Robust Control of PMSG-based Wind Turbine under Grid Fault Conditions

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Abstract

This paper presents modeling of a direct-driven permanent magnet synchronous generator – based wind turbine and proposes a new controller for Back-To-Back (BTB) converters to enhance Low Voltage Ride Through (LVRT). The LVRT is implemented without any additional devices during grid fault conditions. In this structure, the Proportional-Integral (PI) controllers of Machine Side Converter (MSC) and Grid Side Converter (GSC) are replaced by Sliding Mode (SM) controllers. The MSC controls dc-link voltage and the GSC controls Maximum Power Point Tracking (MPPT) by regulating turbine-generator speed. This control strategy implements different grid code requirements such as Danish grid code. The proposed SM controller in comparison with the PI controller can eliminate dc-link voltage oscillations and reduce the converter voltage and current stresses. Simulation results verify the robustness and effectiveness of the proposed strategy. Hence, by using SM controller, there is no need for additional equipments to enhance LVRT in PMSG-based wind turbines and cost and complexity are significantly reduced.

Keywords: DC-Link Voltage, Low Voltage Ride-Through (LVRT), PMSG, Sliding Mode Control, Wind Energy

1. Introduction

Nowadays, wind power is rapidly increasing among the renewable energy sources in many countries. Hence, the European wind energy association’s 2020 assumes 680 TWh of electricity energy being produced from a total installed wind power capacity of 265 GW, satisfying 18.4% of European Union electricity demand. Therefore, it is clear that the penetration level of wind power in the grid is extremely growing. Due to this high penetration level of wind power, it is important to analyze its impacts on the power grid, as well as the impacts of grid disturbances on wind farm generators.

There are different types of generator systems used in wind farms, among which the variable speed direct-driven Permanent Magnet Synchronous Generator (PMSG) is more attractive. In this structure, normally a PMSG and a full-scale power electronic converter are used. In comparison to the other structures, it does not need multi-stage gearbox due to the use of multi-pole low-speed high-torque synchronous generator. Furthermore, because of the advances in switching devices as well as increased reliability and efficiency, the use of PMSG-based wind turbine is rapidly growing. Recently, several companies have manufactured some 2MW PMSG-based wind turbines.

One of the important problems that should be paid attention in the wind farms is the grid side fault and its impacts on the wind farm generators. In the past, wind farms could be disconnected from the grid when a fault would occur in the grid. In future however, due to the high penetration level of wind farms, grid codes do not allow them to be disconnected from the grid. Hence, according to the type of wind farm generators, some reactions should be implemented to prevent disconnection of wind farms from the grid. A diagram of LVRT requirements of Danish grid code in which wind turbines should remain connected for voltage sags is shown in Figure 1(a).
Several methods have been introduced to achieve LVRT capability in PMSG-based wind turbines. Most of approaches need to additional equipments which increase the total cost of the system\textsuperscript{5–8}. It is desired, however, to enhance LVRT without any additional cost. Indeed, the power electronic interface between the generator and the grid can be employed for LVRT capability enhancement.

A new control structure is introduced by Anca D. Hansen et al.\textsuperscript{9}. In this structure, dc-link voltage is controlled by Machine Side Converter (MSC) and MPPT is implemented by Grid Side Converter (GSC). In some papers\textsuperscript{10–12}, LVRT capability of this structure is investigated by Proportional-Integral (PI) controller. Due to operating point of system, PI controller has poor performance in transient conditions\textsuperscript{13}. On the other hand, because of nonlinearity in relation between dc-link voltage and rotational speed, a linearization technique using an input-output feedback has been applied to the dc-link voltage control\textsuperscript{14}.

A few research results have suggested the use of Sliding Mode (SM) controller in PMSG based wind turbines\textsuperscript{15}. In all of them, SM controller is applied to control MSC and GSC in conventional method. SM controller is used to control the dc-link voltage in standalone PMSG based wind turbine when electrical load or turbine angular speed changes by M. Merzoug et al.\textsuperscript{16}.

