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Wind speed Wind turbine Drive train PMSG 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 in order 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 modeling 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 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. Related Work

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 standalone 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. Implementation

3.1 SYSTEM CONTROL SCHEME:

In a variable speed wind energy system, the generator speed is adjustable for the reason of tracing maximum available power from the wind which is named MPPT control. MPPT control can be summarized as turbine-generator speed control and it is widely studied in previous works [3]. Mainly Two control functions are implemented on the generator side: one is MPPT control and the other one is optimization of generator operation. Fig.2 illustrates block diagram of DTC method. The basic idea of direct torque control implemented in PMSG is to choose the appropriate stator current vector out of nine possible converter states, according to the difference between the reference and actual torque and flux linkage values. As a result the stator flux linkage vector rotates along the stator reference frame trajectory and products the desired torque. It should be noted that the symbols used in the following, α and β correspond to the stationary frame and d and q subscriptions denoted d-axis and q-axis of the selected synchronous frame respectively.

A. Flux and torque estimation

The α- and β-axis stator flux linkage is estimated by the following equations:

$$\psi_\alpha = \int (v_\alpha - R_a i_\alpha)dt + \Psi_{\alpha 0} \quad (1)$$

$$\psi_\beta = \int (v_\beta - R_a i_\beta)dt + \Psi_{\beta 0} \quad (2)$$

$$\Psi_s = \sqrt{(\psi^2_\alpha + \psi^2_\beta)} \quad (3)$$

$$\theta_s = \tan^{-1}(\frac{\psi_\beta}{\psi_\alpha}) \quad (4)$$

vα and vβ are the terminal voltages, iα and iβ are armature currents, both in stationary frame, Ra is armatureresistance. ψs is estimated stator flux linkage and θs is the estimated position of the stator flux linkage vector which is the angular difference between the stator flux linkage vector and α-axis . Since in the steady state operation, velocity of the generator corresponds to velocity of the stator flux, the estimated position of the stator flux can be used to determine the generator speed. Actually the estimated generator speed, ωg, is calculated, using a subtraction over time of estimated position of the stator flux. In the proposed system, reference currents are used for flux estimation instead of armature currents. The estimated electromagnetic torque Tg is calculated as bellow:

$$T_g = P_n(\varphi_\alpha i_\beta - \varphi_\beta i_\alpha) \qquad (5)$$

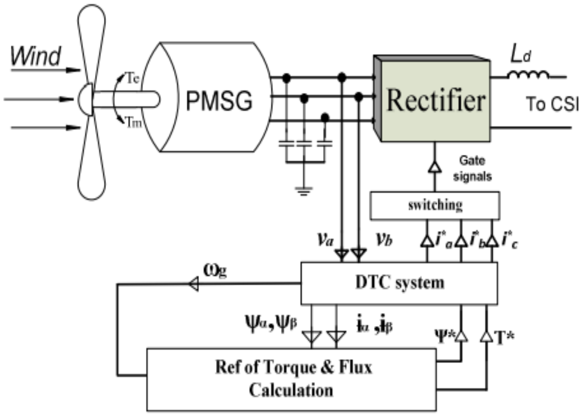


Fig.1. configuration of PMSG wind energy conversion system using CSC.

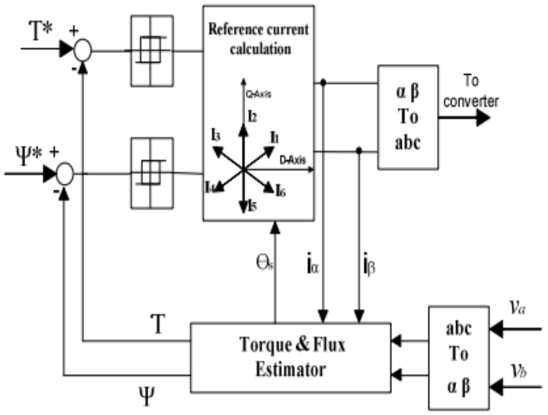


Fig.2. block diagram of the DTC system.

3.2 CONTROL METHOD:

Block diagram of calculating reference values are shown in fig.3. The torque reference is calculated so as maximize the generator output power, mainly related to the Armature current and the flux reference is calculated so as minimize losses and flux weakening control, mainly related to terminal voltages.

