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Design and Control of Permanent Magnet Synchronous Generator for Variable Speed Wind Energy Conversion System Using Sliding Mode Control

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Abstract: ***The wind energy conversion system for the generation of electricity in variable speed needs the control of speed of permanent magnet synchronous generator inorder to maintain its efficiency. Inorder to maintain the efficiency proper control of the generator is necessary. One such promising controlling method is sliding mode control. This control method, provides ideal characteristics for the application in the control of permanent magnet synchronous generator. The modelling of the wind energy system and corresponding sliding mode design is done. Application of this method for control using dynamic models of the d axis and q axis currents, the shaft rotational speed is controlled according to the wind speed.***

Keywords: Wind speed, Wind turbine, Drive train, PMSG, Sliding mode control (SMC)

1. Introduction

Now a days the consumption of fossil fuel is increasing day by day. The main reason behind the use of fossil fuel is to generate more and more energy. Due to consumption of more fossil fuel all living and non living beings including the environment is badly affected .Wind energy is one of the best technologies available today to provide a sustainable supply to the world development, due to abundant ,inexhaustible potential. In terms of the generators for wind power applications, there are different concepts today. The major distinction among them is made between fixed and variable speed wind turbine generator concepts. The generators used for the wind energy conversion systems mostly of either doubly fed induction generator (DFIG) or permanent magnet synchronous generator(PMSG).However the variable speed directly driven multi pole permanent magnet synchronous generator. DFIG have windings on both stationary and rotating parts both windings transfer significant power between shaft and grid. In DFIG the converters have to process only percent of total generated power and the rest being fed to grid directly from stator. The converter used in PMSG has to process 100 percent power generated.

Proposed control method helping us to achieve high efficiency ,robustness, and stabililty is sliding mode control(SMC).The strength of SMC comes from the ability to control high order systems, exhibiting against disturbances and variations in model parameters. The positive attributes of SMC make it seem an ideal control method.SMC oscillates about the desired reference known as the sliding surface.

2. Literature Survey

Non-linear speed controller method which the rotor or wind speed estimation [1].According to this study, stator flux estimation allows the system to estimate the rotor speed. A value of constant is chosen to achieve the best performance. The control system has been designed into two independent parts, machine side converter control and grid side converter control. Machine side converter control allows the wind turbine to operate at MPP, so that it extracts the maximum possible power generation.

Another technique to control the speed of wind turbine through pitch regulation is the use of basic PID controller [2]. To apply the PID control technique a transfer function of a wind turbine has been derived. Non-linearities and step response of a wind turbine has been considered to derive the transfer function in order to design the PID controller for speed control.

Digital robust control technique controls the speed of a wind turbine[3] by reducing the dynamic loads of the blades using a pitch regulation method . The strategy considers the Above Rated Wind Speed (ARWS) zone. During the above rated wind speed condition, the controller regulates the pitch angle of the turbine blades thus the speed is being controlled. The controller has been designed using a discrete-time control model. This method allows the wind turbine to be operated at desired speed within the ARWS zone.

An adaptation technique can be applied to control the speed of wind turbines [4] . The adaptation strategy updates a sliding gain and a turbine torque which is unknown to the controller. A sliding mode control method has been applied by deriving a mathematical model to update the sliding gain to improve the system response. The control system tracks the speed profile to operate the wind turbine at maximum power extraction point which is also known as MPPT. Adaptive sliding mode control controls the speed of wind turbine by controlling the actual turbine torque.

Maximum power point tracking of a wind power system based on the PMSG using sliding mode direct torque control[5] to maximize the generated power from wind turbine .The efficiency of the WECS can be greatly improved using an appropriate control strategy. The system has strong nonlinear multivariable with many uncertain factors and disturbances. Accordingly, the control strategy combines the technique of Direct Torque Control (DTC) and Sliding Mode (SM) nonlinear control theory. Considering the variation of wind speed, the grid-side converter injects the generated power into the AC network, regulates DC-link voltage and it's used to achieve unity power factor, whereas the PMSG side converter is used to achieve Maximum Power Point Tracking (MPPT).