This paper presents SM controllers to control MSC and GSC in a MW class PMSG-based wind turbine strategy, MSC regulates the dc-link voltage and it does not need additional equipments, because the mechanical part of system acts as energy storage. Then this structure is compared with the PI controller. Compared with the PI controllers, these controllers are robust against grid faults and can implement grid code requirements. Moreover, the dc-link voltage fluctuations can be increased by SM controller. The simulation is carried out in Simulink/ MATLAB software. The simulation results verify the robustness and effectiveness of the proposed strategy.

2. System Modeling

In this section, the global structure of PMSG-based wind turbines is presented in four parts: Mechanical wind turbine characteristics, Modeling of PMSG, dc-link model and grid model. Figure 2 shows PMSG wind power system, connected to the grid by back-to-back converters.

2.1 Wind Turbine Characteristics

The mechanical output power of wind turbine is formulated as follows\textsuperscript{17,18}:

\[ P_m = 0.5 \rho A \nu_w C_p(\lambda, \beta) \]  

where \( \rho \) is the air density, \( A \) is the blade swept area, \( \nu_w \) is
the wind speed and $C_p(\lambda, \beta)$ is the turbine power coefficient. Power coefficient is a function of the tip-speed ratio ($\lambda$), and also pitch angle ($\beta$) in a pitch-controlled wind turbine. The Tip-Speed Ratio (TSR) depends on the rotation speed of the shaft ($\omega_m$) and wind speed, defined as:

$$\lambda = \frac{R\omega_m}{v_w}$$  \hspace{1cm} (2)

The state equation of mechanical part of the system is expressed as

$$\frac{d\omega_m}{dt} = \frac{1}{J_{eq}}(T_m - T_e - B\omega_m)$$  \hspace{1cm} (3)

where $T_m$ is the turbine driving torque, $J_{eq}$ is the total equivalent inertia of turbine and generator, $B$ is the damping coefficient representing turbine and generator rotational losses, and $T_e$ is the electromagnetic torque that will be described in the next section.

### 2.2 Generator Model

A popular PMSG model is the d-q equivalent circuits. The state equations of the PMSG are expressed in the synchronous d-q coordinates as

$$\frac{di_{ds}}{dt} = \frac{1}{L_d}(\omega_L i_{ds} - \omega_L i_{qs} - \omega_L v_{ds})$$  \hspace{1cm} (4)

$$\frac{di_{qs}}{dt} = \frac{1}{L_q}(\omega_L i_{qs} - \omega_L i_{ds} - \omega_L v_{qs})$$  \hspace{1cm} (5)

where $R_s$ is the resistance of the stator winding, $v_{ds}$, $v_{qs}$, $i_{ds}$ and $i_{qs}$ are the d-q components of stator voltage and current respectively, $L_d$ and $L_q$ are the stator d and q-axis inductances that are equal in the surface-mounted PMSG, $\psi$ is the magnetic flux, and $\omega_e$ is the generator electrical angular speed. The electromagnetic torque is given as:

$$T_e = \frac{3p}{2}(\psi_L i_{ds} + (L_d - L_q)i_{ds}i_{qs})$$  \hspace{1cm} (6)

where $p$ is the number of machine's poles.

### 2.3 DC-Link Model

The dc-link capacitor is interface between MSC and GSC; therefore, it is affected by the both generator and grid sides. The deference between incoming power to the dc-link and outgoing power to the grid is stored in the dc-link capacitor. By neglecting the converters losses, the state equation of the dc-link voltage can be expressed as

$$\frac{d}{dt}\left(\frac{CV_{dc}^2}{2}\right) = (P_{MSC} - P_{GSC})$$  \hspace{1cm} (7)

where $C$ is the dc-link capacitor, $V_{dc}$ is the dc-link voltage, $P_{GSC}$ is the grid power, and $P_{MSC}$ is incoming power to the dc-link, which can be expressed as

$$P_{GSC} = P_m - J_m\omega_m^2 - B\omega_m^3 - \frac{3p}{2}R_s(i_{ds}^2 + i_{qs}^2)$$  \hspace{1cm} (8)