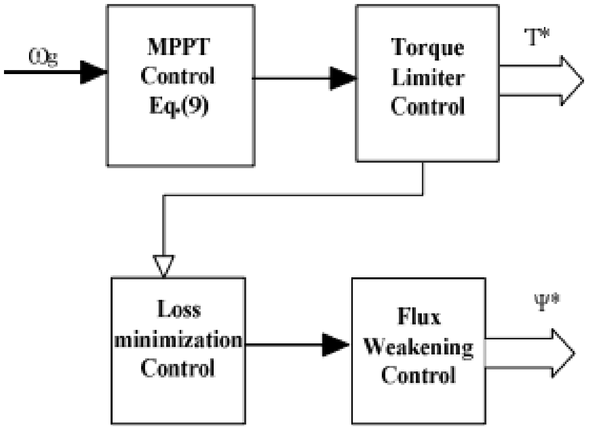


Fig.3. Block diagram of calculation of reference values.

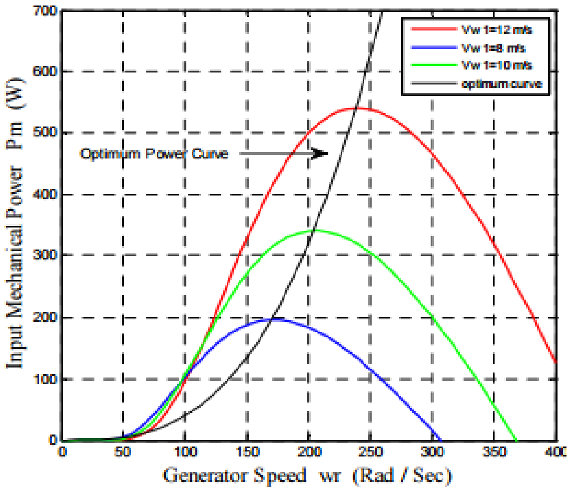


Fig.4. power of wind turbine versus generator speed at various wind speeds characteristic.

A. Torque reference calculation

Torque reference is calculated base of achieving MPPT control. Figure.4 shows a mechanical input power versus generator speed curve at various wind speeds. This figure indicates that the input mechanical power from turbine is functions of wind speed and the generator speed. The optimum operating point obtaining the maximum mechanical power exists. In the optimum points, the generator speed is proportional to the wind speed as (6); moreover the maximum mechanical power and optimum torque power can be measured by wind speed as bellow: [4]

$$\omega_{opt} = K_w V_w \tag{6}$$

$$T_{opt} = K_t V_w^{\ 2} \tag{7}$$

$$P_{m-\max} = K_p V_w^{\ 3} \tag{8}$$

Where Kw, Kt and Kp are constants determined by the wind turbine characteristics. When the generator speed is always controlled at the optimum speed, MPPT is investigated. The maximum power point in various wind speeds can also investigate by tracking optimum torque measured by: [4].

$$T_{opt} = \frac{K_t}{K_w^{\ 2}} \omega^2_{opt} = K_{opt} \omega^2_{opt} \tag{9}$$

In proposed paper MPPT is achieved by controlling the generator torque on the optimum curve according to the generator speed as (9).

B. Flux reference calculation

The generator losses consist of mechanical, copper and iron losses. The mechanical loss is speed dependent and not controllable. Fig.5 shows the d- and q-axis equivalent circuits of PMSG in the d-q coordinate which rotate synchronously with an electrical angular velocity ωg.

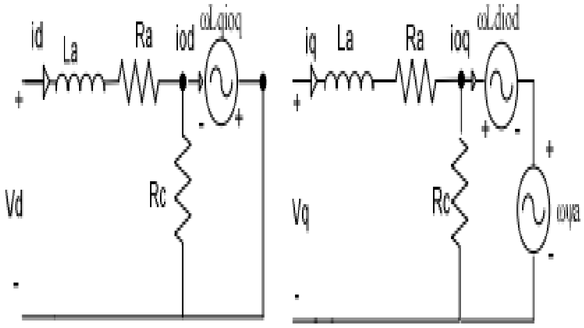


Fig.5. d-axis and q-axis equivalent circuits of PM generator.