High-order sliding control for a wind energy conversion based on a PMSG paper[6] presents the output power control of a wind energy conversion system (WECS) based on a permanent magnet synchronous generator (PMSG). It is assumed that the considered wind module integrates a stand-alone hybrid generation system, jointly with a battery bank, a variable ac load, and other generation subsystems. The operation strategy of the hybrid system determines two possible operation modes for the WECS, depending on the power requirements of the load and the wind availability. The paper deals with the design of a combined high order sliding mode (HOSM) controller for the power control of the WECS on both operational modes. The main features of the obtained controller are its chattering-free behavior, its finite-time reaching phase, its simplicity, and its robustness with respect to external disturbances and unmodeled dynamics. The performance of the closed-loop system is assessed through representative computer simulations. To avoid discontinuities in the control signal and the associated jumps or spikes in the surface switchings, both controllers were implemented using only one integrator, whose input is switched according to the current operation mode. This procedure ensures a smooth surface switching, and therefore, a better system behavior. The very good system performance, the robustness control features, and the smooth surface switching were corroborated through representative simulation.

3. System Description

The figure 1 shows the pmsg based wind energy conversion systems(WECS). It consists of wind turbine, drive train, PMSG and converter. Wind turbine is connected to PMSG through drive train and connected to back to back.

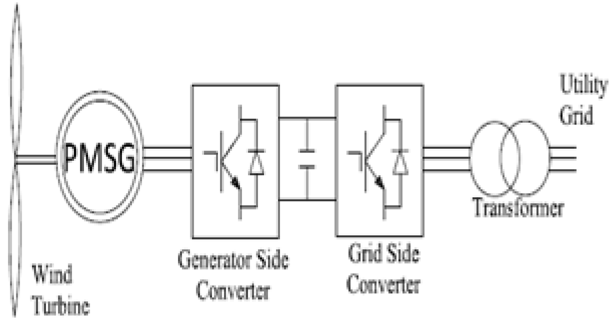

Figure 1: A PMSG based WECS

Wind turbine is one of the most important elements in wind energy conversion systems. Wind turbine produce electricity by using the power of wind to work an electrical generator. Wind moves over the blades, generating lift. The rotating blades turn a shaft inside the nacelle, which goes into a gearbox. The gearbox increases the rotational speed to which is suit for the generator, uses magnetic fields to convert the rotational energy to electrical energy. The power output goes to a transformer, which convert the electricity from the generator by regulating the voltage. Wind turbine is applied to convert the wind energy into mechanical torque. The mechanical torque of turbine can be calculated from mechanical power, the turbine extracted from wind power. The power coefficient is function of pitch angle and tip speed, pitch angle is angle of turbine blade whereas tip speed is the ratio of rotational speed and wind speed.

There were significant differences between wind power and conventional power generation systems. Wind turbines employ, often converter based generating systems. Wind is the prime mover of the wind turbines. The typical size of the wind turbines is much smaller compared to the conventional utility generators. Due to these differences, the power generation from wind interacts with the network. The configuration is developed with PMSG based wind energy conversion system and two controlled two-level voltage source converters. The major concern of wind energy conversion system is to control the speed of a wind turbine.

4. System Modelling

4.1 Wind Energy Conversion

The wind consists of a source that generates wind speed signal to be applied to the wind turbine.The kinetic energy is given by

$$E_c = \frac{1}{2} m v^2 \tag{1}$$

The wind power is given by

$$p_w = \frac{1}{2} \rho S v^3 \tag{2}$$

where m is the air mass, ρ is the air density,S is the covered surface of the turbine,v is the wind speed.

4.2 Wind Turbine

Wind turbine is able to convert the wind energy to mechanical torque. The mechanical torque of turbine can be calculated from mechanical power, the turbine extracted from wind power. The wind speed after the turbine isnt zero. The power coefficient of the turbine is used. The pitch angle and tip speed is function of the power coefficient.

Wind turbine is applied to convert the wind energy to mechanical torque

$$T_m = \frac{\rho S C_p(\lambda,\beta) v^3}{2\omega} \tag{3}$$

The power coefficient is given by

$$C_p(\lambda,\beta) = c_1\left(\frac{c_2}{\lambda_i} - c_3\beta - c_4\right)e^{-\frac{c_5}{\lambda_i}} + c_6\lambda \tag{4}$$

where c1=0.516,c2=116,c3=0.4,c4=5,c5=21,c6=0.0068

$$\frac{1}{\lambda_i} = \frac{1}{\lambda + 0.08\beta} - \frac{0.035}{\beta^3 + 1} \tag{5}$$

where λ is the tip speed ratio, β is the blade pitch angle.

