Keywords: direct-driven wind power system, fault tolerant capability, second order harmonic compensation control, feed-forward control, asymmetrical grid fault

Abstract

In order to improve the fault tolerant capability for direct-driven wind power system under asymmetric grid faults, an optimal integrated control strategy is proposed in this paper. Based on mathematical model of grid-side converter in rotating reference frame, the double base frequency voltage equation represented by second order harmonic components is decomposed through coordinate transformation. In the analysis of grid-side output power characteristics, positive and negative sequence components of grid-side voltage and current is calculated by being converted to the same reference frame and an additional compensation control loop for simultaneously suppressing the second harmonic components of active and reactive power is designed. Moreover, to reduce DC voltage swell during faults, mathematical model of DC-link voltage is analyzed and a feed-forward modified component is added to the traditional grid-side DC voltage control loop. According to synthesizing the two aspects improved control methods, this paper put forward an optimal control strategy to enhance the fault tolerant capability for direct-driven wind power system under asymmetrical grid faults. The effectiveness of the improved control strategy is verified by PSCAD/EMTDC simulation results.

1 Introduction

With tremendously growing total installed capacity of wind power in power system, large scale wind power integration brings new challenges to the secure and stable operation of power system[1]. Due to the high efficiency, low maintenance requirements and quiet drive-trains, the permanent magnet synchronous generator (PMSG) wind turbines are expected to be widely deployed in the future[2]. Along with the growing adoption of PMSG, fault tolerant capability in wind power transmission and power converters is becoming more and more important in order to increase their reliability and availability[3], especially during asymmetrical faults.

Various control strategies have been proposed in order to improve the fault tolerant capability for wind power system. Reference[4] establishes the mathematical model of DFIG under asymmetrical voltage and proposes a dual-PI current control strategy to achieve the attenuation of active power pulsation. Reference[5] proposes a dual sequence current control of PMSG grid-side converter to reduce DC voltage fluctuation. Reference[6] presents a new transient management scheme for VSC-HVDC connecting offshore wind farm, which utilizes negative sequence current injection to minimize DC-link voltage ripples. In reference[7], a new direct power control algorithm based on space vector modulation using sliding mode control is presented, which aims at inhibiting the second order harmonics of DC-bus voltage. The application of a dynamic voltage restorer (DVR) connected to DFIG wind turbine to allow wind turbine system an uninterruptible fault ride-through of voltage dips is investigated in reference[8]. Although these improved control schemes make some certain control effect on the fault tolerant capability of wind turbine, only one aspect of various problems is solved and some control schemes apply extra hardware, such as crowbar, DVR and so on.

In this paper, an optimal integrated control strategy to reduce the fluctuation of DC voltage, active power and reactive power for PMSG is presented. First, the double base frequency voltage equation represented by second order harmonic components is decomposed through coordinate transformation. Second, an in-depth analysis of power transmission characteristics in PMSG wind power system is carried out to investigate the compensation control loop for suppressing the DC voltage and transmission power ripples. Third, the feed-forward control principle is adopted to optimize the traditional grid-side DC voltage control loop. Finally, the correctness and effectiveness of the proposed control strategies is validated by PSCAD/EMTDC simulations.

2 Mathematical description of PMSG wind power system under asymmetrical faults

The topological structure of PMSG wind power system is shown in Fig. 1. PMSG is drove by wind turbine directly and connected to grid by back-to-back PWM converters.
During asymmetrical faults in grid, DC voltage, transferred grid-side active and reactive power fluctuate seriously caused by the unbalanced voltage. In this paper, the characteristics of transmission power in PMSG wind power system is analysed in detail.

According to Fig. 1 and Fig. 2, the exit side voltage and current of grid-side converter can be decomposed into positive and negative sequence components in positive rotating frame and negative sequence rotating frame. Equation \[ P \] and \[ Q \] denote voltage and current components in \( \alpha \beta \) stationary frame; \( P^N_{\text{gclq}} \) and \( P^P_{\text{gclq}} \) denote voltage and current components in positive and negative rotating frame; \( U^N_{\text{gclq}} \) and \( I^N_{\text{gclq}} \) represent voltage and current components in negative clockwise rotating frame. Based on the relationship of voltage and current in Equation (1) between \( dq \) rotating frame and stationary frame, the exit side voltage \( U_{\text{gclq}} \) and current \( I_{\text{gclq}} \) of grid-side converter, and the grid voltage \( U_{\text{sdq}} \) can be transformed into positive sequence rotating frame as

