Analysis of the influence of control parameters on the interaction between direct-driven wind turbines

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Abstract. In order to study the influence of control parameters on the interaction between direct-driven wind turbines, this paper presents the interaction model and analysis method of direct-driven wind turbines. Firstly, the harmonic linearization method is used to establish the interaction model of two direct-driven wind turbines, and the interaction mechanism between the two units is studied; secondly, the influence of phase-locked loop and DC voltage loop on the interaction between the two units is analyzed from the perspective of bandwidth and damping ratio of second-order closed-loop transfer function, and the interaction law of phase-locked loop and DC voltage loop on the interaction between the two units is studied and summarized; finally, the time-domain simulation of the two units grid-connected system is carried out, and the results are compared with the frequency domain analysis results to verify the rationality of the theoretical analysis.

1. Introduction

In recent years, the power system is undergoing profound changes, one of the outstanding characteristics and development trends is the widespread access of power electronic converters[1]. With the rapid development of new energy represented by wind power, direct-driven permanent magnet synchronous generator (D-PMSG) including power electronic converters has been widely used. At the same time, with the continuous expansion of the scale and capacity of wind turbines, multiple wind turbines will operate in parallel at the point of common coupling (PCC). Most of these wind turbines are connected to the power grid by power electronic converters. Due to different control parameters and operation modes, the converters may interact with each other, which may lead to oscillation[2-3]. Therefore, it is necessary to study the system oscillation caused by the interaction of direct-driven wind turbines.

In order to study the influence of the interaction between wind turbines on the stability of large-scale wind farms, the corresponding research is carried out in article [4-7]. Article [4] proposes an equivalent method of wind farm sequence impedance considering frequency coupling and converging network, but the influence of control link on the stability of wind farm system with multiple wind farms has not been considered. The improved impedance model of interface between multiple doubly-fed induction machines and series compensation network is derived in article [5], and the sub-synchronous oscillation caused by different factors is quantitatively analyzed by using the aggregated RLC circuit model. In article [6-7], the equivalent model of multiple grid connected inverters in weak network is established, but the influence of phase-locked loop (PLL) and DC voltage loop on the interaction between inverters is not considered.
In view of the above, this paper mainly considers the influence of control links on the interaction between units. The work done is as follows: firstly, the interaction model between two direct-driven wind turbines is established by using the harmonic linearization method; secondly, the interaction rules of PLL and DC voltage loop on the interunit interaction are analyzed from the perspective of bandwidth and damping ratio of the second-order closed-loop transfer function; finally, the simulation diagram is compared with the results of frequency domain analysis to verify the rationality of the law of the influence of the control link on the interaction between the units.

2. Interaction model and mechanism between two direct-driven wind turbines

For the multi-wind turbines with common connection points, they are connected with each other through PLL, which may have mutual influence. In order to study the influence mechanism of control parameters on the interaction between PMSGs under terminal voltage control, two PMSGs connected to the common node are established, as shown in figure 1. In the figure: $\vec{U}_{w1}$ and $\vec{U}_{w2}$ represent the output voltage vector of the two units before filtering, $\vec{U}_{11}$ and $\vec{U}_{12}$ are the output voltage vectors of the two units, $\vec{U}_{\text{pcc}}$ is the voltage vector of PCC, $\vec{U}_{g}$ is the voltage vector of AC grid bus, $\vec{I}_{1}$ and $\vec{I}_{2}$ are the line current vector of the two units; $X_{1}$ and $X_{2}$ are the impedance of the transformer and transmission line on the wind turbines side, $X_{g}$ is the impedance of the transmission line on the grid side; $L_{1}$ and $L_{2}$ are filter inductors, $C_{fw1}$ and $C_{fw2}$ are filter capacitors, $R_{fw1}$ and $R_{fw2}$ are damping resistors; $C_{dc1}$ and $C_{dc2}$ are DC side capacitances; $U_{dc1}$ and $U_{dc2}$ are DC side bus voltage.