The equivalent circuit includes the effect of copper and iron losses; Ra represents the armature copper losses. The iron loss consists of hysteresis and eddy current which is represented by Rc. the copper and iron losses are expressed as:

$$W_{cu} = R_a(i_d^2 + i_q^2) = R_a\left\{(i_{od} - \frac{\omega L_q i_{oq}}{R_c})^2 + (i_{oq} + \frac{\omega(L_d i_{od} + \psi_f)}{R_c})^2\right\} \quad (10)$$

$$W_{fe} = R_c(i_{cd}^2 + i_{cq}^2) = \frac{\omega^2(L_q i_{oq})^2}{R_c} + \frac{\omega^2(\psi_f + L_d i_{od})^2}{R_c} \quad (11)$$

The electrical losses are given by:

$$W_E = W_{cu} + W_{Fe} \quad (12)$$

WE are a function of iod , ioq and ωg. The variable of ioq in these equations can be canceled by:

$$T = P_n i_{oq}(\psi_f + (L_q - L_d) i_{od}) \quad (13)$$

As a result WE can be expressed as a function of iod ,T and ωg. In the steady state operation where the speed and torque are constants, the condition of minimizing electrical losses can be derived by differentiating WE given as a function of iod , T and ω with respect to iod and equating the derivatives to zero. As a result, the loss minimization condition is given by [12]:

$$AB = T^2 C \quad (14)$$

Where

$$A = P_n^2 (R_a R_c^2 i_{od} + \omega^2 L_d (R_a + R_c) (L_d i_{od} + \psi_f))$$
$$B = \{ \psi_f + (L_d - L_q) i_{od} \}^3$$
$$C = R_a R_c^2 + (R_a + R_c) (\omega L_q)^2 (L_d - L_q)$$

In steady state operation when T and ω are constant, optimum value of iod can be calculated by (14). The optimum value of flux in order to minimize the machine losses are derived by:

$$\psi_s = \sqrt{(L_q \frac{T}{P_n(\psi_f + (L_d - L_q) i_d)})^2 + (L_d i_d + \psi_f)^2} \quad (15)$$

The optimal flux value is used as flux reference for the control system.

4. Experimental Work

1. Simulation Results

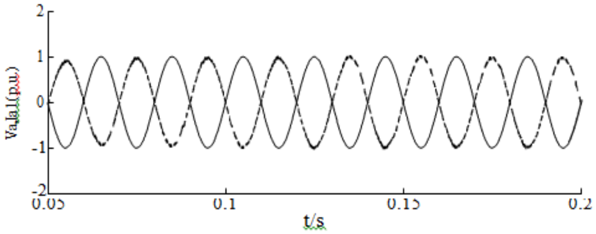
To verify the feasibility of the proposed configuration and control strategy, simulations were performed using a system model that was constructed using MATLAB/Simulink. The following simulation parameters were used: PMSG rated power, 400 kW; PMSG rated voltage, 690 V; DC-link voltage of U*dcref*= 1600 V; DC-link capacitance, 10 mF; main GSC capacity, 400 kVA; auxiliary GSC capacity, 200 kVA; upper bound on the converter current, 1.2 to 1.5 p.u. of the rated current value (1.5 p.u. was used in this study); main GSC grid filtering reactance, 2.0 mH; main GSC grid filtering capacitor, 500 uF; auxiliary GSC grid filtering reactance, 1.3 mH; and PWM with a switching

Frequency of 12.8 kHz is used for both the main and auxiliary GSC. An uncontrolled three-phase diode rectifier was utilized to simulate nonlinear loads with currents of approximately 100A.

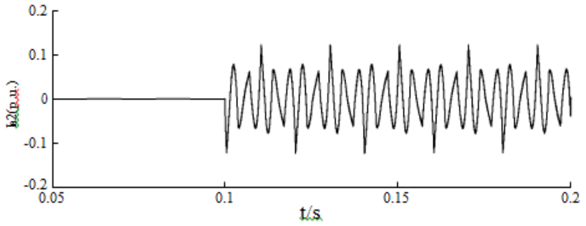
1.1. Operation under Normal Grid Conditions

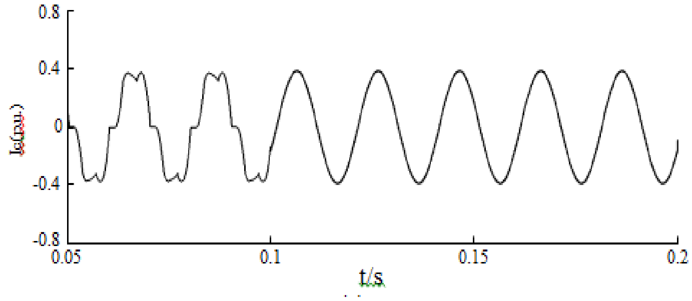
Figure 9 illustrates the system performance under normal conditions with nonlinear loads. At t = 0.1 s, the auxiliary GSC initiated the APF control mode to implement harmonic compensation for the nonlinear loads around the wind farm.

