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Sliding Mode Control of PMSG Wind Turbine

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Abstract: *This paper proposes a sliding mode control of permanent magnet synchronous generator wind turbine. This method can be used for low and medium power wind turbine applications. It is also less costly than back to back two level converters. The SMC approach has great performance in nonlinear systems control such as WECS. In this paper we compare the SMC controller with the PI controller. To avoid the chattering issue caused by the SMC.A SMC controller with a modified reaching law is applied. It reduces the chattering issue and improves the total harmonic distortion property.*
Keywords: *Enhanced Exponential Reaching Law(EERL),Proportional Integral Derivative Controller (PID), Permanent Magnet Synchronous Generator(PMSG),Sliding Mode Controller(SMC),Wind Energy Conversion System(WECS)*

I. Introduction

The world seems to be developing but, at present there are more than two billion people sustain without electric power. Renewable energy sources are considered as the most sustainable energy in today's world. An alternative source of power which lights up the entire world. Solar, Wind, hydro, ocean all seems to renewable energy sources. Out of, wind is considered as the fastest growing energy source among all the new power generation sources which does not cause any pollution and the energy can be harvested easily .Modern advancement in the wind turbine technology made necessary the design of more powerful control system. The new control strategies made improvement in increasing the wind efficiency, made it more profitable and reliable. Wind energy conversion (WECS) equipped with Permanent Magnet Synchronous Generator (PMSG) are becoming more popular today because of its offshore applications due to the elimination of gearbox and excitation box.

The main objective of the paper is to opt a better control strategy for PMSG based wind turbine and a comparative study of various wind turbine controllers. The modeling of Permanent Magnet Synchronous Generator is done using d-q modeling of PMSG [1].The Park's model has been preferred for the modeling. Initially the wind turbine modelling is done. The wind turbine has been coupled to the PMSG using a drive train technology[2].The drive train enables the coupling of wind turbine with PMSG.

Various control strategies can be adopted for the PMSG.The sliding mode control based on Exponential Reaching Law (ERL) and Enhanced Exponential Reaching Law (EERL) is studied and applied to the PMSG.A simple Proportional Derivative Control (PID) control is also applied to the PMSG and a comparative study has been conducted. The SMC involve vector control of PMSG. The PID controls have main disadvantages such as inability to track sinusoidal trajectory references and poor capability to reject system disturbances. It present a nonlinear control technique [3].The advantages of PID control of PMSG is that it offers a reduction in steady state error and increase the stability.

Sliding Mode Control theory was introduced for the first time, the context of the variable structure system (VSS).It become so popular that now it represents this class of control system. The SMC theory was over looked because of the development in the famous linear control theory [4].The SMC method can be applied to both linear and non-linear system. It has gained a lot of attention due to its robustness, insensitivity to parameter variation, order reduction, disturbance rejection and good dynamic behavior etc. This is considered as the advantages of SMC control. The main drawback of SMC is the chattering issue - an effective method to reduce chattering phenomenon is the Adjustable Reaching Law (ARL)[5]

The proposed ARL technique performs the controller gain correction based on the discrepancy between the actual and desired system state. The error value is high, the gain is increased such that to force the system state to move towards the desired state .When the error signal is small, the applied gain is going to decreases in a way that once the gain is tend to zero. There for the proposed ARL is more pragmatic. So in this paper, SMC based on enhanced exponential reaching law approach which meets the requirement in power applications. The main disadvantage of EERL is that it reduces the reaching time of the system trajectory to the equilibrium point even the initial condition of the system parameters far from the sliding surface. EERL has the capability to further mitigate chattering issues of the SMC.

The paper is structured as follows. A brief review of modeling of wind turbine and modeling of PMSG has been explained in section II.In section III, a brief review of various controllers such as Proportional Integral

Derivative (PID) and Sliding Mode Theory (SMC) based on EERL is presented. In section IV, Numerical simulation and experimental resulted are reported. Finally section V, concludes the summary of key features of the proposed controller.

