\omega}_{opt}\\ \dot{\omega}_{opt}=\frac{\lambda_{opt}}{R}\dot{v}\end{cases}\rightarrow\dot{s}=f(\omega)+g(\omega)\,u+h-\dot{\omega}_{opt} \tag{21}$$

In the third step, the controller is designed in such a way that the sliding variable is going to be reached zero. Given that sliding variable dynamic is first order, thus the controller can be designed with following Lyapunov equation:

$$v=\frac{1}{2}s^2 \tag{22}$$

The sliding variable reaching condition to zero and ensuring its stability require the stability of Lyapunov function (negative Lyapunov function derivative):

$$\dot{V}=s\dot{s}<0 \tag{23}$$

Establishing of this condition ($\dot{V}<0$) in the best status lead to asymptotic stability, for gain stability in the limited time, the following sliding condition is defined:

$$\dot{V}=s\dot{s}\leq-\gamma\,|s| \tag{24}$$

Where γ is a real positive value.

In the fourth step, In order to gain the time that slide variable becomes zero, it must be integrated from both sides of the slide condition.

$$s=\frac{ds}{dt}\leq-\gamma\,|s|\rightarrow\frac{s}{|s|}\,ds\leq-\gamma\,dt\rightarrow\int_{s_0}^{0}\frac{s}{|s|}\,ds\leq\int_{0}^{t_r}-\gamma\,dt\rightarrow\begin{cases}t_r\leq\frac{S_0}{\gamma} & S>0\\ t_r\leq\frac{-S(0)}{\gamma} & S<0\end{cases}\rightarrow t_r\leq\frac{|S(0)|}{\gamma} \tag{25}$$

Thus t_r is the time of reaching the slide variable to zero, which can be adjusted by γ.

By replacing the dynamic of slide variable of equation 21 in to equation 24, the slide condition is established as follows:

$$\dot{V}=S\,(f(\omega)+g(\omega)\,u+h-\dot{\omega}_{opt})\leq-\gamma\,|s| \tag{26}$$

In the fifth step, for designing the controller these two parts are applied:

$$u=u_{eq}+u_r \tag{27}$$

Where u_r is reaching part and is called reaching law [17, 18], and u_{eq} is the equivalent control that is used for removing certain nonlinear terms and includes:

$$u_{eq} = \frac{1}{g(\omega)}(-f(\omega) + \dot{\omega}_{opt}) \tag{28}$$

$$u_r = -ksgn\ (s) \tag{29}$$

In this equation, $sgn(s)$ is a sign function which is defined as:

$$sgn(s) = \begin{cases} 1 & if \quad s > 0 \\ 0 & if \quad s = 0 \\ -1 & if \quad s < 0 \end{cases}$$

In the sixth step, by replacing the equation 27, 28 in to equation 26, the slide condition will be simplified as follow:

$$S\,(g(\omega)\,u_r + h) \leq -\,\gamma\ |s| \tag{30}$$

In order to calculate k, equation 29 in equation 30 is replaced:

$$S\,(-g(\omega)\,ksgn(s) + h) \leq -\,\gamma\ |s| \rightarrow \frac{s}{|s|}\,(-g(\omega)\,ksgn(s) + h) + \gamma \leq 0 \rightarrow -g(\omega)\,k + h\,\frac{s}{|s|} + \gamma \leq 0 \rightarrow k \geq \frac{1}{g(\omega)}\left[h\,\frac{s}{|s|} + \gamma\right]$$

For establish slide condition, k is selected as the maximum of $\left[h\,\frac{s}{|s|} + \gamma\right]$.

$$k = \frac{1}{g(\omega)}(\alpha + \gamma) \tag{31}$$

Where α is the maximum of uncertainties.

In the seventh step, by replacing equation 28, 29 and 31 in equation 27, auxiliary sliding mode control equation for the rotor optimal speed tracking system is proposed as follow:

$$\begin{aligned} u &= \frac{1}{g(\omega)}(-f(\omega) + \dot{\omega}_{opt}) - \frac{1}{g(\omega)}(\alpha + \gamma)\,sgn(s) \rightarrow \\ u = i_q &= \frac{2}{3n_p(\psi)_f}(k_{opt}\omega^2 - B\omega - j\dot{\omega}_{opt} + j(\alpha + \gamma)\,sgn(s)) \end{aligned} \tag{32}$$

Due to availability of sign function in auxiliary controller, mechanical power coefficient curve has chattering, and in order to remove it, the function of $sat(s, \varphi)$ is used instead of the sign function [19]:

$$sat(s, \varphi) = \begin{cases} sgn(s) & if \quad |s| \geq \varphi \\ s/\varphi & if \quad |s| < \varphi \end{cases}$$

Where φ is boundary layer thickness.

