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. In order 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 stability 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 robust 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.

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

$$E_k = \frac{1}{2}mv^2$$  \hspace{1cm} (1)

The wind power is given by

$$P_w = \frac{1}{2}\rho S\nu^3$$  \hspace{1cm} (2)

where m is the air mass, $\rho$ is the air density, S is the covered surface of the turbine, $\nu$ 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 isn’t 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

\[ T_m = \frac{\rho S C_p (\lambda, \beta) v^2}{2} \]  

(3)

The power coefficient is given by

\[ C_p (\lambda, \beta) = c_1 (\frac{\lambda}{\beta})^{c_2} - c_3 (\beta - c_4) e^{-\frac{c_5}{\lambda}} + c_6 \lambda \]  

(4)

where \( c_1=0.516, c_2=116, c_3=0.4, c_4=5, c_5=21, c_6=0.0068 \)

\[ \frac{1}{\lambda} = 1 - \frac{0.035}{\lambda + 0.08\beta / \beta^2 + 1} \]  

(5)

where \( \lambda \) is the tip speed ratio, \( \beta \) 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 acceptable efficiency. The rotational speed can be of the following equation

\[ \frac{d\omega_r}{dt} = \frac{T_m - T_e}{J} - \frac{B\omega_r}{J} \]  

(6)

\( T_m \) is the torque has been transfered to generator side, \( T_e \) is the electromechanical torque, \( B \) is the damping coefficient, \( J \) is the moment of inertia, \( \omega_r \) 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. Figure 2 shows the dq reference frame used in a salient -pole synchronous machine.

\[ u_d = R_s i_d + \frac{d\varphi_d}{dt} - \omega \varphi_q \]  

(7)

\[ u_q = R_s i_q + \frac{d\varphi_q}{dt} + \omega \varphi_d \]  

(8)

\( u_d \) is the d axis voltage, \( u_q \) is the q axis voltage, \( i_d \) is the d axis current, \( i_q \) is the q axis current, \( R_s \) is the stator resistance, \( \varphi_d, \varphi_q \) are the d axis and q axis flux linkage respectively, \( \omega \) is the electrical speed.

\[ \varphi_d = L_d i_d + \varphi_m \]  

(9)

\[ \varphi_q = L_q i_q \]  

(10)

\( L_d \) is the d axis inductance, \( L_q \) is the q axis inductance, \( \varphi_m \) is the permanent magnet flux linkage.

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

\[ u_d = R_s i_d + \frac{d}{dt}(L_n i_d + \varphi_m) - \omega_i (L_n i_q) \]  

(11)

\[ u_q = R_s i_q + L_n \frac{d}{dt} i_d + \omega_i (L_d i_d + \varphi_m) \]  

(12)

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

\[ v_d = R_s i_d + \frac{di_d}{dt} - L \omega \varphi_q \]  

(13)

\[ v_q = R_s i_q + L \frac{di_d}{dt} - \omega L i_d + \varphi_m \omega \]  

(14)

The general mechanical equation of the machine is

\[ \frac{d\omega_r}{dt} = \frac{T_m - T_e}{J} - \frac{B\omega_r}{J} \]  

(15)
where
\[ K_r = \frac{3}{4} P \varphi_m \] \hspace{1cm} (16)
\[ T_r = K_i i_q \] \hspace{1cm} (17)

The mathematical model of PMSG is
\[ \frac{d^2 \dot{x}}{dt^2} = -\frac{R}{L} \dot{x} + \frac{P}{2} i_q \omega - \frac{1}{L} u \] \hspace{1cm} (18)
\[ \frac{d^2 \dot{\omega}}{dt^2} = -\frac{R}{L} \dot{\omega} + \frac{P}{2} (i_q - \frac{\varphi_m}{L}) \dot{\omega} - \frac{1}{L} u \] \hspace{1cm} (19)
\[ \frac{d \omega}{dt} = \frac{J}{T_m} - \frac{k_i i_q}{J} - \frac{K \varphi_m}{J} \] \hspace{1cm} (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 first 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 uncertainties.

The sliding surfaces are defined as
\[ s_q(t) = [i_q(t) - i_q^*(t)] \] \hspace{1cm} (21)
\[ s_d(t) = [i_d(t) - i_d^*(t)] \] \hspace{1cm} (22)
\[ s_{qr}(t) = [w_r(t) - w_r^*(t)] \] \hspace{1cm} (23)
\[ i_q^*(t), i_d^*(t), w_r^*(t) \] 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
\[ u_d(t) = u_{d,eq}(t) + u_{d,N}(t) \] \hspace{1cm} (24)
Where \( u_{d,eq}(t), u_{d,N}(t) \) is the equivalent control, the switching control respectively.