\[
\begin{align*}
U_{\text{sdq}} &= U^P_{\text{sdq(+)}} + U^N_{\text{sdq(-)}} = U^P_{\text{sdq(+)}} + U^P_{\text{sdq(-)}} e^{j2\omega t} \\
I_{\text{gclq}} &= I^P_{\text{gclq(+)}} + I^N_{\text{gclq(-)}} = I^P_{\text{gclq(+)}} + I^P_{\text{gclq(-)}} e^{j2\omega t}
\end{align*}
\]

where subscripts “(+)” and “(-)” represent positive sequence component and negative sequence component respectively; superscripts “P” and “N” denote being in positive rotating frame and in negative sequence rotating frame separately; the negative sequence component in the negative rotating frame \( U^N_{\text{sdq(-)}} \), \( U^N_{\text{gclq(-)}} \), and \( I^N_{\text{gclq(-)}} \) are converted to the ones in positive rotating frame as \( U^P_{\text{sdq(+)}} e^{j2\omega t} \), \( U^P_{\text{gclq(+)}} e^{j2\omega t} \) and \( I^P_{\text{gclq(+)}} e^{j2\omega t} \).

According to the transform factor \( e^{j2\omega t} \) in Equation (2), the exit side voltage and current of grid-side converter, and the grid-side voltage can be expressed as the sum of DC components and second harmonic components.

In order to control the second harmonic components of voltage and current, the grid-side voltage equations of PMSG wind power system can be expressed as

\[
\begin{align*}
U_{\text{sd}} &= R I_{\text{sd}} + L \frac{d I_{\text{sd}}}{dt} + U_{\text{gcl}} - \omega L I_{\text{sd}} \\
U_{\text{sq}} &= R I_{\text{sq}} + L \frac{d I_{\text{sq}}}{dt} + U_{\text{gcl}} - \omega L I_{\text{sq}}
\end{align*}
\]

where the double frequency voltage equations can be established by

\[
\begin{align*}
U^P_{\text{sd(-)}} &= R I^P_{\text{gcl(-)}} + L \frac{d I^P_{\text{gcl(-)}}}{dt} + U^P_{\text{gcl(-)}} - \omega L I^P_{\text{sd(-)}} \\
U^P_{\text{sq(-)}} &= R I^P_{\text{gcl(-)}} + L \frac{d I^P_{\text{gcl(-)}}}{dt} + U^P_{\text{gcl(-)}} - \omega L I^P_{\text{sd(-)}}
\end{align*}
\]

When asymmetrical faults occur in grid, the power transmission in wind power system can be calculated as

\[
S = \frac{3}{2} (P + jQ) = \frac{3}{2} \left( U_{\text{gcl}} I_{\text{gcl}}^* \right) = \frac{3}{2} \left( U^P_{\text{gclq(+)}} e^{j\omega t} + U^N_{\text{gclq(-)}} e^{j2\omega t} \right) \left( I^P_{\text{gclq(+)}} e^{j\omega t} + I^N_{\text{gclq(-)}} e^{j2\omega t} \right)
\]

where

\[
\begin{align*}
P &= P_0 + P_2 \cos(2\omega t) + P_2 \sin(2\omega t) \\
Q &= Q_0 + Q_2 \cos(2\omega t) + Q_2 \sin(2\omega t)
\end{align*}
\]

According to Equation (7) and Equation (2), the sum of active and reactive second harmonic power components can be calculated and expressed as

\[
\begin{align*}
P_{C2} &= \frac{3}{2} \left( U^P_{\text{gclq(+)}} I^N_{\text{gclq(-)}} + U^P_{\text{gclq(-)}} I^N_{\text{gclq(+)}} + U^N_{\text{gclq(+)}} I^P_{\text{gclq(-)}} + U^N_{\text{gclq(-)}} I^P_{\text{gclq(+)}} \right) \\
P_{Q2} &= \frac{3}{2} \left( U^P_{\text{gclq(+)}} I^N_{\text{gclq(-)}} - U^P_{\text{gclq(-)}} I^N_{\text{gclq(+)}} - U^N_{\text{gclq(+)}} I^P_{\text{gclq(-)}} + U^N_{\text{gclq(-)}} I^P_{\text{gclq(+)}} \right) \\
Q_{C2} &= \frac{3}{2} \left( U^P_{\text{gclq(+)}} I^N_{\text{gclq(-)}} + U^P_{\text{gclq(-)}} I^N_{\text{gclq(+)}} - U^N_{\text{gclq(+)}} I^P_{\text{gclq(-)}} - U^N_{\text{gclq(-)}} I^P_{\text{gclq(+)}} \right)
\end{align*}
\]