4.2 Designing the main Sliding Mode Controller

The aim of main sliding mode controller in PMSG-based wind turbines during wind speed changes to ensure maximum mechanical torque tracking by output electromagnetic torque. In designing this controller, the wind turbine motion mechanical equation in 17 equation is used and stator current component (i_q), is selected as controller input ($u = i_q$).

In the first step of designing, tracking error is defined as follows:

$$e = T_m - (T_e + T_o) = K_{opt}\omega^2 - \left(\frac{3}{2}\,n_p\psi_f i_q + B\omega\right) = j\dot{\omega} - h \tag{33}$$

In order to design the controller for PMSG-based wind turbine precisely, it is necessary that maximum mechanical torque tracking error asymptotically tend toward zero. Therefore, in the second step of designing, three state variables are defined as follows:

$$x_1 = \int_0^t edt \tag{34}$$

$$x_2 = \dot{x}_1 = e = j\dot{\omega} - h \tag{35}$$

$$x_3 = \dot{x}_2 = \ddot{x}_1 = \frac{de}{dt} \tag{36}$$

In the third step, derivatives of Equations 34, 35, and 36 are calculated, and Equation 17 and 33 are replaced in them:

$$\dot{x}_1 = e = T_m - (T_e + T_o) = j\dot{\omega} - h = x_2 \tag{37}$$

$$\dot{x}_2 = \ddot{x}_1 = \dot{e} = \dot{T}_m - \dot{T}_e - \dot{T}_o = 2K_{opt}\,\omega\dot{\omega} - B\dot{\omega} - \frac{3}{2}n_p\psi_f\dot{u} = x_3 \tag{38}$$

$$\dot{x}_3 = \ddot{e} = 2k_{opt}[\dot{\omega}^2 + \omega\ddot{\omega}] - B\ddot{\omega} - \frac{3}{2}n_p\psi_f\ddot{u} \tag{39}$$

In the fourth step, Assuming the target of controlling is to make the state variables x_1, x_2 and x_3 be zero, the sliding variables is defined as the weighted total of the system states as follows:

$$s = a_1x_1 + a_2x_2 + a_3x_3 = a_1\int edt + a_2e + a_3\frac{de}{dt} \tag{40}$$

In where a_1, a_2 and a_3 are the positive real values that are used to weight the states rather together.

In the fifth step, to derive from slide variable, slide variable dynamic is formed and Equation 37, 38 and 39 are replaced in it:

$$\dot{s} = a_1(j\dot{\omega} - h) + a_2x_3 + 2a_3k_{opt}[\dot{\omega}^2 + \omega\ddot{\omega}] - Ba_3\ddot{\omega} - \frac{3}{2}a_3n_p\psi_f\ddot{u} \tag{41}$$

In the sixth step, for designing the controller, Lyapunov function equation 22 is used:

$$v = \frac{1}{2}s^2$$

For ensuring the system stability and reaching sliding variable to zero in the limited time, it is used from sliding condition of equation 24, which with placement sliding variable dynamic equation 41 in it:

$$\dot{V} = s\,(a_1(j\dot{\omega} - h) + a_2x_3 + 2a_3k_{opt}[\dot{\omega}^2 + \omega\ddot{\omega}] - Ba_3\ddot{\omega} - \frac{3}{2}a_3n_p\psi_f\ddot{u} \leq -\gamma\,|s| \tag{42}$$

In the seventh step, in order to sliding mode main controller designing, two parts of equation 27 is used:

$$u = u_{eq} + u_r \rightarrow \ddot{u} = \ddot{u}_{eq} + \ddot{u}_r \tag{43}$$

Where:

$$\ddot{u}_{eq} = \frac{2}{3a_3n_p\psi_f}(a_1j\dot{\omega} + a_2x_3 + 2a_3k_{opt}[\dot{\omega}^2 + \omega\ddot{\omega}] - Ba_3\ddot{\omega}) \tag{44}$$

$$\ddot{u}_r = -ksgn(s) \tag{45}$$

In eighth step, the equation of 43 and 44 are replaced in equation 42:

$$s\left(-a_1 h - \frac{3}{2} a_3 n_p \psi_f \ddot{u}_r\right) \leq -\gamma\ |s| \tag{46}$$

