An Improved Control Strategy to Suppress the DC-Link Voltage Fluctuation for PMSG Wind Turbines

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Abstract. Frequency droop control can provide active power for permanent magnet synchronous generator (PMSG) wind turbines when grid frequency varies. However, it would cause dc-link voltage fluctuations. According to the law of the dc-link voltage fluctuations, a improved feedforward control method is proposed to limit voltage fluctuations through adjusting the feedforward coefficient from a fixed value to an variable value in this paper. Compared with the traditional current feedforward control method, it has better performance in stabilizing the dc-link voltage. Results demonstrate that the dc-link voltage fluctuations can be reduced by 70% in some specified cases, which proves that the proposed strategy can be applied to protect dc-link capacitor when PMSG wind turbines provide system inertia supports by frequency droop control. PMSG wind turbines can work as traditional thermal power to provide system inertia supports when grid frequency varies. The analysis results is very beneficial to widely application of PMSG wind turbines.

1. Introduction
Renewable energy, especially wind power, has rapidly been widely utilized in modern power systems [1]-[7]. The Permanent magnet synchronous generator (PMSG) wind turbine has more benefits than traditional wind power system in terms of adapting low wind speed, reliability and excellent control characteristics [1]-[8]. Therefore, PMSG wind turbines are popular in wind power. However, it cannot provide system inertia support when grid frequency varies in traditional control strategy, which will result in weak frequency recovery capability.

Many frequency control methods have been proposed to provide active power support [9]-[13]. Frequency droop control is a commonly used method among them [9]-[10]. In [9], a cascading control strategy, which introduces the frequency droop control to use energy that stored in rotor and DC-link capacitor, is proposed. In [10], effects of utilizing the frequency difference term to realize droop control strategy for PMSG wind turbines is investigated. Reference [11] focused on using the frequency deviation term to provide system inertia support. However, the frequency droop control will cause voltage fluctuations. It may breakdown the dc-link capacitor [12]. Therefore, reducing the dc-link voltage fluctuations is significant. Reference [12] proposes a current feedforward control strategy to suppress the dc-link voltage fluctuations. It introduces the active current signal of PMSG to change the active current reference signal of grid-side controller. The active current of the grid-side converter of the proposed feedforward control strategy responses faster than that of tradtional frequency droop control strategy, which can decrease the fluctuations of the dc-link voltage. This paper analyze the other factors that related to the effect that decreasing the dc-link voltage variations. Then, a new feedforward control method is proposed to suppress the dc-link voltage variations by adjusting
feedforward coefficient. It is found that the fluctuations of the dc-link voltage of improved feedforward control method are lower than that of previously mentioned current feedforward control method. The new feedforward control method could guarantee that the dc-link voltage fluctuates within acceptable range.

2. Conventional control of PMSG

The topology diagram of PMSG wind turbine system is illustrated in figure 1. We can notice that the PMSG wind turbine system are included by generator-side system, dc-link capacitor and grid-side system. The generator-side system consists of wind turbine, PMSG, generator-side converter and generator-side controller. The grid-side system includes grid-side converter and grid-side controller.

![Figure 1. Topology diagram of the PMSG wind turbine system.](image_url)

2.1. Basic generator-side control method and grid-side control method

The generator-side converter usually adopts $i_{sd}=0$ control [6]. Figure 2 shows that the generic control scheme of it. From figure 2, power control loop utilizes proportional–integral (PI) controller to realize maximum power point tracking (MPPT) strategy. Current control loop also utilizes PI controller to separately regulate the $d, q$-axis current $i_{sd}$ and $i_{sq}$ of PMSG to their reference value $i_{sd}^*$ and $i_{sq}^*$. In order to decouple them, feedforward compensation $\omega_r L_{sq} i_{sd}$, $\omega_r L_{sq} i_{sq}$ and $\omega_r \psi_{PM}$ are introduced.

![Figure 2. Generic control scheme of the generator-side converter.](image_url)

The function of the grid-side converter is keeping the dc-link voltage unchanged[12]-[14]. Figure 3 shows the generic control diagram of it. From figure 3, the voltage control loop uses the PI controller to adjust the dc-link voltage to reference value. The current loop utilizes the PI control to regulate $d, q$-axis current $i_{gd}$ and $i_{gq}$ of grid to reference value respectively. The decoupling of $d, q$-axis current $i_{gd}$ and $i_{gq}$ of grid can be realized by the introduction of feedforward compensation $\omega L_{gd}$, $\omega L_{gq}$ and $u_{gd}$.
2.2. Traditional frequency droop control