II. Modeling Of Subsection

2.1. Modeling of Wind Turbine

A wind turbine is a machine which converts the kinetic energy in the wind into mechanical energy. Wind turbines can further be classified into horizontal-axis and vertical-axis. In vertical axis wind turbine , blades are connected vertical to ground. All components are close to the ground. In a horizontal axis wind turbine the shaft is horizontal to the ground. Wind hits the blades of turbine that are connected to a shaft which cause rotation. Here using horizontal shaft wind turbine.

The three input are the generator speed in p u of the nominal speed of the generator , the pitch angle in degrees and wind speed in m/s. To obtain the torque characteristics we give ramp signal to the system , pitch angle is set to zero to obtain maximum power and wind speed is a constant value given as 6m/s. The general expression used to model the wind energy conversion system efficiency for extracting the mechanical energy from wind kinetic energy is;

$$C_p(\lambda, \beta) = c_1\left(\frac{c_2}{\lambda_i} - c_3\beta - c_4\beta^x - c_5\right)e^{\frac{-c_6}{\lambda_i}} + c_7\lambda \quad (1)$$

Where,

$$\frac{1}{\lambda_i} = \frac{1}{(\lambda+0.08\beta)} - \frac{0.035}{\beta^3+1} \quad (2)$$

Cp is the Power coefficient C1 to C7 and x are the Cp curve fitting coefficient. λ is the tip speed ratio,it is defined as the ratio between the speed of the tips of the blades of wind turbine and speed of the wind. β is the blade pitch angle It is conventional to plot the variation of the performance coefficient, Cp against the tip speed ratio λ , rather than against the wind velocity, as this creates a dimensionless graph. A typical Cp vs.λ curve is shown in Figure.