To calculate the value of k, equation 45 is replaced in equation 46:

$$k = \frac{2}{3a_3 n_p \psi_f}\left(-\gamma + a_1 h \frac{s}{|s|}\right)$$

For establish slide condition, k is selected as the maximum of $\left(-\gamma + a_1 h \frac{s}{|s|}\right)$.

$$k = \frac{2}{3a_3 n_p \psi_f}\ (-\gamma + \alpha) \tag{47}$$

Where α is the maximum of uncertainties.

In the ninth step, with replacing equations 44, 45, and 47 into equation 43, the original sliding mode control law is determined for maximum mechanical torque tracking system through output electromagnetic torque:

$$\ddot{u} = \frac{2}{3a_3 n_p \psi_f}\,[a_1 j\dot{\omega} + a_2 x_3 + 2a_3 k_{opt}\,[\dot{\omega}^2 + \omega\ddot{\omega}] - Ba_3\ddot{\omega} + (\gamma - \alpha)\,sgn(s)] \tag{48}$$

In the tenth step, with taking twice integral from equation 48, it can be achieved the actual control input signal for PMSG:

$$u = i_q = \frac{2}{3a_3 n_p \psi_f}\iint [a_1 j\dot{\omega} + a_2 x_3 + 2a_3 k_{opt}\,[\dot{\omega}^2 + \omega\ddot{\omega}] - Ba_3\ddot{\omega} + (\gamma - \alpha)\,sgn(s)]\,dt \tag{49}$$

Sliding mode control law ensures that the three state variables of Equations 34, 35, and 36, i.e. tracking error integral, error and its derivative converge toward zero in any primary condition, and it means that the aim of tracking the maximum power point in the wind turbine is achieved through sliding mode control strategy. Moreover, although the original sliding mode control input signal in Equation 48 is discontinuous due to existence of the sign function, the actual control input signal i_q in Equation 49, after which integral is obtained twice, is completely continuous and its chattering phenomenon is completely removed.

5. Simulation Results

The effect of sliding mode controller on maximum power point tracking was compared with that of a classic PI controller, and simulation results were presented using MATLAB software.

PI controller equation is defined as follow:

$$i_q = k_p\, e + k_i \int_0^t edt$$

In this equation, k_p and k_i are controller gain, and their value equals to:

$$k_p = 0.1 \text{ and } k_i = 0.3$$

In the conducted simulation, wind speed randomly changes within the range of 3.3-13.4 m/s.

Figures 4 and 5 shows electric power curve, which tracks maximum mechanical power through sliding mode controller and classic PI controller.

Figures 6 and 7 shows electromagnetic torque curve, which tracks maximum mechanical torque through sliding mode controller and classic PI controllers.