When unit 1 is disturbed, its terminal voltage $\vec{U}_{11}$ will change, which will lead to the change of PCC point voltage $\vec{U}_{\text{pcc}}$. The change of $\vec{U}_{\text{pcc}}$ will affect the change of terminal voltage $\vec{U}_{12}$ of unit 2, $\vec{U}_{12}$ ultimately affect the operation of unit 2 through PLL and DC voltage control link. On the contrary, the disturbance of unit 2 will affect unit 1 through coupling relationship. The interaction between the two PMSGs is shown in figure 2. Next, the interaction model between two PMSGs is established to study the interaction mechanism between the two units.

![Figure 1. Interaction between two PMSGs](image1)

![Figure 2. Schematic diagram of two PMSGs’ interaction](image2)

Based on the structural block diagram shown in figure 2, the interaction model between two PMSGs is established to analyze the terminal voltage stability. In order to simplify the analysis and obtain effective conclusions, the following assumptions are made: (1) the current loop bandwidth is much larger than the voltage control bandwidth, so the dynamic influence of the current loop is ignored\cite{8}; (2) the whole system is lossless; (3) the two PMSGs are identical. So this paper takes unit 1 as an example to deduce its model.

The system shown in figure 1 is disturbed, and the terminal voltage phase of unit 1 is ahead of the steady state phase by a small angle. Due to the dynamic characteristics of PLL, the phase change of terminal voltage of unit 1 can not be tracked immediately, and the phase-locked angle $\theta_{\text{pll1}}$ is slightly larger than the terminal voltage phase $\theta_{\text{t1}}$. Therefore, the transformation relationship of terminal voltage vectors of unit 1 between dq axis coordinate system and xy axis coordinate system is as follows:

\[
\begin{bmatrix}
    u_{w1} \\
    u_{y1}
\end{bmatrix} =
\begin{bmatrix}
    \cos \theta_{\text{pll1}} & -\sin \theta_{\text{pll1}} \\
    \sin \theta_{\text{pll1}} & \cos \theta_{\text{pll1}}
\end{bmatrix}
\begin{bmatrix}
    u_{w1} \\
    u_{y1}
\end{bmatrix}
\]  \tag{1}
Where: $u_{t1}$ and $u_{t2}$ represent $xy$ axis component of unit 1’s terminal voltage, $u_{d1}$ and $u_{d2}$ represent $dq$ axis component. In the same way, we can get the relation of current vector $\vec{I}_1$ from $dq$ axis to $xy$ axis.

From figure 1, the terminal voltage equation of the two units can be obtained as follows:

$$U_{\theta} = jX_u I_{\theta} + jX_i \sum_{i=1}^{2} I_{\theta} + U_g \angle \theta$$  \hspace{1cm} (2)

Where $i=1,2$.

Equation (2) is transformed into $xy$ axis coordinate system and linearized:

$$\begin{align*}
\Delta u_{t1} &= -X_u \Delta i_1 - X_g \sum_{i=1}^{2} \Delta i_{yi} \\
\Delta u_{t2} &= X_u \Delta i_2 + X_g \sum_{i=1}^{2} \Delta i_{yi}
\end{align*}$$  \hspace{1cm} (3)

Then the linearization of equation (1) is transformed into equation (3), and transmission line current and terminal voltage are transformed from $xy$ axis coordinate system to $dq$ axis coordinate system:

$$\begin{align*}
\Delta u_{k1} &= k_{i_1} \angle \Delta i_{d1} + k_{i_2} \angle \Delta i_{q1} + k_{i_3} \angle \Delta \theta_{pl1} + k_{i_4} \angle \Delta i_{d2} + k_{i_5} \angle \Delta i_{q2} + k_{i_6} \angle \Delta \theta_{pl2} \\
\Delta u_{k2} &= k_{i_1} \angle \Delta i_{d2} + k_{i_2} \angle \Delta i_{q2} + k_{i_3} \angle \Delta \theta_{pl2} + k_{i_4} \angle \Delta i_{d1} + k_{i_5} \angle \Delta i_{q1} + k_{i_6} \angle \Delta \theta_{pl1}
\end{align*}$$  \hspace{1cm} (4)