The equivalent control is
\[ u_{d,eq}(t) = -R i_q(t) + \frac{P}{2} L_i(t) w_r(t) - L \frac{d i_q(t)}{dt} \] \hspace{1cm} (25)
The switching portion is determined by
\[ u_{d,N}(t) = -u_{d,0} \text{sgn}(s_d(t)) \] \hspace{1cm} (26)

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
\[ u_q(t) = u_{q,eq}(t) + u_{q,N}(t) \] \hspace{1cm} (27)

The equivalent control can be given as
\[ u_{q,eq}(t) = -R i_q(t) + \frac{P}{2} (L_i(t) - \varphi_m \varphi_0) \omega - L \frac{d i_q(t)}{dt} \] \hspace{1cm} (28)
The switching portion is determined by
\[ u_{q,N}(t) = -u_{q,0} \text{sgn}(s_q(t)) \] \hspace{1cm} (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
\[ i_q^*(t) = i_{q,eq}(t) + i_{q,N}(t) \] \hspace{1cm} (30)
The equivalent control is given by
\[ i_{q,eq}(t) = \frac{1}{K_i} \left[ r_m - B w_r(t) - J \frac{d w_r^*(t)}{dt} \right] \] \hspace{1cm} (31)
The switching control is given by
\[ i_{q,N}(t) = -i_{q,0} \text{sgn}(s_{qr}(t)) \] \hspace{1cm} (32)
i_q 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 component in MATLAB/Simulink is done. The parameters used in the study are given in the Table I.
The variable wind conditions are considered, the results are shown below.

### Table 1

| Description                | Symbol | Unit | Value |
|----------------------------|--------|------|-------|
| Air density                | $\rho$ | kg/m$^3$ | 1.023 |
| Rotor radius               | $R$    | m    | 38    |
| Stator resistance          | $R_s$  | $\Omega$ | 0.08  |
| d-axis inductance          | $L_d$  | H    | 0.334 |
| q-axis inductance          | $L_q$  | H    | 0.217 |
| Permanent magnet flux      | $\Phi_m$ | Wb  | 0.4832 |
| Pole pairs                 | $p$    | –    | 3     |

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

**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.
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 $u_d$ and $u_q$ is shown below.

These control input is responsible for the fluxionless 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.

References

[1] J. Thongam, R. Beguenane, M. Tarbouchi, A. Okou, A. Merabet, I. Fofana and P. Bouchard, "A rotor speed estimation algorithm in variable speed permanent magnet synchronous generator wind energy conversion system," International Journal of Robust and Nonlinear Control, vol. 23, no. 16, pp. 1880-1890, 2013.
[2] C. Jauch, S. Islam, P. Sorensen and B. Jensen, "Design of a wind turbine pitch angle controller for power system stabilization," Renewable Energy, vol. 32, no. 14, pp. 2334-2349, 2007.
[3] H. Camblong, "Digital robust control of a variable speed pitch regulated wind turbine for above rated wind speeds," Control Engineering Practice, vol. 16, no. 8, pp. 946-958, 2008.
[4] A. Merabet, R. Beguenane, J. Thongam and H. Ibrahim, "Adaptive sliding mode speed control for wind turbine systems," IECON 2011-37th Annual Conference on IEEE Industrial Electronics Society, pp. 2461-2466, 2011.
[5] Youssef.Errami "Maximum power point tracking of a wind power system based on the PMSG using sliding mode direct torque control," IEEE Transactions on Energy conversion, 4673-6374.
[6] Valenciaga,F.,& Puleston,P.F.(2008).Higher-order sliding control for a wind energy conversion system based on a permanent magnet synchronous generator.IEEE Transactions on Energy Conversion,23(3),860-867.
[7] F.Luo,K.Meng,et al.Coordinated operational planning for wind farm with battery energy storage system.IEEE Transactions On Sustainable Energy,2015,6(1):253-262.
[8] Akhmatov V.,"Variable Speed Wind Turbines with Doubly-Fed Induction Generators Part III:Model with the back-to-back Converters",Wind Engineering,Volume 27,No.2,pp 79-91,2003.
[9] Boyle G.,Renewable Energy,OXFORD university press,2004.
[10]Mukund R.Patel,Design,Analysis, and Operation,Wind and Solar Power System,Taylor and Francis Group,2nd Edition,2006.
[11]Khan B.H,Non-Conventional Energy Resources,Tata Mcgraw-Hil Publishers,2nd Edition,2009.
[12] Global wind energy council (GWEC) global wind 2012 report, available online at http://www.awea.org/publication/reports.

[13] T. Ackermann, Wind power in power systems, John Wiley & Sons, Ltd, UK, 2005.

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