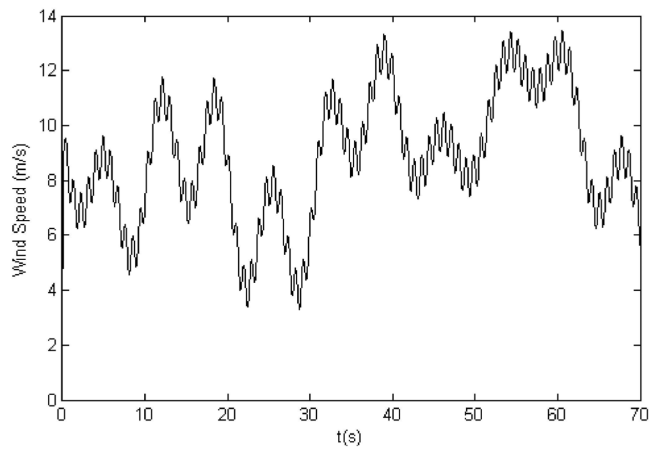

Figure 3. Wind speed

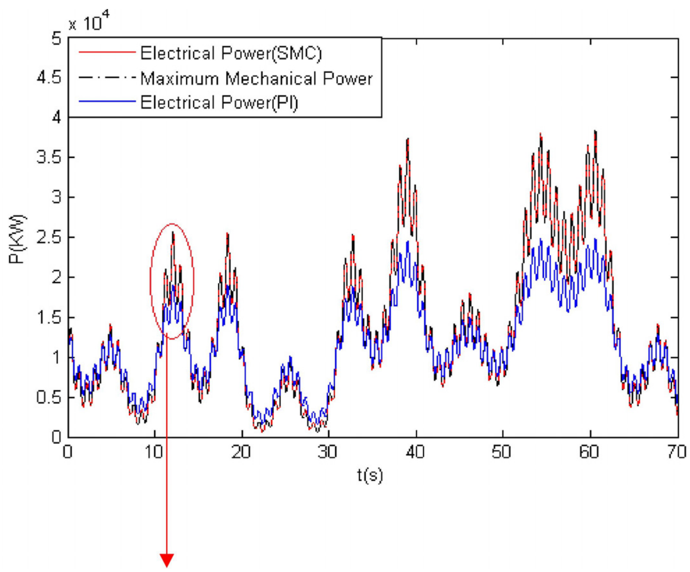

Figure 4. PMSG electric power

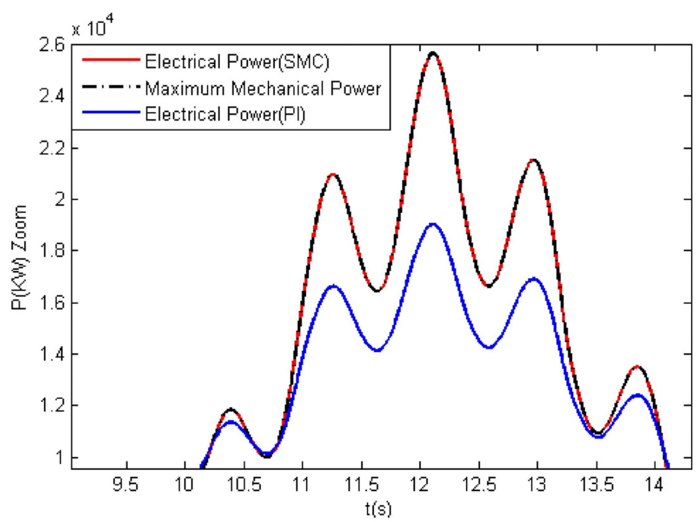

Figure 5. PMSG electric power in zoom mode

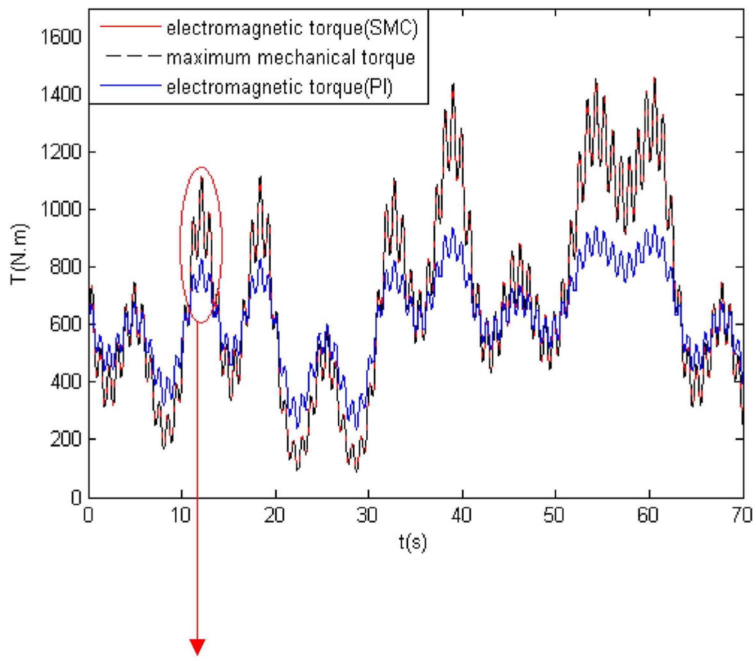

Figure 6. PMSG electromagnetic torque

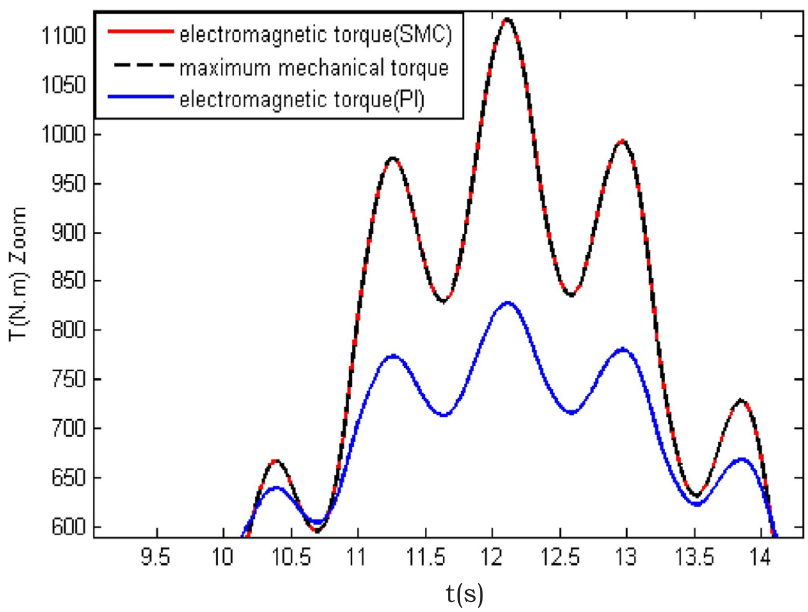

Figure 7. PMSG electromagnetic torque in zoom mode

As seen in the simulations, both sliding mode and PI controllers track maximum mechanical power and torque; however, the sliding mode control is more precise and can function more firmly against rapid changes in wind speed.

Moreover, decrease in electromechanical torque changes by sliding mode controller in PMSG enhances the wind turbine's power against mechanical stress.