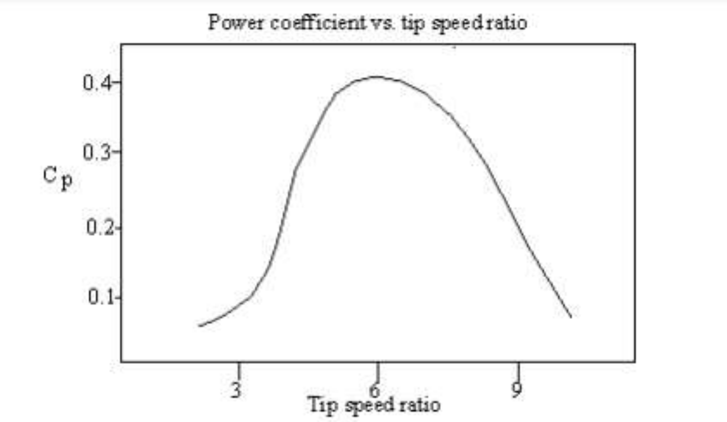

Fig. 1. Cp Vs._ for a typical wind turbine

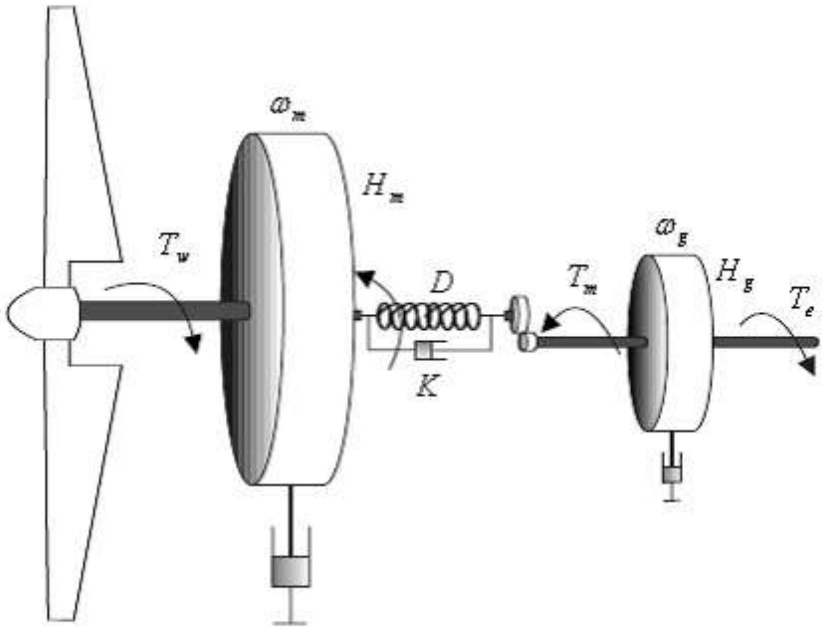

Fig. 2. Drive train dynamics

2.2. Modelling of Drive Train

The drive train (mechanical parts) of a wind turbine system in general consists of a blade pitching mechanism, a hub with blades, a rotor shaft (relatively long in wind energy conversion systems with asynchronous generators) and a gearbox with generator. It include the inertia of both the generator and the turbine.90% of the drive train total moment is the moment of inertia of wind wheel. The generator rotor moment of inertia is equal to 10%.

The equation of the induction generator is given by;

$$H_g.\frac{d\omega_g}{dt} = T_e + \frac{T_m}{n} \quad (3)$$

Taking laplace transform on both sides;

$$s.\omega_g = \frac{T_e + \frac{T_m}{n}}{H_g} \quad (4)$$

The equation of motion of the windmill shaft is given by;

$$H_m.\frac{d\omega_r}{dt} = T_w - T_m \quad (5)$$

Taking Laplace transform on both sides;

$$s.\omega_r = \frac{T_w - T_m}{H_m} \quad (6)$$

The mechanical torque Tm is modeled by the following equation;

$$T_m = k.\frac{\theta}{n} + D.\frac{\omega_g - \omega_m}{n} \quad (7)$$

$$\frac{d\theta}{dt} = \omega_g - \omega_m \quad (8)$$

$$S.\theta = \omega_g - \omega_m \quad (9)$$

$$\theta = \frac{\omega_g - \omega_m}{s} \quad (10)$$

where H_g and H_m is the inertia of generator and turbine rotor, ω_g and ω_m is the angular speed of generator and the turbine, Te is the electromagnetic torque, n is the gear ratio, K and D are the drive train stiffness and damping constants, θ is the angle between the turbine rotor and the generator rotor,T_w is the torque provided by the wind.

2.3. Modelling of PMSG

The PARK transient model is the park model. Since the stator voltage equation is given by;

$$\begin{bmatrix} V_{sd} \\ V_{sq} \end{bmatrix} = -R_s \begin{bmatrix} I_{sd} \\ I_{sq} \end{bmatrix} - \frac{d}{dt} \begin{bmatrix} \varphi_{sd} \\ \varphi_{sq} \end{bmatrix} + \omega_r \begin{bmatrix} 0 & -1 \\ 1 & 0 \end{bmatrix} \begin{bmatrix} \varphi_{sd} \\ \varphi_{sq} \end{bmatrix} \quad (11)$$

where Rs is the resistance of the stator winding, ω_e is the generator electrical rotational speed, V_{sd},V_{sq},i_{sd},i_{sq},ψ_{sd},ψ_{sq} are the d and q components of the instant stator voltage ,current and flux. The stator flux linkage are given by;

$$\begin{bmatrix} \varphi_{sd} \\ \varphi_{sq} \end{bmatrix} = \begin{vmatrix} L_{ls} + L_{dm} & 0 \\ 0 & L_{ls} + L_{qm} \end{vmatrix} \begin{bmatrix} I_{sd} \\ I_{sq} \end{bmatrix} + \begin{bmatrix} \varphi_f \\ 0 \end{bmatrix} \quad (12)$$

where Lls is the leakage inductance of the stator winding, L_{dm} L_{qm} are the stator & rotor d & q axis mutual inductance.ψ_f is the flux linkage produced by the permanent magnet. The electromagnetic torque is;

$T_{em} = P((\psi_{sd}\, i_{sq})-(\psi_{sq}\, i_{sd}))$ (13)