Figure 2.2. shows the control diagram of traditional frequency droop control. It is shown that the frequency droop control is introduced to change the active power reference of wind turbine. $P_{WT}^*$ is the improved reference value of the active power outer loop control. $P_{MPPT}$ is the initial power reference that obtained by MPPT strategy. $P_{ad}$ reflects the variation of grid frequency. The relationship between $P_{WT}^*$ and $P_{MPPT}$ can be expressed as

$$P_{WT}^* = P_{MPPT} + P_{ad}$$  \hspace{1cm} (1)$$

$P_{ad}$ can be obtained by proportional controller [15]. $P_{ad}$ can be written as

$$P_{ad} = K_f (f_0 - f_{PLL})$$  \hspace{1cm} (2)$$

where $K_f$ is the coefficient that reflect the influence of frequency fluctuation on active power fluctuation, $f_0$ is the grid frequency reference value, $f_{PLL}$ is the frequency that calculated by phase locked loop (PLL) algorithm. $P_{WT}^*$ also changes accordingly to support grid frequency recovery using the kinetic energy of the rotor when grid frequency varies.

3. Improved feedforward control strategy

In this section, we propose an improved current feedforward control method to enhance dc-link voltage fluctuations suppression. Reference [12] proposed a current feedforward control strategy to limit dc-link voltage fluctuations when PMSG wind turbines provide system inertia supports by frequency droop control. The control diagram of it is illustrated in figure 5. From figure 5, it introduces the generator-side active current $i_{qg}$ to modify the grid-side active current reference value $i_{gd}^*$. Figure 6 shows the power flow across the dc-link capacitor. The dynamic process of the current control loop of the grid-side controller can be ignored. Therefore, $i_{gd}$ is equal to $i_{gd}^*$. From figure 6, the equation, which reflects the power that flow through the dc-link capacitor, can be given as
\[
C \frac{du_{dc}}{dt} u_{dc} = -P_e - P_i
\]

\[
= -\frac{3}{2} \left( u_{gd} i_{gq} - u_{sq} i_{qs} \right) - \frac{3}{2} u_{gi} (u_{qi} - u_{gs})
\]

\[
= -\frac{3}{2} u_{gd} \left( K_p (u_{ds} - u_{dg}) + K_i (u_{di} - u_{dg}) \right) - \frac{3}{2} u_{gi} (u_{gd} K_u + u_{in})
\]

where \( K_p \) and \( K_i \) is the proportional coefficient and integral coefficient of the voltage (outer) loop controller respectively, \( i_{sq} \) is the \( q \)-axis current of PMSG. \( u_{gd} \) is a constant. \( u_{sq} \), which is related to the motor speed \( \omega_e \) and \( i_{sq} \), is not a constant. \( K_a \) is a constant in the current feedforward control strategy shown in figure 5. Therefore, \( u_{gd} K_a + u_{sq} \) can not equal to 0 always. From (3), dc-link voltage would fluctuate when PMSG wind turbines provide system inertia supports. To suppress the dc-link voltage fluctuations more effectively, this paper proposes an improved current feedforward control method. The control diagram is shown in figure 7. From figure 7, compared the original current feedforward strategy with the improved current feedforward strategy, \( K_a \) changes from a constant to a variable parameter. Therefore, \( u_{gd} K_a + u_{sq} \) equals to 0. Based on (3), the fluctuations of the dc-link voltage of the proposed feedforward control method are lower than that of the original current feedforward control method.

**Figure 5.** The control scheme of the traditional current feedforward control strategy.

**Figure 6.** The power flow through the dc-link capacitor.

**Figure 7.** The control scheme of improved current feedforward control strategy.
4. Small Signal Analysis

In this section, the small signal model of the PMSG wind turbine system is given. According to the small signal model, the effect of the feedforward coefficient on the voltage variation is analyzed. Table 1 lists the main system parameters.

According to reference [16], the small signal model of the whole system is expressed as

\[
\Delta \dot{x} = A \Delta x + C \Delta u \\
\Delta y = F \Delta x + Z \Delta u
\]  
(4)

where \(\Delta x\) is the small perturbation of the state variable of the PMSG wind turbine system, \(\Delta y\) is the small perturbation that introduced to output signal, \(\Delta u\) is the small perturbation that introduced to the input signal, \(A\) is the Jacobian matrix, \(C\) is the coefficient matrix of input signal, \(F\) is the coefficient matrix of output signal, \(Z\) is the coefficient matrix of feedforward signal. In order to study the effect of frequency perturbation on the dc-link voltage variations, the frequency deviation \(\Delta f\) is selected as the small perturbation of the state variable \(\Delta x\). \(\Delta u_d\) is selected as the small perturbation of the output signal deviation \(\Delta y\). According to (4), \(\Delta u_d/\Delta f\) can be obtained as

\[
\Delta u_d/\Delta f = F(\delta I - A)^{-1} C + Z
\]  
(5)

The closed-loop transfer function \(\Delta u_d/\Delta f\) determines the effect of frequency perturbation on the dc-link voltage variations. Therefore, \(\Delta u_d/\Delta f\) could be used to analyze the amplitude of the feedforward coefficient to the dc-link voltage variations.