Sliding mode control in maximum mechanical torque tracking process reduces tracking errors in PMSG effectively due to existence of integral in implementing the law of sliding mode actual control, which leads to extraction of higher wind energy compared to PI control. The conducted simulations show that sliding mode control can absorb more wind energy with higher efficiency than PI controller, and implementing a conventional controller alone in PMSG cannot track severe fluctuations in torque.

Figures 8 shows the mechanical power coefficient curve of the wind turbine.

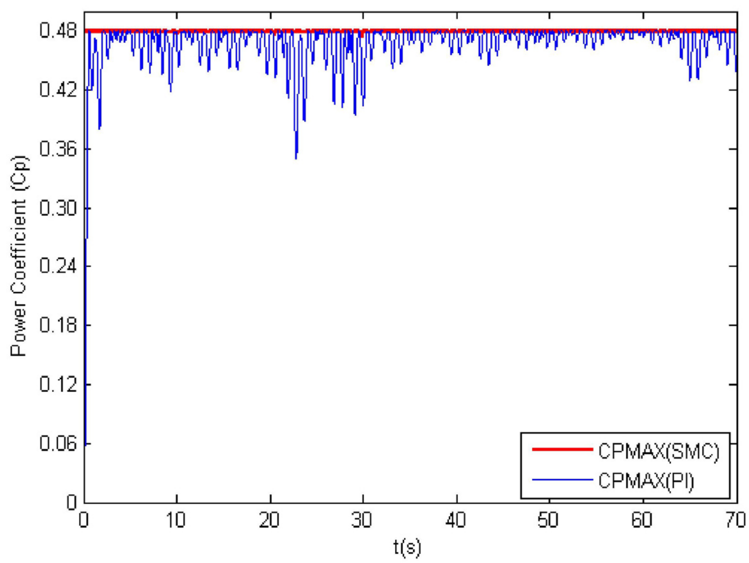

Figure 8. Power coefficient

Figures 9 and 10 show error integral curves, error, and error derivative in maximum mechanical torque tracking using electromagnetic torque.