4.3 Drive Train Model

Drive train of a wind turbine generator system consists a blade-pitching mechanism with a spinner, a hub with blades, a rotor shaft and gear box with breaker and generator. The gearbox is not considered because the analyzed system consists of wind turbine equipped with a multipole PMSG. The drive train can be treated as lumped mass model for the sake of the time and aceptable efficiency. The rotational speed can be of the following equation

$$\frac{dw_r}{dt} = \frac{T_m - T_e}{J} - \frac{Bw_r}{J} \tag{6}$$

Tm is the torque has been transfered to generator side, Te is the electromechanical torque, B is the damping coefficient, J is the moment of inertia, wr is the rotational speed.

4.4 PMSG Model

Dynamic model of the PMSG is obtained from the two phase synchronous reference frame, which the q axis is 90 degree ahead of the d axis with respect to the direction of rotation. The synchronization between the d-q rotating frame is maintained by a phase locked loop.Figure2 shows the dq reference frame used in a salient -pole synchronous machine.

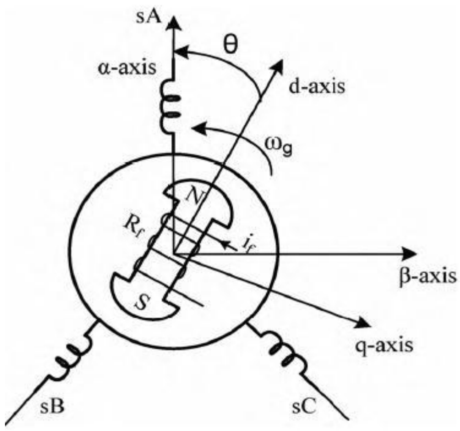

Figure 2: dq axis of salient pole synchronous machine

where θ is the mechanical angle ,the angle between the rotor d axis and the stator axis .The stator windings are positioned sinusoidal along the air-gap as far as the mutual effect with the rotor. The stator winding is symmetrical, damping windings are not considered, the capacitance of all the windings can be neglected and the resistances are constant. The mathematical model of the PMSG in the synchronous reference frame is

$$u_d = R_s i_d + \frac{d\varphi_d}{dt} - \omega_e \varphi_q \tag{7}$$

$$u_q = R_s i_q + \frac{d\varphi_q}{dt} + \omega_e \varphi_d \tag{8}$$

ud is the d axis voltage,uq is the q axis voltage ,id is the d axis current,iq is the q axis current,,Rs is the stator resistance, φ_d, φ_q are the d axis and q axis flux linkage respectively, ω_e is the electrical speed.

$$\varphi_d = L_d i_d + \varphi_m \tag{9}$$

$$\varphi_q = L_q i_q \tag{10}$$

Ld is the d axis inductance,Lq is the q axis inductance, φ_m is the permanent magnet flux linkage.

substitute(9)and (10) in(7) and (8)

$$u_d = R_s i_d + \frac{d}{dt}(L_q i_d + \varphi_m) - \omega_e L_q i_q \tag{11}$$

$$u_q = R_S i_q + L_q \frac{di_q}{dt} + \omega_e (L_d i_d + \varphi_m) \tag{12}$$

The surface mounted PMSG is considered ,the inductance are equal for d axis and q axis ,the equation becomes

$$u_d = R_S i_d + \frac{di_d}{dt} L - \omega_e L i_q \tag{13}$$

$$u_q = R_s i_d + L\frac{di_q}{dt} + \omega_e L i_d + \varphi_m \omega_e \tag{14}$$

The general mechanical equation of the machine is

$$\frac{dw_r}{dt} = \frac{T_m - T_e}{J} - \frac{Bw_r}{J} \tag{15}$$

where

$$K_t = \frac{3}{4} P \varphi_m \quad (16)$$

$$T_e = K_t i_q \quad (17)$$

The mathematical model of PMSG is

$$\frac{di_d}{dt} = -\frac{R_s}{L} i_d + \frac{P}{2} i_q \omega_r - \frac{1}{L} u_d \quad (18)$$

$$\frac{di_q}{dt} = -\frac{R_s}{L} i_q - \frac{P}{2} (i_d - \frac{\varphi_m}{L}) \omega_r - \frac{1}{L} u_q \quad (19)$$

$$\frac{d\omega_r}{dt} = \frac{T_m}{J} - \frac{k_t i_q}{J} - \frac{B\omega_r}{J} \quad (20)$$

5. Sliding Mode Control Design

Sliding mode control (SMC) is a nonlinear control technique .SMC has remarkable properties of accuracy, robustness , easy tuning and implementation.