According to Equation (7) and Equation (2), the sum of active and reactive second harmonic power components can be calculated and expressed as

\[
\begin{align*}
P_2 &= P_{C2} + P_{Q2} \\
Q_2 &= Q_{C2} + Q_{Q2}
\end{align*}
\]
3 Optimal control scheme

3.1 Control strategy to restrain power oscillation

In order to restrain the oscillation of grid-side active and reactive power, a compensation control loop for second harmonic components is added to the traditional dual-loop PI control scheme in the base of Equation (4). In this paper, d-axis voltage component depicts the grid-side voltage amplitude, which means $U_{gd(+)}^p = 0$. Typically, the amplitude of negative sequence voltage component in positive rotating frame $U_{gd(-)}^p$ fluctuates slightly around 0.

Therefore, Equation (8) can be simplified as

$$P_2 = \frac{3}{2} \left( U_{gd(+)}^p I_{gd(+)}^p + U_{gd(-)}^p I_{gd(-)}^p \right)$$

and

$$Q_2 = \frac{3}{2} \left( U_{gd(+)}^p I_{gd(+)}^p + U_{gd(-)}^p I_{gd(-)}^p \right)$$

The derivation of Equation (9) is

$$\frac{dP_2}{dt} = \frac{3}{2} \left( U_{gd(+)}^p \frac{dI_{gd(+)}^p}{dt} + U_{gd(-)}^p \frac{dI_{gd(-)}^p}{dt} \right)$$

$$+ P_{gd(+)}^p \frac{dU_{gd(+)}^p}{dt} + P_{gd(-)}^p \frac{dU_{gd(-)}^p}{dt}$$

$$\frac{dQ_2}{dt} = \frac{3}{2} \left( U_{gd(+)}^p \frac{dI_{gd(+)}^p}{dt} + U_{gd(-)}^p \frac{dI_{gd(-)}^p}{dt} \right)$$

$$+ Q_{gd(+)}^p \frac{dU_{gd(+)}^p}{dt} + Q_{gd(-)}^p \frac{dU_{gd(-)}^p}{dt}$$

where the positive sequence components in positive rotating frame $U_{gd(+)}^p$, $I_{gd(+)}^p$ and $I_{gd(-)}^p$ are DC components, the derivation of which are zero and thus Equation (10) can be expressed as

$$\frac{dP_2}{dt} = \frac{3}{2} \left( P_{gd(+)}^p \frac{dI_{gd(+)}^p}{dt} + P_{gd(-)}^p \frac{dI_{gd(-)}^p}{dt} \right)$$

$$\frac{dQ_2}{dt} = \frac{3}{2} \left( Q_{gd(+)}^p \frac{dI_{gd(+)}^p}{dt} + Q_{gd(-)}^p \frac{dI_{gd(-)}^p}{dt} \right)$$

According to Equation (11), Equation (4) can be rewritten as

$$U_{gd(-)}^p = \frac{L_I^p}{U_{sd(+)}} \frac{dU_{sd(-)}^p}{dt} + U_{sd(-)}^p - R_P^p$$

$$+ \omega L_I^{p(sq)} = \frac{2L}{3U_{sd(+)}} \frac{dP_2}{dt}$$

$$U_{gd(-)}^p = \frac{L_I^p}{U_{sd(+)}} \frac{dU_{sd(-)}^p}{dt} - U_{sd(-)}^p + R_P^p$$

$$+ \omega L_I^{p(sq)} = \frac{2L}{3U_{sd(+)}} \frac{dQ_2}{dt}$$

where $U_{gd(+)}^p$ and $U_{gd(-)}^p$ are second harmonic compensation control voltage in the optimal control strategy. To describe the optimal control structure clearly, Equation (12) can be expressed as

$$U_{gd(-)}^p = U_{gd} - \frac{2L}{3U_{sd(+)}} U_{gd2}$$

$$U_{gd(-)}^p = U_{gd} - \frac{2L}{3U_{sd(+)}} U_{gd2}$$

In Equation (14), the components in brackets are included in traditional PI control equations; $V_{sd1}$ and $V_{sd2}$ are regarded as the compensation voltage components. In Equation (15), $P_2ref$ and $Q_2ref$ are reference values of active power and reactive power second harmonic components respectively, and $P_2ref=Q_2ref=0$.