$T_{em} = P((\psi_f\, i_{sq})+(L_d-L_q)(i_{sq}i_{sd}))$ (14)

$$L_d = L_{ls} + L_{dm} \quad (15)$$

$$L_q = L_{ls} + L_{qm} \quad (16)$$

Under steady state condition (13) reduces;

$$V_{sd} = -R_s I_{sd} - \frac{d}{dt}\varphi_{sd} + \omega_r \varphi_{sq} \quad (17)$$

For a direct driven multiple pole PMSG the stator winding resistance is much smaller that the synchronous reactance the difference between d & q axis mutual inductance is very small. Therefore (17) reduces to (22); Therefore the steady state d & q axis currents from (21) are given by;

$T_{em} = P\psi_{sd}\, i_{sq}$ (18)

$$I_{sq} = \frac{V_{sd}}{\omega_e L_q} \quad (19)$$

$$I_{sq} = \frac{V_{sq} - \omega_e \psi_f}{\omega_e L_d} \quad (20)$$

From equation (17);

$$V_{sd} = -R_s I_{sd} - \frac{d}{dt}\varphi_{sd} + \omega_r \varphi_{sq} \quad (21)$$

From equation (18);

$$\psi_{sd} = (L_{ls} + L_{dm}) i_{sd} + \psi_f \quad (22)$$

$$\varphi_{sd} = L_d I_{sd} + \varphi_f \quad (23)$$

$$V_{sd} = -R_s I_{sd} - \frac{d}{dt}(L_d I_{sd} + \varphi_f) + \omega_e \psi_{sq} \quad (24)$$

$$V_{sd} = -R_s I_{sd} - L_d \frac{d}{dt} I_{sd} + \omega_e \psi_{sq} \quad (25)$$

$$L_d \frac{d}{dt} I_{sd} = -R_s I_{sd} - V_{sd} + \omega_r L_q I_{sq} \quad (26)$$

$$\varphi_{sd} = L_d I_{sd} + \varphi_f \quad (27)$$

$$\varphi_{sq} = L_q I_{sq} \quad (28)$$

$$I_{sd} = \frac{1}{SL_d}\left[R_s I_{sd} + \omega_r L_q I_{sq} p - V_{sd}\right] \quad (29)$$

$$V_{sq} = -R_s I_{sq} - \frac{d}{dt}\varphi_{sq} + \omega_e \varphi_{sd} \quad (30)$$

$$\psi_{sq} = (L_{ls} + L_{qm}) i_{sq} \quad (31)$$

$$V_{sq} = -R_s I_{sq} - \frac{d}{dt} L_q I_{sq} + \omega_r \varphi_{sd} \quad (32)$$

$$\frac{d}{dt} I_{sq} = \frac{1}{L_q} [-R_s I_{sq} - \omega_r I_d L_d + \omega_r \varphi_f - V_{sq}] \quad (33)$$

$$\psi_{sd} = I_d L_d + \psi_f \quad (34)$$

$$I_{sq} = \frac{1}{S L_q} [-R_s I_{sq} - V_{sq} - \omega_r I_d L_d p + \omega_r p * \psi] \quad (35)$$

III. Design Of Controlllers

3.1 Design of PID Controller

The PID controller consist of three parameters proportional(K_p),integral(K_i) and derivative(k_d).The setting of these parameters improve the dynamic response, overshoot is reduced, steady state error is eliminated and the stability of the system is increased.[6] The element used in PID are :

i.Element P: proportional to the error at the instant t.

ii.Element I: proportional to the integral of the error at the instant t.

iii.Element D: proportional to the derivative of the error at the instant t.