SMC systems are designed to drive the system states onto a particular surface in the state space named sliding surfaces. SMC is a two part controller design, the frist part involves the design of a sliding surface. The second is concerned with the selection of a control law.

Advantages of sliding mode control

- The dynamic behaviour of the system may be tailored by the particular Choice of the sliding function.
- The closed loop response becomes totally insensitive to some particular uncertainities.

The sliding surfaces are defined as

$$s_q(t) = [i_q(t) - i_q^*(t)] \quad (21)$$

$$s_d(t) = |i_d(t) - i_d^*(t)| \quad (22)$$

$$s_{wr}(t) = |w_r(t) - w_r^*(t)| \quad (23)$$

$i_d^*(t), i_q^*(t), \omega_r^*(t)$ are the reference values for their respective surfaces.

5.1 Direct Axis Current Control

In order to develop the d-axis control ,the d-axis control law as

$$u_d(t) = u_{d,eq}(t) + u_{d,N}(t) \quad (24)$$

Where $u_{d,eq}(t), u_{d,N}(t)$ is the equivalent control, the switching control respectively.

The equivalent control is

$$u_{d,eq}(t) = -R_s i_d(t) + \frac{P}{2} L i_q(t) w_r(t) - L \frac{di_d^*(t)}{dt} \quad (25)$$

The switching control is

$$u_{d,N}(t) = -u_{do} \operatorname{sgn}(s_d(t)) \quad (26)$$

u_{do} is the positive constant

5.2 Quadrature axis control design

Considering the q axis control, the sum of the equivalent and switching controls is the control law of the q axis. The control law is given by

$$u_q(t) = u_{q,eq}(t) + u_{q,N}(t) \quad (27)$$

The equivalent control can be given as

$$u_{q,eq}(t) = -R_s i_q(t) + \frac{P}{2} (L i_d(t) - \varphi_m) w_r(t) - L \frac{di_q^*(t)}{dt} \quad (28)$$

The switching portion is determined by

$$u_{q,N}(t) = -u_{qo} \operatorname{sgn}(s_q(t)) \quad (29)$$

The result of this control design gives the appropriate result.

5.3 Control design based on rotational speed dynamics

Making use of the similar method used for the d and q axis controls, and ensuring the inequality can be done. For the rotational speed controller, the control variable becomes the quadrature axis references current. The control law is designated as

$$i_q^*(t) = i_{q,eq}^*(t) + i_{q,N}^*(t) \quad (30)$$

The eqivalent control is given by

$$i_{q,eq}^*(t) = \frac{1}{K_t} \left[\tau_m - Bw_r(t) - J \frac{dw_r^*(t)}{dt} \right] \quad (31)$$

The switching control is given by

$$i_{q,N}^*(t) = -i_{qo} \operatorname{sgn}(s_{wr}(t)) \quad (32)$$

iqo is the positive constant

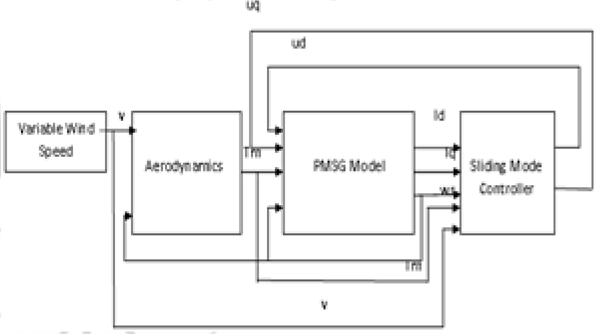

Figure 3: Block diagram of wind energy system with SMC

The system with controller is shown in fig.3.The sliding mode control output is feed back to the PMSG for better results. ud and uq are the control input to PMSG .Variable wind is applied to the system inorder to control the rotational speed of the shaft the control technique is used.

6. Simulation Results

The mathematical model of PMSG based wind energy conversion system is studied and to evaluate the system and its corresponding output the detailed modelling of each componentd in MATLAB/Simulink is done. The parameters used in the study are given in the Table1.