3.2 Control strategy to restrain DC voltage swell

In order to restrain DC voltage swell during grid-side faults, a feed-forward corrective control term is added to the traditional DC voltage control loop. The dynamic model of converters on DC side can be represented by the following equation as

$$CU_{dc} \frac{dU_{dc}}{dt} = P_s - P_g$$

where $P_s$ and $P_g$ denote the generator-side active power and grid-side active power respectively. Both sides of Equation (16) are divided by grid-side voltage $U_{dc}$ and then Equation (16) can be rewritten as

$$CU_{dc} \frac{dU_{dc}}{dt} = \frac{P_s}{U_{dc}} - \frac{P_g}{U_{dc}} = \frac{P_s - P_g}{U_{dc}} = I_g$$

where $I_g$ represents the grid-side current component.

In order to restrain the adverse effects of grid-side faults on DC voltage, grid-side current component $I_g$ representing the characteristics of grid can be added to the output of DC voltage outer PI control loop as an extra correction signal.
According to the description and analysis of the proposed optimal control schemes in 3.1 and 3.2, the overall control block diagram is shown in Fig. 3 below.

Fig. 3 Overall control diagram of grid-side converter improved control

4 Simulation results

To verify the effectiveness of the proposed optimal control strategy, PSCAD/EMTDC simulations are conducted with the wind turbine and generator parameters in Table 1, and the simulation model is based on the system structure of Fig. 1.

<table>
<thead>
<tr>
<th>Wind Turbine</th>
<th>PMSG</th>
</tr>
</thead>
<tbody>
<tr>
<td>Blade Radius</td>
<td>58(m)</td>
</tr>
<tr>
<td>Cut-in Speed</td>
<td>4(m/s)</td>
</tr>
<tr>
<td>Rated Wind Speed</td>
<td>12(m/s)</td>
</tr>
<tr>
<td>Cut-out Speed</td>
<td>25(m/s)</td>
</tr>
<tr>
<td>Rated Power</td>
<td>5.3(MVA)</td>
</tr>
<tr>
<td>Rated Frequency</td>
<td>10(Hz)</td>
</tr>
<tr>
<td>d-axis Reactance</td>
<td>11(mH)</td>
</tr>
<tr>
<td>q-axis Reactance</td>
<td>11(mH)</td>
</tr>
<tr>
<td>Leakage Reactance</td>
<td>1(mH)</td>
</tr>
<tr>
<td>Air Density</td>
<td>1.225(kg/m³)</td>
</tr>
<tr>
<td>Cp</td>
<td>0.466</td>
</tr>
<tr>
<td>Rated DC voltage</td>
<td>4.8(kV)</td>
</tr>
</tbody>
</table>

Table 1 Main parameters of simulation model

In the simulations: two-phase (AB) short circuit fault is set as the asymmetrical grid fault; wind speed is set to 10m/s and constant during the fault; the fault in grid occurs at t=3s and is cleared at t=3.3s; the simulation time is 10s. Simulation results are shown in Fig. 4a) ~Fig. 4f).

a) DC voltage

b) second harmonic components of \( U_{dc} \)

c) active and reactive power in grid when traditional control strategy is used

d) active and reactive power in grid when the proposed optimal control strategy is used
Fig. 4 Simulation results of two-phase fault in grid

Fig. 4a) and Fig. 4b) shows the characteristics of DC voltage during asymmetrical fault with different control strategies. When the proposed optimal control scheme is used, the voltage swell when grid fault occur and the second harmonic components of DC voltage during grid fault are reduced significantly.

Fig. 4c) ~Fig. 4f) depict the characteristics of grid transmission power during asymmetrical fault with different control schemes. When the proposed optimal control strategy is applied, the second harmonic components of active power and reactive power are restrained simultaneously.

According to the plots in Fig. 4a) ~Fig. 4f), the effectiveness of the proposed optimal control scheme is validated.

5 Conclusions

In order to restrain the DC voltage swell and the oscillation of DC voltage, active power and reactive power, this paper analyses the power transmission characteristics of PMSG wind power system in depth and proposes an optimal control strategy with the combination of second harmonic components compensation control loop and feed-forward correction control scheme. With the regulation effect of the proposed control scheme, the swell and fluctuation of DC voltage and transmitted power are reduced significantly by the simulated validation on PSCAD/EMTDC. When the optimal control scheme is used, the fault tolerant capability of PMSG wind power system is improved.

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References