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Wide-area synthetic inertia control of multiple resources incorporating primary frequency control of wind turbines

Chen Xu¹, Xiaodong Chu¹,²* and Haoyi Huang²

¹School of Electrical Engineering, Shandong University, Jinan, China
²China Energy Engineering Group Zhejiang Electric Power Design Institute Co. Ltd, Hangzhou, China

*Corresponding author e-mail: chuxd@sdu.edu.cn

Abstract. With a large proportion of renewable energy sources integrated through the power electronics interface, power systems are challenged with decreased inertia threatening the system stability. Synthetic inertia control aims to emulate inertial response of various available resources. A wide-area synthetic inertia control strategy for multiple resources is proposed in this paper. The offshore wind farm composed of DFIG wind turbines is interconnected by the VSC-HVDC link. Synchronous condensers are installed to improve the system dynamic characteristics. Synthetic inertia control is designed for DFIG wind turbines, VSC-HVDC link and synchronous condensers, respectively. Wide-area frequency signal is employed to overcome the limitation of local signal. Primary frequency control support by DFIG wind turbines is incorporated to improve the control effect of the strategy. Simulation results on New England 39-bus system verify the effectiveness of the proposed wide-area synthetic inertia control strategy.

1. Introduction

The continuous increase of renewable energy has become a development trend of the future power system, but the reduction of traditional generators will reduce the inertia level of power system, which is not conducive to the stability of the system. Therefore, how to use various resources to participate in the frequency regulation of the system more accurately and efficiently is particularly important.

The emerging energy is mainly dominated by wind power. We can set relevant control strategies to make the wind farm participate in the frequency modulation in the AC grid, and we will build a simulation model to verify the validity of frequency modulation of DFIG in this paper. However, the offshore wind farm is usually connected to the power system through VSC-HVDC, which directly decouples the frequency between the power system and the wind farm. Therefore, the method of DFIG participating in the system frequency modulation in the AC grid cannot be directly used. In view of the above proposed, reference [1-2] propose a control strategy of coupling offshore wind farm frequency and onshore AC grid frequency manually, but they haven’t considered the inertial response characteristics provided by the wind farm. Reference [3] shows a strategy of using the energy of the DC capacitor to simulate the inertial time constant of traditional generators so that the energy stored in DC capacitor can be used to participate in the active power regulation of the system. Considering all deficiencies above, reference [4] proposes a synthetic inertia control strategy using the DC capacity and the rotor kinetic energy of the DFIG, which can provide large scale inertial support for the grid in case of any disturbances. However, for a large power system, when disturbance occurs, differences in...
geographical locations will cause differences in frequency changes between the different regions. The control strategy proposed in reference [4] uses the local frequency signal of the fault point cannot guarantee all sources respond to the frequency deviation accurately and efficiently.

Reference [5-7] shows the control strategy of modifying the active reference value of DFIG by using the droop control and the virtual inertia control always used in the AC grid, respectively. Reference [8] shows the slow homology group theory, which describes that all the generators in the power system are divided into several groups, and the information of the dominant generator sets of those groups is extracted to form the wide-area information. The wide-area information will reduce the limitation of the local information to a certain extent, which will improve the calculation accuracy.

This paper mainly studies the synthetic inertia control strategy of three kinds of resources and then designs the synthetic control mechanism based on the wide-area signal. Section 2 introduces the control mechanism of DFIG, VSC-HVDC and synchronous condenser responding to the active power fluctuation of the system, respectively. The synthetic control strategy of the DFIG and VSC-HVDC is also introduced in section 2. Section 3 describes the wide-area synthetic control strategy of three kinds of resources based on the slow coherency grouping principle and the wide-area frequency signal for a large power system. In section 4, the validity of DFIG participating system primary frequency modulation will be verified, and three inertial resources are connected to the IEEE39-bus system to verify the validity of the wide-area synthetic inertia control strategy based on the wide-area signal.

2. Synthetic inertia control of multiple inertial resources.

2.1. Inertial support by DC capacitor of PSVSC

In power systems including VSC-HVDC, the variation of the DC voltage reflects the active power unbalance between the rectifier side and inverter side of the HVDC. The DC capacitor of the power system side VSC (PSVSC) can respond to the frequency deviation of the system by absorbing or releasing energy. The dynamic characteristic of the DC capacitance of PSVSC is expressed as:

$$CU_z \frac{dU_z}{dt} = P_{WS} - P_{PS}$$  \hspace{1cm} (1)

$$C = \frac{C_z U_{ZN}^2}{S_N}$$  \hspace{1cm} (2)

where $U_z$ and $U_{ZN}$ are the reference value and rated value of the DC voltage, $S_N$ is the rated capacity of the system, $C$ and $C_z$ are the equivalent capacitance and the total capacitance of DC capacitor, $P_{WS}$ and $P_{PS}$ are the active power transmitted to the PSVSC and the power system. Equation (1) shows that the change of DC voltage of VSC-HVDC causes the energy change of DC capacitor, so the control strategy can be designed to make the DC capacitor provide certain inertial support for the system.

In the power system, synchronous generators can respond to the imbalance between the load and power generation by using their mechanical inertia, and the process can be described as:

$$2H \frac{d\omega}{dt} = \Delta P$$  \hspace{1cm} (3)

where $H$ is the inertial time constant of the synchronous generator, $\omega$ is the rotor speed of the generator, and $\Delta P$ is the difference value between the mechanical power and electromagnetic power.