The error between process variable and a desired set point is monitored. From this error, a corrective signal is computed and is eventually fed back to the input side to adjust the process. The differential equation of the PID controller is;

$$u(t) = K_p\, e(t) + T_i D^{-1} e(t) + T_d D e(t) \quad (36)$$

The transfer function PID controller is given as;

$$G_c(S) = K_p(1 + \frac{1}{ST_i} + T_d S) \quad (37)$$

$$G_c(S) = K_p + \frac{K_i}{S} K_d S \quad (38)$$

Voltage equation for generator side control used in PMSG is given as;

$$U_{sq} = R_s i_{sd} + L_q \frac{di_{sq}}{dt} - L_d \omega i_{sd} + \omega \Psi \quad (39)$$

where U_{sd},U_{sq} and i_{sd},i_{sq} are d-axis and the q-axis voltage and current respectively.L_s and R_s are the generator inductance and resistance.! is the generator speed and is the magnetic flux. when using isd=0 control method the electromagnetic is obtained by

$$T_e = \frac{3}{2} P \Psi i_{sq} \quad (40)$$

where P is the pole pair numbers of generator.

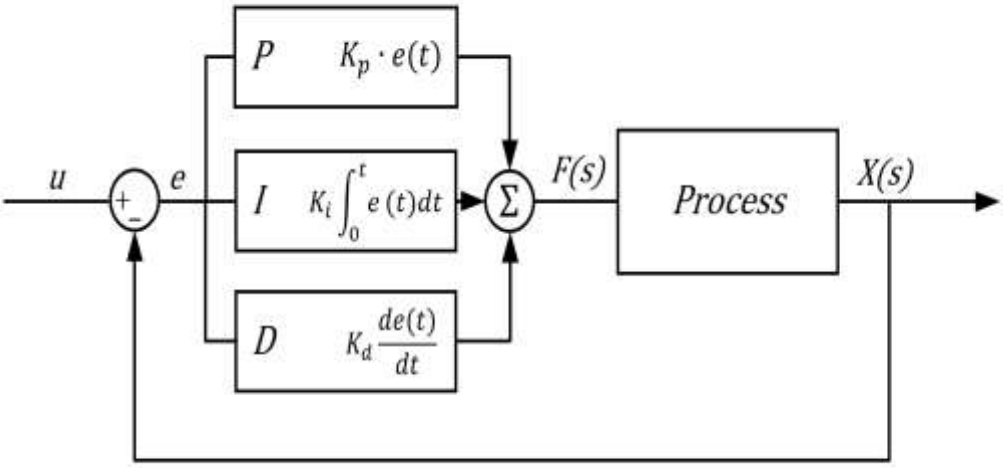

Fig .3. Block diagram of PID controller

3.2 Design of SMC Controller

A control system needs to be robust if it has the strength of keeping the system performance stable. SMC is the most powerful control method of uncertain systems in various theoretical and industrial applications. The SMC method replaces the n^{th} order system by a first order system which can be controlled easily by choosing a well-mannered function of the tracking error called sliding surface or sliding manifold. It helps in moving the system trajectory from its initial point to the sliding surface in finite time and then constraints the variables by a control law.The SMC theory for a second order non-linear system has the following state equation;

$$x = f(x, \ddot{x}) + g(x, \dot{x})u \quad (41)$$

where x and u are stable and input vectors, and f and g are bounded non-linear matrix function of the system states. The function g is continuous and invertible.

Let

$$\tilde{x} = x - x_d \quad (42)$$

be the trajectory error in state vector x, where x_d is the desired state vector. The time varying sliding surface for a n^{th} order system is chosen as

$$S(t) = (\frac{d}{dt} + A)^{n-1}(x - x_d) \quad (43)$$

where A is a strictly positive number. For a second order system one can slide the following surface

$$S(t) = A\tilde{x} + \dot{\tilde{x}} \quad (44)$$

Now the problem of tracking the desired vector is equal to keeping S at zero all the time.The problem of keeping the error vector on the sliding surface can be obtained by defining the control law u such that,

$$\frac{1}{2}\frac{d}{dt}S^2 \leq -\eta|S| \quad (45)$$

Now η is a strictly positive constant. The sliding condition can be expressed as

$$S\dot{S} < 0 \quad (46)$$

On integrating,

$$t_{reach} \leq \frac{|S(t=0)|}{\eta} \quad (47)$$

Where t_{reach} is the reaching time. It is the required time for ~x to reach the sliding surface. The control input takes the form