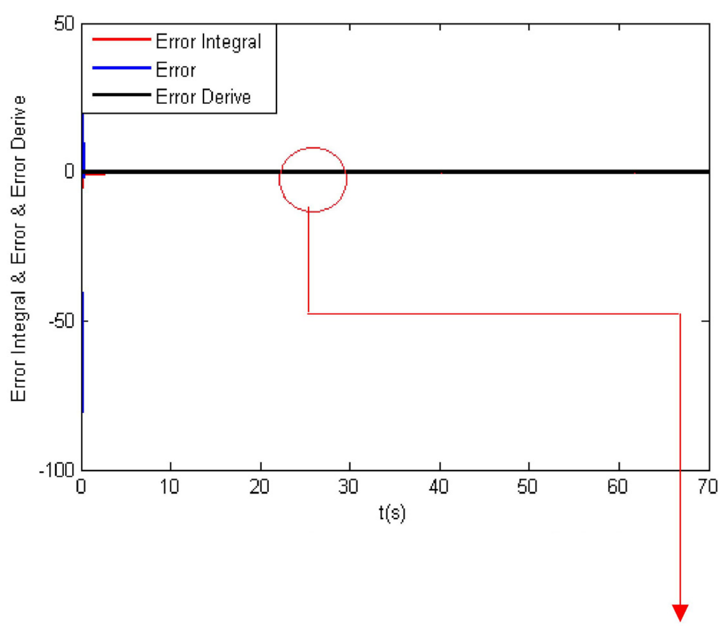

Figure 9. Error integral curve, error, and error derivative

Simulation results show that the value of error integral, error and its derivative asymptotically tends toward zero. As a result, tendency of tracking error toward zero ensures the correct and precise performance of sliding mode control in MPPT.

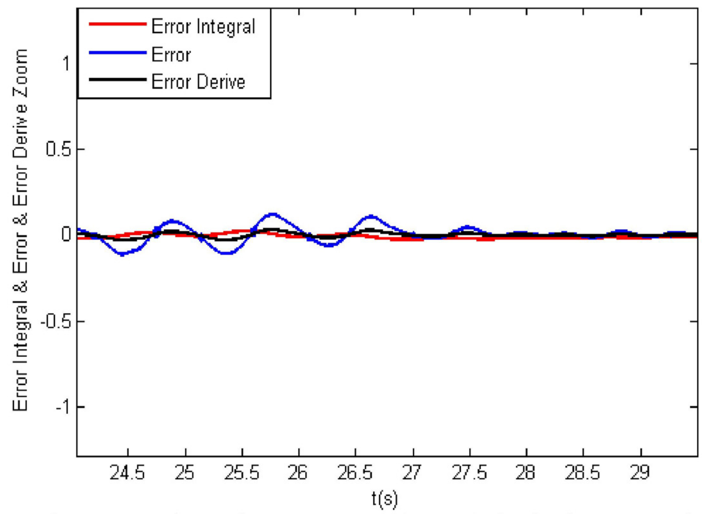

Figure 10. Error integral curve, error, and error derivative in zoom mode

Figure 11 shows the sliding surface curve of the main control sliding mode. That sliding surface becomes zero leads to correct performance of SMC.

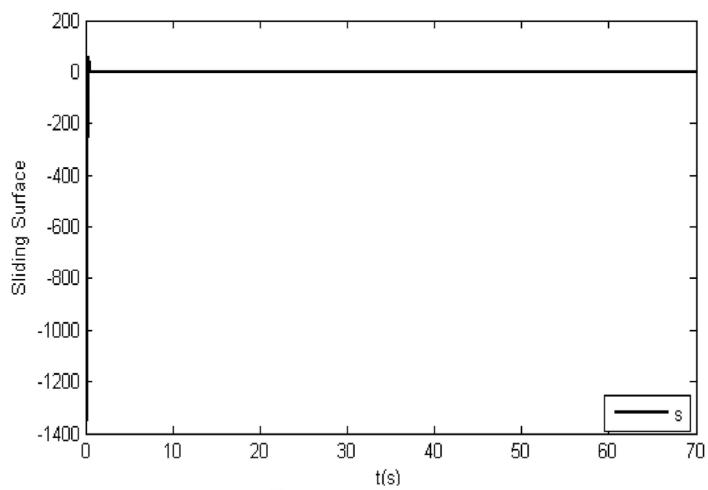

Figure 11. Sliding surface

Figures 12 and 13 shows rotor speed curve, which tracks rotor optimal speed during changes in wind speed through sliding mode and classic PI controllers.

In Figure 14, the input curve of the main sliding mode controller to obtain MPPT in the PMSG-based wind turbine is presented.

6. Conclusion

In the present study, a sliding mode control strategy was proposed for variable speed wind turbines in order to carry out MPPT task. In tracking maximum mechanical torque, this controller can extract maximum wind energy in a wide range of changes in allowed wind speed. In order to reduce error and improve dynamic response, maximum mechanical torque tracking error integral, error and its derivative were used as state variables in order to create a model for MPPT control system. Simulating the designed model indicates that the value of error integral, error and its derivative in maximum mechanical torque tracking asymptotically tends toward zero. Therefore, it can be concluded that by using sliding mode controller, the electric power received from the turbine in different wind speeds is always maximum. In designing the proposed model, original sliding mode control law was not