The generator terminal voltage is linearized, and the equation (4) is substituted into equation (5):

$$\begin{align*}
\Delta U_{t1} &= \frac{u_{d10}}{u_{t10}} \Delta u_{d1} + \frac{u_{q10}}{u_{t10}} \Delta u_{q1} \\
\Delta U_{t2} &= \frac{u_{d20}}{u_{t20}} \Delta u_{d2} + \frac{u_{q20}}{u_{t20}} \Delta u_{q2}
\end{align*}$$  \hspace{1cm} (5)

By using DC voltage control and PLL relationship to eliminate $i_{d1}$ and $\theta_{pl1}$ in equation (5), the relationship between $U_{t}$ and $i_{q1}$ is constructed and expressed in matrix form as follows:

$$\begin{bmatrix}
\Delta U_{t11} & \Delta U_{t12} \\
\Delta U_{t21} & \Delta U_{t22}
\end{bmatrix} =
\begin{bmatrix}
D_{11}(s) & D_{12}(s) \\
D_{21}(s) & D_{22}(s)
\end{bmatrix}
\begin{bmatrix}
\Delta i_{q1} \\
\Delta \theta_{pl2}
\end{bmatrix}$$  \hspace{1cm} (6)

Thus, the interaction block diagram of two PMSGs under terminal voltage control can be obtained as follows:

Figure 3. Small signal model of interaction between two PMSGs under terminal voltage control

In the definition equation (6), the main diagonal elements $D_{11}(s)$ and $D_{22}(s)$ are the self influence components, while the sub-diagonal elements $D_{12}(s)$ and $D_{21}(s)$ are the interaction components. The larger the amplitude and phase lag of $D_{12}(s)$ and $D_{21}(s)$, the greater the interaction between units. Next, the influence of control link on the interaction between two DPSGs is studied from the perspective of bandwidth and damping ratio.
3. Analysis of the influence of control parameters on the interaction between two PMSGs

PMSG control involves multiple controllers cooperating with each other to achieve flexible control and stable operation according to the expected objectives. It can be seen from equation (6) that the interaction between the two units is affected by PLL, DC voltage loop and other links. The frequency domain characteristics of each controller body are determined by its control bandwidth and damping ratio performance index.

The PLL closed-loop transfer function and equivalent second-order system in typical control structure of PMSG are as follows:

\[ T_{\text{pll}}(s) = \frac{k_{pp}s / U_i + k_{pi}}{s^2 + U_i k_{pp}s + U_i k_{pi}} = \frac{2\xi_{\text{pll}}\omega_n s + \omega_n^2}{s^2 + 2\xi_{\text{pll}}\omega_n s + \omega_n^2} \]  

(7)

Where: \( k_{pp} \) and \( k_{pi} \) are the proportional and integral coefficients of the PLL; \( U_i \) is the fundamental frequency voltage; \( \omega_n \) is the natural frequency. According to \( T_{\text{pll}}(s) \) relation, we can get the following results:

\[
\begin{align*}
\xi_{\text{pll}} &= \frac{k_{pp}}{2\sqrt{k_{pi}}} \\
\omega_n &= \sqrt{\frac{U_i k_{pi}}{1 + \frac{4\xi_{\text{pll}}^2}{\omega_n^2} - 2\xi_{\text{pll}}^2}}
\end{align*}
\]  

(8)

Where \( \omega_n \) is the control bandwidth of PLL, \( \omega_n = 2\pi f_{\text{pli}} \). According to equation (8), different control characteristics can be obtained by selecting different bandwidth \( f_{\text{pli}} \) and damping ratio \( \xi_{\text{pli}} \). Similarly, the bandwidth \( f_{\text{dc}} \) and damping ratio \( \xi_{\text{dc}} \) of DC voltage loop can be obtained. From the perspective of bandwidth and damping ratio, the influence of PLL and DC voltage loop on the interaction component \( D_{12}(s) \) is analyzed, and then the interaction law of control link between two units is studied.