Table 1

Description	*Symbol*	*Units*	*Values*
Air density	ρ	Kg/m3	1.025
Rotor radius	R	M	38
Stator resistance	Rs	Ω	0.08
d-axis inductance	Ld	H	0.334
q-axis inductance	Lq	H	0.217
Permanent magnet flux	φ_m	Wb	0.4832
Pole pairs	P	-	3

The variable wind conditions are considered, the results are shown below.

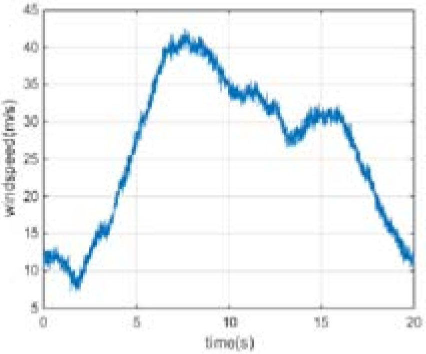

Figure 4: Simulation of wind speed

The above fig.4.gives the simulation of variable wind speed. When a reference speed wr is given to the system it should track the referenc speed and corresponding fluctuation less output should be obtained.

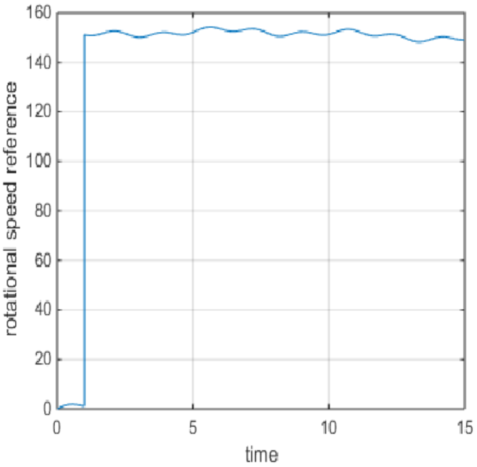

Figure 5: Simulation of rotational reference speed

Next step is to track these reference speed using the SMC. After the modelling the system with the controller the simulation result of corresponding rotational speed is obtained as follows.

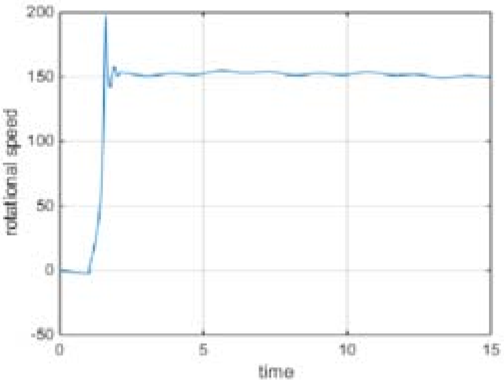

Figure 6: Simulation of rotational speed

From the graph it is clear that the reference speed is tracked .When a variable speed approaches the system the reference speed is tracked correspondingly using the controller. As a result the corresponding q axis and d axis is shown below.