$$u = u_{con} + u_{discon} \quad (48)$$

Therefore,

$$u = g^{-1}(-f + \ddot{x}_d - A\tilde{x} - Ksign(S)) \quad (49)$$

The control law is composed of two terms. The discontinuous term is applied due to impression of the system modelling and disturbance called chattering. This method is called CRL sliding mode approach. It choose the appropriate value of K between reaching time and level of chattering.Constant proportional rate reaching law has the given form

$$\dot{S} = -AS - Ksign(S) \quad (50)$$

On integrating

$$\int_{S_0}^{S(t_{reach})} \frac{dS}{AS + Ksign(S)} = \int_0^{t_{reach}} -dt \quad (51)$$

$$t_{reach} = \frac{1}{A} ln\frac{A|S_0| + K}{K} \quad (52)$$

The main disadvantage is that the relation of its robustness due to the rapid loosening of the exponential term

$$\dot{S} = K|S|^{rx} sign(S) \quad (53)$$

$$\dot{S} = -\frac{K}{P(S)} sign(S) \quad (54)$$

Where

$$P(S) = \alpha + (1-\alpha)e^{-\beta|s|} \quad (55)$$

Here $0 < \alpha < 1$ and $\beta > 0$. This method is called exponential reaching law(ERL). The reaching time is obtained as

$$t_{reach} = \frac{1}{k}(\alpha|S_0| + \frac{(1-\alpha)}{\beta} e^{-\beta|s|} \quad (56)$$

This method has the advantage of gain adaptation smaller reaching time and chattering reduction but shows higher THD. To solve these issues the EERL is applied which is a combination of different concept. The EERL is as follows:

$$\dot{S} = -AS\frac{-K}{D(S)}|S|^{r} sign(S) \quad (57)$$

The EERL method does not have any impact on the SMC approach stability. The above mentioned method adjusts the reaching time to approach the sliding surface.

IV. Simulations And Result

The simulation model of various controllers is built with MATLAB/SIMULINK,where the system parametrs are the PMSG L_d=1.5731mH,Lq=1.5731, f =6.5029Wb,Rs=.821m and P=26.The PWM rectifier DC side capacitor C=18.8mF. For a PID controller initial wind speed is set as 8m/s and will change as 12m/s at 0.2sec.The SMC control has the following simulation result. The maximum value of power coefficient is Cpmax=0.4382.ForERL approach ,parameters are as βd= βq=10 and αd= αq=0.1