3.1. Influence of PLL bandwidth and damping ratio on the interaction between two PMSGs

According to the structural block diagram shown in figure 1, the grid connection model of two PMSGs is established on MATLAB software. The main electrical and control parameters are shown in Table 1. Next, the influence of PLL on the interaction between two units is studied from the perspective of bandwidth and damping ratio.

| Parameter | Value | Parameter | Value |
|-----------|-------|-----------|-------|
| Rated voltage \( U_1/V \) | 690 | Filter inductance \( L/mH \) | 1.5 |
| fundamental frequency \( f_1/Hz \) | 50 | Rated power \( P/MW \) | 1.5 |
| Rated current \( I_1/A \) | 1500 | Damping resistance \( R_{fw}/ \) | 1 |
| DC bus voltage \( U_{dc}/V \) | 1100 | Filter capacitor \( C_{fw}/mF \) | 1 |
| DC bus capacitance \( C_{dc}/mF \) | 90 | PLL \( (k_{pp},k_{pi}) \) | 60,1400 |
| AC voltage control \( (k_{ac},k_{vi}) \) | 2.80 | DC voltage control \( (k_{ac},k_{vi}) \) | 1.1,27.5 |

When the PLL control parameters of the two units are \( k_{pp}=60, k_{pi}=1400 \), and other electrical parameters are of P.U. value, according to equation (8), the PLL bandwidth is \( f_{\text{pli}}=13Hz \), and the damping ratio \( \xi_{\text{pli}}=0.802 \). Firstly, keeping the PLL bandwidth and damping ratio of unit 1 unchanged, and keeping the PLL damping ratio of unit 2 at 0.802, changing the PLL bandwidth of unit 2 to observe the bode diagram of the interaction component \( D_{12}(s) \); Then keeping the bandwidth unchanged, changing its damping ratio to observe the bode diagram of the interaction component \( D_{12}(s) \):
The interaction component corresponding to changing the PLL bandwidth

The interaction component corresponding to changing the PLL damping ratio

Figure 4. The influence of bandwidth and damping ratio of PLL on $D_{12}(s)$

It can be seen from figure 4 that when the PLL bandwidth and damping ratio of the two units are the same, the amplitude and phase lag in the bode diagram of the interaction component $D_{12}(s)$ are the largest, which means that the interaction between the two units is the greatest. Therefore, it can be concluded that: (1) due to the influence of the interaction between the two units, the interaction between the units first increases and then decreases with the increase of the bandwidth and damping ratio of PLL of the unit 2; (2) when the bandwidth and damping ratio of PLL of the two units are identical, the interaction between the units is the greatest.

3.2. Influence of DC voltage loop bandwidth and damping ratio on the interaction between two PMSGs

When the DC voltage loop control parameters of the two units are both $k_{vp}=1.1$, $k_{pi}=27.5$, and other electrical parameters are of P.U. value, according to equation (8), the DC voltage loop bandwidth is $f_{dc}=5\text{Hz}$, $\xi_{dc}=0.350$. Firstly, keeping the DC voltage loop bandwidth and damping ratio of unit 1 unchanged, and keeping the damping ratio of unit 2 at 0.350, changing its bandwidth, and then keeping the bandwidth of unit 2 at 5Hz, changing its damping ratio to observe the bode diagram of interaction component $D_{12}(s)$:

Figure 5. The influence of bandwidth and damping ratio of DC voltage loop on $D_{12}(s)$

It can be seen from figure 5 that when the DC voltage loop width of two units is the same, the amplitude and phase lag of the bode diagram of $D_{12}(s)$ is the largest, which means that the interaction between the two units is the greatest. With the increase of DC voltage loop damping ratio of unit 2, the amplitude and phase lag in bode diagram of $D_{12}(s)$ gradually decrease, which means that the interaction between the two units is gradually reduced. Therefore, it can be concluded that: (1) when the bandwidth of DC voltage loop of the two units are identical, the interaction between the units is the greatest; (2) the interaction between two units gradually decreases with the increase of damping ratio of DC voltage loop of unit 2.
4. Simulation verification