From (3), (6), (7) and (8) state equation of the dc-link voltage can be derived as follows:

$$\frac{d}{dt}\left(\frac{CV_{dc}^2}{2}\right) = (-\frac{3p}{2}v_{ds}^2 + (L_d - L_q)v_{qs}^2 - \frac{3}{2}R_s(i_{ds}^2 + i_{qs}^2))$$  \hspace{1cm} (9)

Equation (9) shows the nonlinear relationship of $V_{dc}$ with $i_{ds}$, $i_{qs}$ and $\omega_m$.

### 2.4 Grid Side Model

Figure 3 shows the schematic of the GSC and grid, in which the dc-link capacitor is on the left and GSC is
connected to the Point Of Common Coupling (PCC) by inductance and resistance of the grid filter. In d-q reference frame, the state equations, derived from the voltage balance across the grid filter can be expressed as:

\[
\begin{align*}
\frac{di_{df}}{dt} & = \frac{1}{L_f} (-R_f i_{df} + \omega_f L_f i_{qf} - v_{df} + e_{df}) \\
\frac{di_{qf}}{dt} & = \frac{1}{L_f} (-R_f i_{qf} - \omega_f L_f i_{df} - v_{qf} + e_{qf})
\end{align*}
\]  

(10)  

(11)

where \(\omega_f\) is the angular frequency of the grid voltage, \(L_f\) and \(R_f\) are inductance and resistance of the grid filter, respectively, \(v_{df}\), \(v_{qf}\), \(e_{df}\), and \(e_{qf}\) are the d- and q-axis components of PCC voltage and GSC output voltage, respectively, and \(i_{df}\) and \(i_{qf}\) are the d- and q-axis components of the current flowing between the GSC and PCC.

\[Q_{PCC} = -\frac{3}{2} V_i_{qf}\]  

(16)

3. Control of the PMSG-based Wind Turbine

In this section, at first, SMC is briefly introduced. Then, new SM controllers for MSC and GSC are proposed.

3.1 A Brief Introduction of Sliding Mode Control

Among different types of modern techniques, SMC has proved to be especially appropriate for nonlinear systems, presenting robust features with respect to system parameter uncertainties and external disturbances.
can be expressed by
\[ u_n = -k \cdot \text{sat}(s) \]  
where \( k \) is a positive constant and sat is saturation function:
\[ \text{sat}(s) = \begin{cases} s & \text{if } |s| \leq 1 \\ \text{sgn}(s) & \text{if } |s| > 1 \end{cases} \]  
By using saturation function instead of sign function, chattering can be reduced.
Accordingly, the control law becomes:
\[ u(t) = u_{eq}(t) + u_n(t) \]  
In order to determine the stabilizing function, following Lyapunov function is defined.
\[ V = \frac{1}{2} s^2 \]  
By taking time derivative of \( V \), to prove stability the following condition must be satisfied:
\[ \dot{V} = z^T z < 0 \]  

### 3.2 SM Controller Design for MSC

In order to design the MSC controller, synchronous rotating reference frame is used. The \( d \)-axis current is set to zero to reduce the copper loss and to avoid demagnetization of the permanent magnet\(^3\). In the \( q \)-axis controller, \( q \)-axis current reference is produced by dc-link voltage SM controller then \( q \)-axis control input can be produced. Figure 4 shows a block diagram of SM controller for MSC.