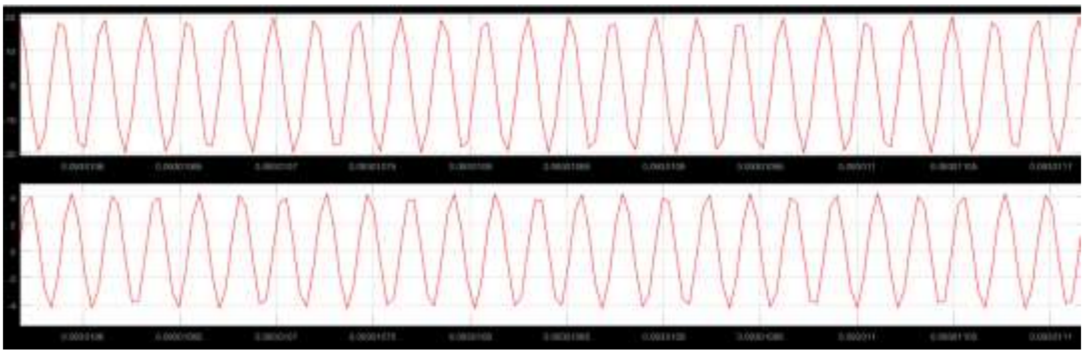

Fig. 4. Output iq,Te of PID controller

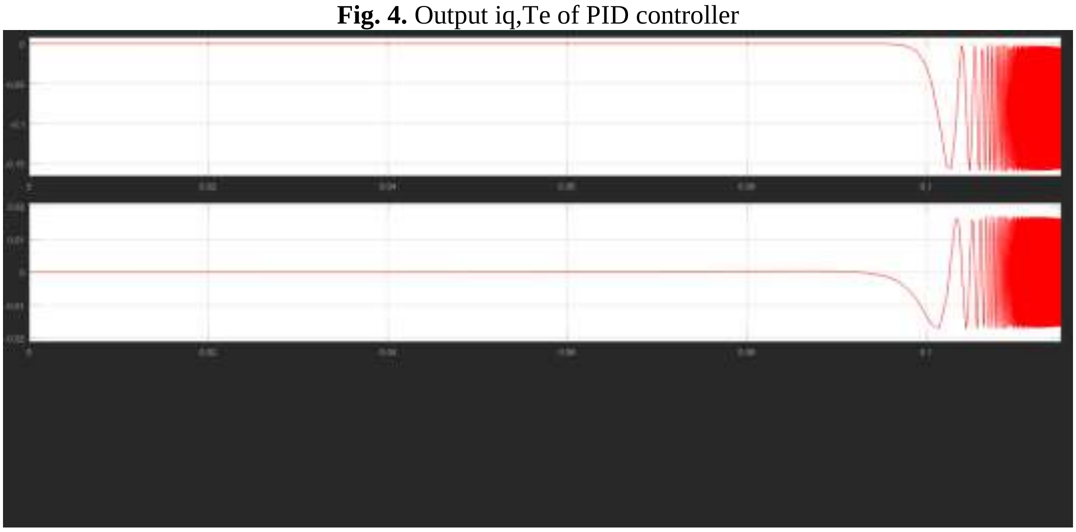

Fig. 5. Output iq,Te of SMC with ERL controller

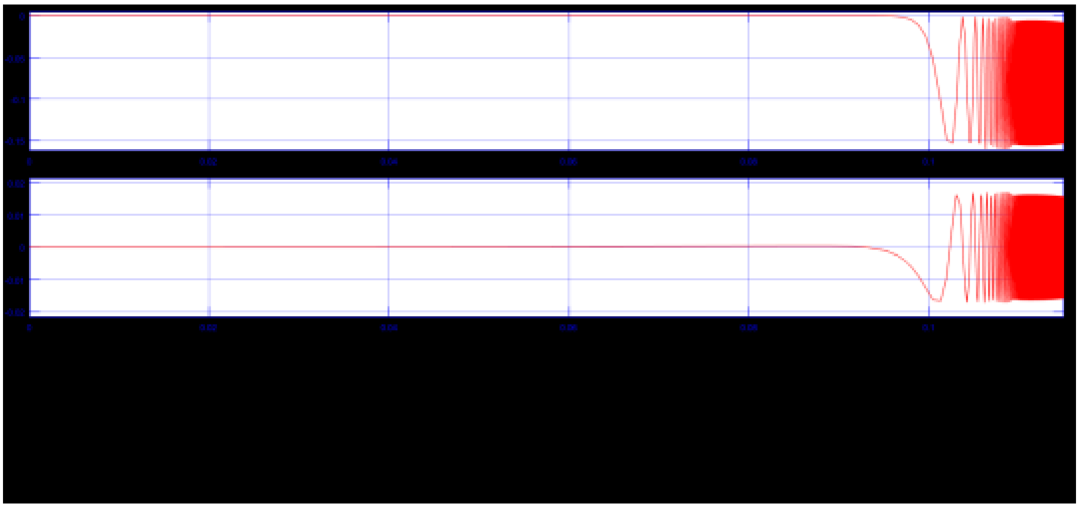

Fig. 6. Output iq,Te of SMC with EERL controller

V. Conclusion

Green energy has opened an important branch and shows in the rise of technology. In this paper we compared the control techniques for PMSG wind turbine. Here we compared the SMC controller with EERL,ERL and PID controller.The SMC controller regulates the Id and Iq components. The advantages of using SMC with EERL approach is chattering minimization with respect to ERL and conventional pid controllers.Non linearity is decreased using SMC with EERL approach.

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