In order to verify the rationality of the above theoretical analysis and modeling, according to the structural block diagram shown in figure 1, a simulation model of the two PMSGs connected in parallel to infinite power supply is built on the MATLAB/Simulink simulation platform. The main electrical and control parameters are shown in table 1. Firstly, the system works in a stable state, and the grid disturbance (load suddenly increases) occurs in 5s. The changes of electrical state parameters in the model are observed.

4.1. Simulation results show that the influence of PLL bandwidth and damping ratio on the interaction between units

Firstly, the simulation keep the PLL bandwidth and damping ratio of unit 1 unchanged, and keep the PLL damping ratio of unit 2 at 0.802, change the PLL bandwidth of unit 2, and then keep the PLL bandwidth of unit 2 at 13Hz, change its damping ratio, and the corresponding output active power waveforms of the two units are shown in the following figure:

![The output active power waveform corresponding to changing the bandwidth and damping ratio of PLL](image)

Figure 6. The output active power waveform corresponding to changing the bandwidth and damping ratio of PLL

It can be seen from figure 6 that when the PLL bandwidth and damping ratio of the two units are gradually close to the same, the active power output waveform from the interconnected system oscillates to the divergent state, indicating that the stability of the system due to interaction is the worst at this time. Then, as the bandwidth and damping ratio of the PLL of the two units are gradually far away, the stability of the system is enhanced. This is the same as the theoretical analysis results in figure 4, which verifies the effectiveness of the interaction component model and mechanism analysis.

4.2. Simulation results show that the influence of DC voltage loop bandwidth and damping ratio on the interaction between units

Firstly, the simulation keep the DC voltage loop bandwidth and damping ratio of unit 1 unchanged, and keep the DC voltage loop damping ratio of unit 2 at 0.350, change the PLL bandwidth of unit 2, and then keep the PLL bandwidth of unit 2 at 5Hz, change its damping ratio, and the corresponding output active power waveform of the two units is shown in the following figure:
The output active power waveform corresponding to changing the DC voltage loop bandwidth

Figure 7. The output active power waveform corresponding to changing the bandwidth and damping ratio of DC voltage loop

It can be seen from figure 7 that when the DC voltage loop bandwidth of the two units is gradually approaching the same, the active power output waveform from the interconnected system oscillates to the divergent state, indicating that the stability of the system due to interaction is the worst at this time. At the same time, with the increase of damping ratio of DC voltage loop of unit 2, the stability of interconnected system is gradually enhanced. This is the same as the theoretical analysis results in figure 5, which verifies the effectiveness of the interaction component model and mechanism analysis.

5. Conclusion

In this paper, a model of interaction between the two units under terminal voltage control is established. The influence of PLL and DC voltage loop on the interaction between the two units is analyzed from the perspective of bandwidth and damping ratio of closed-loop control system. The effectiveness of the proposed model and mechanical analysis is verified by simulation. Through the theoretical and simulation analysis, it is shown that:

(1) With the increase of PLL bandwidth and damping ratio of unit 2, the interaction between the two units first increases and then decreases, leading to the weakening and then enhancement of system stability; when the bandwidth and damping ratio of PLL are identical, the interaction between units is the largest, resulting in the system stability is the worst;

(2) The interaction between the two units first increases and then decreases with the increase of DC voltage loop bandwidth of unit 2, and when the bandwidth is equal, the interaction between units is the largest, resulting in the system stability is the worst; the interaction between the two units gradually decreases with the increase of DC voltage loop damping ratio of unit 2, resulting in the system stability gradually enhanced.

In the following research, according to the analysis conclusion of this paper, the measures to suppress the oscillation of wind turbines due to interaction will be further studied.

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