#### 3.2.1 DC-link Voltage Controller

In order to design the dc-link voltage controller, following sliding surface with \( n = 1 \) in (17) is defined.
\[ s_{vdc} = \frac{1}{2} (V_{dc-ref}^2 - V_{dc}^2) \]  
By taking time derivative of \( s_{vdc} \), it follows that:
\[ \dot{s}_{vdc} = \frac{d}{dt} (V_{dc-ref}^2 - V_{dc}^2) \]  
In order to obtain control low and give the smoothness of the dynamics in the neighborhood of sliding surface, it is sufficient to have:
\[ z_{vdc} = \dot{z}_{vdc} = 0 \]  
From (9), (26), and (27), the \( q \)-axis current reference can be reached:
\[ i_{qs-ref} = \frac{4P^*}{3pu \omega_m} \]  
where
\[ P^* = \left( \frac{C}{2} \frac{d}{dt} (V_{dc-ref}^2) + \frac{3}{2} R_s (i_d^2 + i_q^2) + P_{el} \right) - k_{dc} \cdot \text{sat}(s_{vdc}) \]  
And \( k_{dc} > 0 \).

#### 3.2.2 Q-axis Current Controller

The \( q \)-axis current sliding surface is defined as:
\[ s_{qs} = i_{qs-ref} - i_{qs} \]  

![Figure 4. Block diagram of SM controller for MSC.](image-url)
By taking time derivative of $s_{qs}$, it follows that:

$$\dot{s}_{qs} = i_{qs-ref} - i_{qs}$$  \hspace{1cm} (31)

To eliminate the tracking error, it is necessary to have:

$$\varepsilon_{qs} = \dot{\varepsilon}_{qs} = 0$$  \hspace{1cm} (32)

From (5), (28), (31), and (32), the q-axis controlled voltage is defined by:

$$v_{qs} = v_{eq-qs} + k_{qs}sat(s_{qs})$$  \hspace{1cm} (33)

where $k_{qs}>0$ and

$$v_{eq-qs} = L_q \dot{i}_{qs-ref} + R_q i_{qs} + \omega_q L_d i_{ds} + \omega_q y_q$$  \hspace{1cm} (34)

3.2.3 Q-axis Current Controller

Similar to q-axis current controller design, for d-axis current, a sliding surface is defined as:

$$s_{ds} = i_{ds-ref} - i_{ds}$$  \hspace{1cm} (35)

By taking time derivative of $s_{ds}$, it follows that:

$$\dot{s}_{ds} = i_{ds-ref} - \dot{i}_{ds}$$  \hspace{1cm} (36)

To eliminate the tracking error, it is necessary to have:

$$\varepsilon_{ds} = \dot{\varepsilon}_{ds} = 0$$  \hspace{1cm} (37)

From (4), (36) and (37), the q-axis controlled voltage is defined by:

$$v_{ds} = v_{eq-ds} + k_{ds}sat(s_{ds})$$  \hspace{1cm} (38)

where $k_{ds}>0$ and

$$v_{eq-ds} = L_d \dot{i}_{ds-ref} + R_d i_{ds} - \omega_d L_q i_{qs}$$  \hspace{1cm} (39)

3.3 SM Controller Design for GSC

In order to design the GSC controller, synchronous rotating reference frame is used. The grid voltage is oriented on d-axis. Hence, the q-axis voltage will be zero. In this section, only MPPT controller to calculate d-axis current of GSC is design. Other SMC controllers are designed similar MSC controller. Indeed control input of d and q-axis are written. Figure 5 shows a block diagram of SM controller for GSC.

3.3.1 MPPT Controller

In order to design the MPPT controller, following sliding surface with n=1 in (17) is defined.

$$s_{ωm} = \frac{1}{2}(ω_{m-ref}^2 - ω_{m}^2)$$  \hspace{1cm} (40)

ω_{m-ref} is obtained from optimal tip speed ratio method11. By taking time derivative of $s_{ωm}$, it follows that:

$$\dot{s}_{ωm} = \frac{d}{dt} \left( \frac{ω_{m-ref}^2}{2} - \frac{ω_{m}^2}{2} \right)$$  \hspace{1cm} (41)

In order to obtain control low and give the smoothness of the dynamics in the neighborhood of sliding surface, it is sufficient to have:

$$s_{ωm} = \dot{s}_{ωm} = 0$$  \hspace{1cm} (42)

From (3), (41), and (42), the d-axis current reference can be reached:

$$i_{df-ref}^* = \frac{2P_{grid}^*}{3V_{df}}$$  \hspace{1cm} (43)

where

$$P_{grid}^* = (P_m - J \frac{d}{dt}(ω_{m-ref}^2) - Bω_m^2 - \frac{3}{2}R_d(i_d^2 + i_q^2) - k_{ωm}sat(s_{ωm}) \frac{s_{ωm}}{η})$$  \hspace{1cm} (44)

where $k_{ωm}$ and η are positive constant. Since ωm is small then η will be taken very small to reduce chattering amplitude.