Figure 9.The simulation results for the D-PMSG WT with an auxiliary GSC under normal conditions. (a) Phase-a voltage of the power grid (solid line); phase-a current of the main GSC (dashed line); (b) Phase-a current waveform for the auxiliary GSC; (c) The grid current before and after the compensation.



(a)





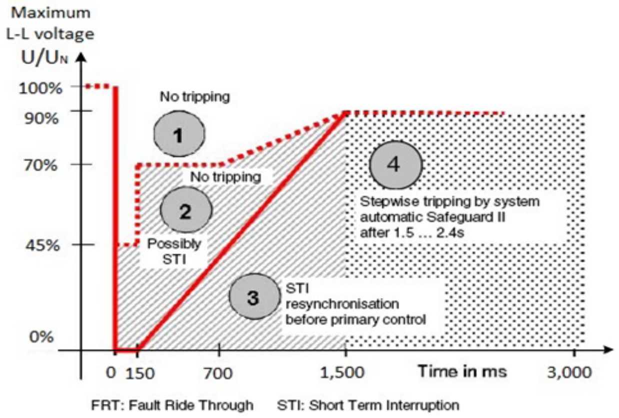
In Figure 9a, the solid line corresponds to the phase-a grid voltage, and the dashed line corresponds to the phase-an output current of the main GSC, *i.e.*, the grid-connected current of the main GSC (with a measured current direction that was opposite to the actual flow). Figure 9a demonstrates that GSC transfers the active power extracted from the wind turbine to the grid at a power factor of1.

The nonlinear load in the system produced various harmonics in the grid current. At t = 0.1 s, the auxiliary GSC initiated APF control and the harmonic compensation current is injected to the grid, as showninFigure9b.ItcanbefoundfromFigure9cthatthegridcurrentwassignificantlyimproveddue to this compensation. Therefore, it is evident that the system successfully unified control for the wind power integration and the active power filter under normal operating conditions.

1.2. Operation during Grid Faults

Wind turbines have to withstand not only the most likely unbalanced fault but also three-phase short circuits near the grid connection node. Consequently, zero voltages in all three phases in the connection points have to be considered. According to E.ON, wind farms must withstand voltage drops down to 0% of the nominal voltage for durations up to 150 ms, as shown in Figure10.

Figure 10.Fault ride through requirement [3].



However, the requirements apply for the connection point to the power grid, generally at HV level. Depending on the network and wind farm configuration, it does not necessarily lead to zero voltages at the wind generator terminal side. Taking into account the typical impedance values for the step-up transformers and interconnecting lines, a relatively simple calculation indicates that the corresponding voltage dip at lower voltage levels, near the WT terminals, are likely to be somewhat above 15% [29], facilitating compliance to the LVRTrequirements.

To validate the effectiveness of the proposed control strategy, the most serious case was considered, in which the WT was operating at the rated wind speed, a power factor of 1 and maximum power output prior to the grid fault, whereas the generator maximum speed reached 1.4 p.u., and the output power was reduced to 0.75 p.u after the gridfault.

Duetothegridfaults, att=0.2s, thevoltageatWTterminaldroppedto0.8p.u.foradurationof 0.1 s; at t = 0.3 s, the grid voltage further dropped to 0.5 p.u. for a duration of 0.2 s; and at t = 0.5 s, the grid voltage dropped to 0.15 p.u. for a duration of 0.15s.

Table 1 shows the calculated Ug ranges and the corresponding control measures for each level of the LVRT control hierarchy using the parameters of the studied WT power system. Figure 11 illustrates the system dynamic response during the grid faults.

5. Conclusion

In this paper a direct torque control method for CSC based direct driven PMSG based wind energy conversion system was proposed. The control strategy was developed for independent torque and flux control while tracing the maximum power from wind. In particular, electric power losses are minimized in steady state. Torque and flux limits are employed to ensure generator security at high wind speeds. The proposed control scheme is verified in simulation on a wind energy conversion system, it was confirmed that stable power generation from the cut-in wind speed and fast speed response were achieved.

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