Table 1. Parameters for Theoretical Analysis.

| Parameters | Descriptions                  | Values    |
|------------|-------------------------------|-----------|
| \(S_b\)   | Base power                    | 2MVA      |
| \(f_0\)   | Rated frequency               | 50Hz      |
| \(L_d\)   | \(d\)-axis inductance of PMSG | 0.00068H  |
| \(L_q\)   | \(q\)-axis inductance of PMSG | 0.00068H  |
| \(\psi_m\)| Flux linkage                  | 4 Wb      |
| \(C\)     | DC-link capacitor             | 0.09F     |
| \(p\)     | pole pairs                    | 48        |
| \(L\)     | inductance of grid side       | 0.000158H |

When wind speed is rated value, the Bode diagram of \(\Delta u_d/\Delta f\) under two different control method is demonstrated in figure 8. It can be observed that the peak value of \(\Delta u_d/\Delta f\) has changed from 44 to 42. The overshoot of this system is determined by the peak value of \(\Delta u_d/\Delta f\). Hence, the dc-link voltage variations of improved feedforward control method are lower than that of traditional current feedforward control method.

**Figure 8.** Bode diagram of the closed-loop transfer function \(\Delta u_d/\Delta f\) when wind speed is rated value.
When wind speed is 0.7 times rated value, figure 9 shows the Bode diagram of $\Delta u_d/\Delta f$ under two different control strategies. From figure 9, the peak value of $\Delta u_d/\Delta f$ has changed from 50 to 33, which means the voltage variations of improved feedforward control strategy are lower than that of traditional current feedforward control strategy.

![Bode diagram of the closed-loop transfer function $\Delta u_d/\Delta f$ when wind speed is 0.7 times rated value.](image)

Figure 9. Bode diagram of the closed-loop transfer function $\Delta u_d/\Delta f$ when wind speed is 0.7 times rated value.

5. Simulation results

Section IV presents the theoretical analysis based on the signal model. In this section, simulation results are given to confirm theoretical analysis.

When wind speed is rated value, the grid frequency is 50Hz before $t=10s$. The grid frequency reduce to 49.8Hz after $t=10s$. Figure 10 shows the simulation waveforms of dc-link voltage under two different control methods. From figure 10, we can notice that the voltage variations of improved feedforward control method are lower than that of traditional feedforward control methods, which coincides with the theoretical results.

![Time-domain waveforms of the dc-link voltage when wind speed is rated value.](image)

Figure 10. Time-domain waveforms of the dc-link voltage when wind speed is rated value.

When wind speed is 0.7 times rated value, the grid frequency is 50Hz before $t=10s$. The grid frequency reduce to 49.8Hz after $t=10s$. Figure 11 shows the simulation waveforms of dc-link voltage under two different control methods. From figure 11, the maximum variations of dc-link voltage of the traditional current feedforward strategy and that of the improved feedforward control strategy are 21V and 6V respectively. The maximum variations of the dc-link voltage are decreased by 70%.

![Time-domain responses of the dc-link voltage when wind speed is 0.7 times rated value.](image)

Figure 11. Time-domain responses of the dc-link voltage when wind speed is 0.7 times rated value.
Wind speed changes from rated value to 0.7 times rated value. The motor speed is different. \( u_{eq} \) is different. Therefore, \( u_{eq}K_r + u_{eq} \) far from 0 under the traditional feedforward control method. However, \( u_{eq}K_r + u_{eq} \) still close to 0 under the improved feedforward control method. The dc-link voltage variations of the traditional feedforward control method would become large a lot. However, the dc-link power is lower than that of the original system. It means that the suppression of the dc-link voltage variations of the improved feedforward control method are still low. This theoretical analysis is validated by simulation results displayed in figure 10 and figure 11.

The dc-link voltage variations of improved feedforward control scheme are always lower than that of traditional feedforward control scheme when system frequency recovers, as shown in figure 10 and figure 11. As the system frequency recovers, \( P_w \) would change. \( P_{w*} \) would change. It means that the motor speed of PMSG would keep changing when the system frequency recovers. \( u_{eq} \) also change. \( u_{eq}K_r + u_{eq} \) cannot always equal to 0 if \( K_r \) is a constant. \( u_{eq}K_r + u_{eq} \) always equals to 0 if grid-side system applies the improved feedforward control scheme. From (3), we can observe that the dc-link voltage fluctuations of the improved feedforward control scheme are lower than that of the original feedforward control scheme.

6. Conclusion
This paper proposes an improved feedforward control method to suppress dc-link voltage fluctuations when PMSG wind turbines provide system inertia supports by frequency droop control. Both simulation and theoretical analysis results were given to test the effect of the improved control strategy. It turns out that the supression of the dc-link voltage variations of the improved control scheme are more effectively than that of the original feedforward control scheme. The research results could guarantee that the dc-link voltage fluctuate within acceptable range. This is instrumental in protecting PMSG wind turbines system.

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