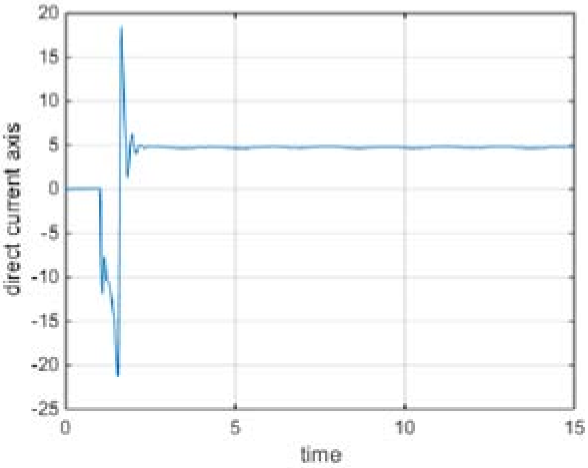

Figure 7: Simulation of d axis current

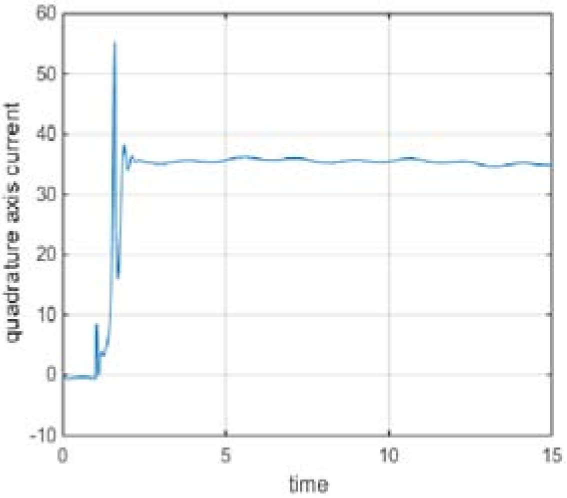

Figure 8: Simulation of q axis current

The corresponding graph of the PMSG output is shown above. By analysing these graphs the q axis and d axis current gives a fluctuation less outputs. Through this controller the maximum efficiency is obtained and hence the power efficiency can be improved using this control.

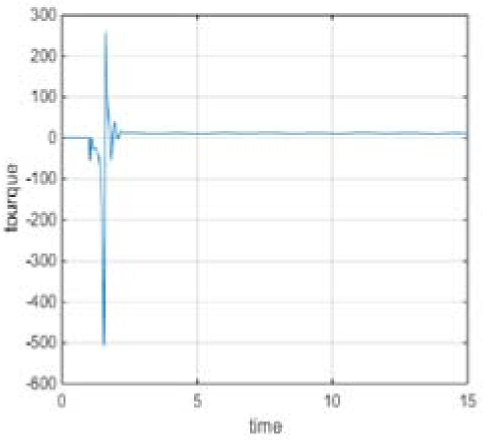

Figure 9: Simulation of torque

The torque output shows which is feedback to the system so that the rotational speed is depend on this torque components. The simulations results help us to studied the system with controller and the efficiency is improved. The control input ud and uq is shown below

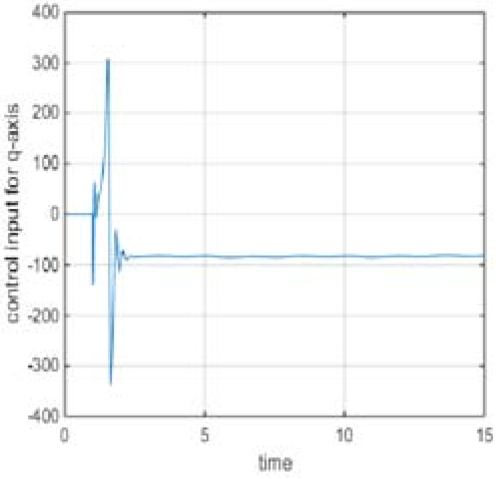

Figure 10: Simulation of control input uq

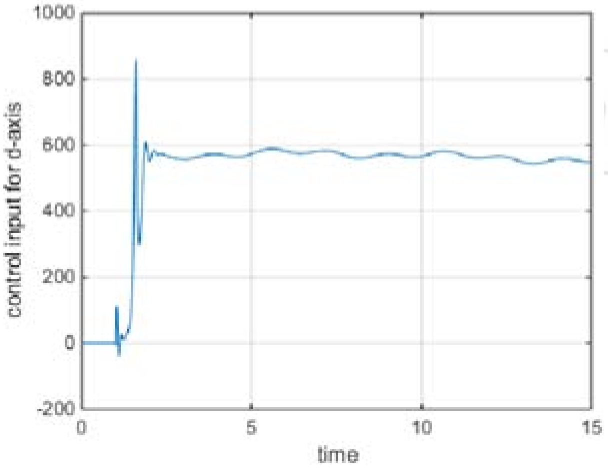

Figure 11: Simulation of control input ud

These control input is responsible for the fluctionless output. These output is feedback to the system from the SMC controller output. One of the key components of the SMC is the active control of the quadrature axis current reference through the implementation of SMC based on the rotational speed dynamics of the WECS. Inspections of these figures accurate speed control is achieved.

7. Conclusion

The sliding mode controller designed for a variable speed WECS ,a surface mounted PMSG has been designed and simulated using MATLAB/SIMULINK. These design results in a system with low sensitivity to disturbances. The active control of the quadrature axis current and direct axis currents based on the use of an SMC control design.

8. Future Scope

The comparison to other methods requires future investigations.

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