3.3.2 D-axis Current Controller

The d-axis controlled voltage is defined by:

$$e_{df} = e_{eq-df} + k_{df}sat(s_{df})$$  \hspace{1cm} (45)

where $k_{df}>0$ and

$$e_{eq-df} = L_d \dot{i}_{df-ref} + R_d i_{df} - ω_d L_q i_{qs} + V_{df}$$  \hspace{1cm} (46)
3.3.3 Q-axis Current Controller

Similar to d-axis current controller design, for q-axis current, the q-axis controlled voltage is defined by:

\[ e_{qf} = e_{eq-qf} + k_{qf} \text{sat}(s_{qf}) \]  (47)

where \( k_{qf} > 0 \) and

\[ v_{eq-ds} = L_f i_{qf-ref} + R_f i_{qf} + \omega_f L_f i_d \]  (48)

3.3.4 Stability Analysis of SM Controller

To ensure global asymptotical stability, Lyapunov stability theorem is used. Lyapunov function is defined as:

\[ V = \frac{1}{2} s_{qf} s_{qf} + \frac{1}{2} s_{df} s_{df} + \frac{1}{2} s_{ds} s_{ds} + \frac{1}{2} s_{qs} s_{qs} + \frac{1}{2} s_{ds} s_{ds} \]  (49)

By taking time derivative of Lyapunov function and by combing (4), (5), (9), (26), (31), (36), (42) and time derivative of d and q-axis of grid side sliding surfaces, it follows that:

\[
\begin{align*}
\dot{V} &= \frac{1}{C} \left( \frac{k_{qf}}{L_f} s_{qf} i_{qf} - \frac{k_{qf}}{L_f} s_{qf} i_{qf} - \frac{k_{qf}}{L_f} s_{qf} i_{qf} - \frac{k_{qf}}{L_f} s_{qf} i_{qf} \right) \quad \text{if} \ 1 < |e_q| \\
\dot{V} &= \frac{1}{C} \left( \frac{k_{qf}}{L_f} s_{qf} i_{qf} - \frac{k_{qf}}{L_f} s_{qf} i_{qf} - \frac{k_{qf}}{L_f} s_{qf} i_{qf} - \frac{k_{qf}}{L_f} s_{qf} i_{qf} \right) \quad \text{if} \ 1 < |e_q| \\
\end{align*}
\]

(50)

Thus, the global asymptotical stability is ensured.

### Table 1. Parameters of Wind Turbine

| Parameter                      | Value          |
|--------------------------------|----------------|
| Rated power                    | 1.5 [MW]       |
| Air density                    | 1.225 [kg/m³]  |
| Blade radius                   | 36.65 [m]      |
| Maximum power coefficient      | 0.48           |
| Rated wind speed               | 11 [m/s]       |
| Total Moment of inertia        | 1872000 [kg.m²]|
| Damping coefficient            | 200 [Nm s/rad] |

### Table 2. Parameters of PMSG

| Parameter       | Value          |
|-----------------|----------------|
| Rated power     | 1.5 [MVA]      |
| Voltage         | 690 [V]        |
| Rated flux      | 7.0172 [wb]    |
| Stator resistance| 0.00317 [mΩ]  |
| Stator inductance| 3.07 [mH]     |
| Number of poles | 80             |

4. Simulation Results

Simulations are carried out in MATLAB/Simulink software for 1.5 MW PMSG-based wind power system to verify the effectiveness of the proposed strategy. Parameters of the wind turbine and PMSG are listed in Table 1 and Table 2 respectively. Dc-link voltage is controlled at 1500 V, dc-link capacitance is 0.05 F, the switching frequency is 5 kHz, and the grid voltage is 690 Vrms /50 Hz.