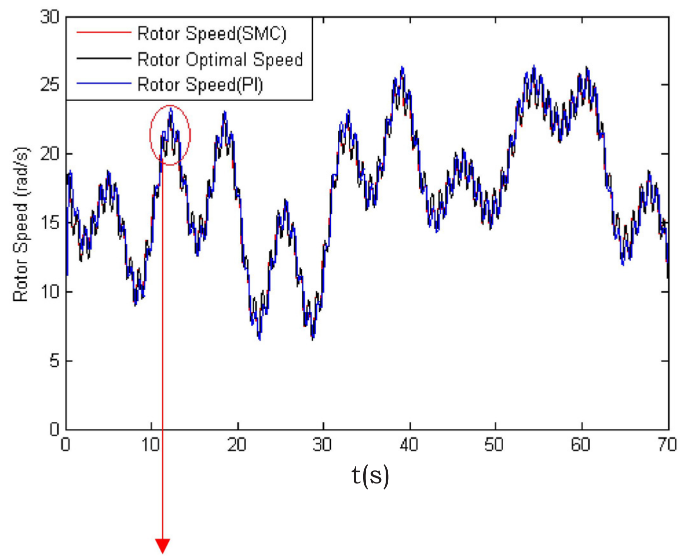

Figure 12. Rotor speed

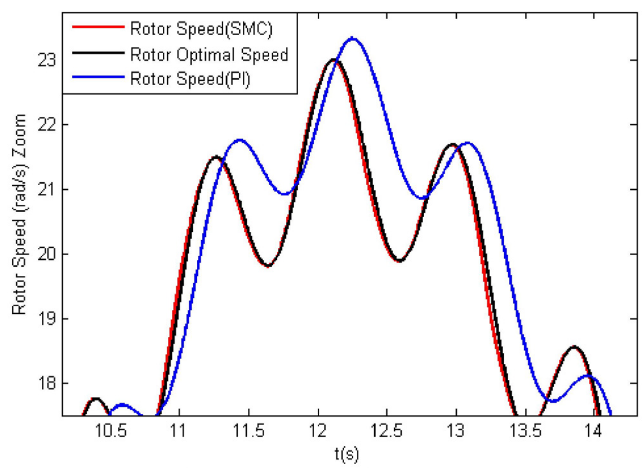

Figure 13. Rotor speed in zoom mode

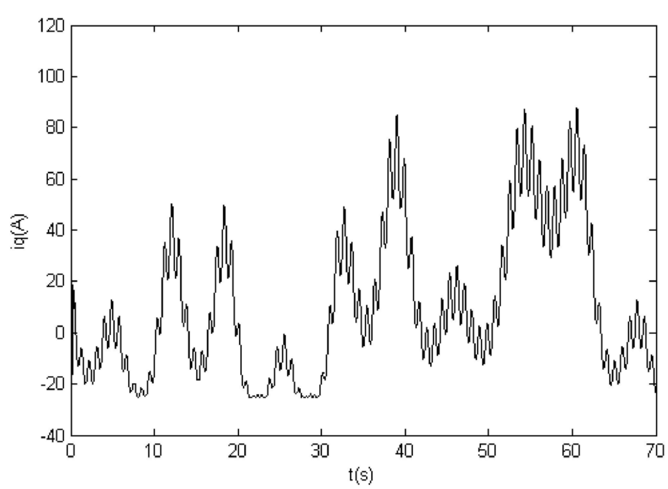

Figure 14. Control input

used because of discontinuity of switching control signal; therefore, by calculating its second order integral, the actual control law is obtained which is continuous, and chattering is completely removed. The simulation results of PMSG-based variable speed wind turbine show that the proposed control strategy, i.e. SMC, has a much better efficiency than PI control method.

7. Appendix

Wind turbine and PMSG parameters		**Mechanical power coefficient parameters**		**Controller parameters**	
Air density (ρ)	1.225 kg/m^3	C_1	0.5176	a_1	4
Moment of inertia (j)	30kg/m^2	C_2	116	a_2	2
Turbine radius (R)	4.41m	C_3	0.4	a_3	0.5
Friction coefficient (B)	1.6 *N.m.s./rad*	C_4	5	Uncertainties	
Generator poles (n_p)	8	C_5	21	α	4
Excitation field flux (ψ_f)	0.5 *wb*	C_6	0.0068	γ	5

Table 1. The value of the parameters of sliding mode control model and wind turbine

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