4.1 Operation with Grid Faults

The system is simulated by both NPI controller and proposed SM controller during symmetrical grid voltage sag. Wind speed remains 10 m/s during fault and after the fault is removed. As shown in Figure 6, the symmetrical grid voltage dip occurs at t = 7 s. Figure 7 shows dc-link voltage in NPI and SM methods. Since, dc-link voltage is controlled by MSC, indeed dc-link voltage oscillations is less than conventional methods. As shown in Figure 7, in NPI method dc-link voltage experiences large-amplitude oscillations rather than SM method. Dc-link voltage oscillations are less than 1% of rated voltage in SM methods. On the other hand, NPI method may be unstable if voltage sag was very dip; hence SM method is the best method against voltage dip conditions. A disadvantage of SM method is chattering. As shown in Figure 7, chattering is limited between -1 and +1 volts and has no effects on system performances.

Figure 6. Symmetrical grid voltage dip.
As mentioned above, in new method, turbine-generator rotational speed is controlled by GSC. During fault condition, injecting power to grid decreases, hence, the turbine-generator speed increases to save wind energy in total mass, as a result, the mechanical drive acts as energy storage and prevents from overvoltage or/and over current in back-to-back converters. The speed increases slowly because the equivalent inertia of turbine and generator is extremely high as shown in Figure 8.

Figure 9 shows the stored power in turbine-generator rotational mass. Because the q-axis current reference of the MSC is produced by dc-link voltage error in NPI method, the q-axis current will be decreased to maintain dc-link voltage constant, but there are the additional fluctuations in it as shown in Figure 10. The q-axis current of PMSG will be rapidly decreased in SM method without additional fluctuations. SM controller can be made d-axis current of PMSG to be zero in different conditions as shown in Figure 11. Figure 12 shows PMSG active power. In NPI method, after remove fault, huge active power produces due to fast change in turbine-generator speed and injects to dc-link. Hence, generator and MSC experience high current and di/dt stresses. Figures 13 and 14, respectively, show d-axis...
current of GSC and injecting active power to the grid. As shown in Figure 13 SM method sets d-axis current of GSC to upper limit value for temporary time and helps to regulate dc-link voltage.

4.2 Operation with Wind Variations and Grid Faults

To discuss PMSG based wind power performances against wind variations and grid fault conditions a simulation is carried out. Wind speed profile is shown in Figure 15. The symmetrical grid voltage dip occurs at $t = 7$ s. In SM method generator speed tracks reference speed to extract maximum power from wind turbine in normal condition as shown in Figure 16. Also, during fault condition, variation of speed is acceptable in SM method. In this condition mechanical part has not additional variations. To ensure MPPT implementation in this system in normal conditions, turbine power coefficient is illustrated in Figure 17. In order to reduce power in high wind speed, a pitch angle controller is used in both methods (Figure 18). Figure 19 shows dc-link voltage with wind variations and grid fault condition. As can be seen dc-link voltage oscillations is acceptable.
Figure 13. Response of d-axis current of GSC.

Figure 14. Active power injecting to the grid.

Figure 15. Wind speed profile.
Figure 16. Turbine-generator speed.

Figure 17. Turbine power coefficient.

Figure 18. Pitch angle.
speed wind turbines. The model contains representations of the wind turbine, the direct drive train by one mass model, the multi-pole PMSG model, the dc-link model and the grid model. In this paper a new SM controller for MSC and GSC is presented. In this method, the dc-link voltage control is performed by MSC. Due to the nonlinear relationship between the state variables, SM controller has a good performance and dc-link voltage can be kept constant in different situations. In this strategy, there is no need for additional equipments to enhance LVRT because the mechanical part is used as energy storage system. Moreover, the proposed strategy is compared with PI control strategy. The simulation results verify the robustness and effectiveness of the proposed strategy.

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