Analogous to the relationship between the inertial time constant and the active power deviation of synchronous generator shown in equation (3), the DC voltage of the capacitor can be analogized to the rotor speed. The synchronous generator’s rotor speed corresponds to its own mechanical inertia, but the DC voltage reflects the virtual inertia provided by the DC capacitor, which can be described as:

$$CU_z \frac{dU_z}{dt} = 2H_z \frac{df}{dt}$$  \hspace{1cm} (4)

where $H_z$ is the equivalent inertial time constant provided by VSC. Integrating both sides of the equation (4), and then using Taylor expansion at $U_{Z0}$:

$$\int_{U_{Z0}}^{U_z} CU_z dU_z = \int_{f_0}^{f} 2H_z df$$  \hspace{1cm} (5)
where \( U_{Z0} \) and \( f_0 \) are the balanced points of the DC voltage and frequency of the power system, and then the new DC voltage slip control variable can be described as:

\[
U'_Z = K_Z \Delta f + U_{Z0}
\]

where \( K_Z \) is the control parameter decided by the inertial time constant value of the VSC.

2.2. Primary frequency control of DFIG

VSC-HVDC decouples the frequency between the wind farm and the power system. Corresponding control strategies must be adopted to make the wind farm feel the power system frequency fluctuation. Considering that the DC voltage at both sides of the VSC are consistent and the wind farm VSC (WSVSC) can work under variable frequency conditions, so the coupling of the system frequency with the WSVSC frequency can be established by the DC voltage of the capacitor. PSVSC can use DC voltage slip control to transform the change of system frequency into the change of DC voltage shown in equation (6), and then into the change of WSVSC frequency as follows:

\[
\Delta f_{WS} = K_{WS} \Delta U_Z
\]

\[
\Delta f_{WS} = K_Z K_{WS} \Delta f
\]

where \( \Delta f_{WS} \) is the frequency deviation of WSVSC, \( \Delta f \) is the frequency deviation of power system, \( K_Z \) reflects the proportion of frequency deviation of WSVSC and DC voltage deviation which is always set as a constant value. So the frequency conversion control of WSVSC can be expressed as:

\[
f_{WS} = \Delta f_{WS} + f_{WS0}
\]

where \( f_{WS0} \) is the initial frequency of the WSVSC.

The control of the active power and reactive power of the DFIG are decoupled, and the active power reference command can be modified through the additional frequency control so that the DFIG can have satisfactory frequency modulation effect on the power system. In this paper, we assume that DFIG runs in sub-optimal power state so that DFIG has a certain active power margin to respond to the change of system frequency. Referring to the control strategies of DFIG participating in the primary frequency control shown in [5-7], and the auxiliary active power reflecting the frequency deviation and frequency deviation derivative will be added to the active power instruction to modify the reference value of the active power, so that DFIG can adjust the active power instruction to respond to the frequency deviation of the system. The control frame is shown as Figure 1:

![Control frame of DFIG participating in primary frequency regulation](image)

**Figure 1.** Control frame of DFIG participating in primary frequency regulation

The offshore wind farm will adopt the strategies of DFIG participating in the frequency control in AC system, however, the power system frequency has decoupled with the wind farm frequency indirectly by HVDC, so the WSVSC frequency change will be used as a frequency signal of DFIG participating in frequency modulation instead of the power system frequency. The auxiliary active power can be expressed as:

\[
P_{4D} = K_{df} \frac{d\Delta f_{WS}}{dt} + K_{pf} \Delta f_{WS}
\]

where \( K_{df} \) weights the frequency deviation derivative while \( K_{pf} \) weights the frequency deviation.
2.3. Synthetic inertia control of synchronous condenser

When the synchronous generator operates in the power system as a synchronous condenser, we can use its own mechanical inertia to respond to the system frequency deviation according to appropriate control strategies. The variable speed synchronous condenser (VSSC) can not only respond to the change of the reactive power, but the kinetic energy stored in its rotor can absorb or input active power to the system so as to respond to the frequency fluctuation of the system. The kinetic energy stored in rotor of VSSC is described as:

\[ W_{VS} = \frac{1}{2} J \omega_V^2 / \rho^2 \]  

(12)

\[ \Delta W_{VS} = W_{VS2} - W_{VS1} \]  

(13)

where \( W_{VS} \) and \( \omega_V \) are the kinetic energy and the angular velocity of VSSC rotor, \( J \) is the rotation inertia, \( \rho \) is the pole logarithm of synchronous generator, \( W_{VS1} \) and \( W_{VS2} \) are the kinetic energy with the rotational speed at \( \omega_{V1} \) and \( \omega_{V2} \), respectively.

Equations (12) and (13) show that when rotor speed decreases, the stored kinetic energy in the rotor will be transferred to the power system in the form of active power, while when the system has active power surplus, VSSC will absorb active power from the system and store it in form of kinetic energy. Therefore, the change of rotor speed of VSSC affects active power output. Corresponding control strategy can be designed to make VSSC provide certain inertial support for the power system.

By controlling the q-axis component of the rotor current of VSSC, we can control the active power output independently. Therefore, adjusting the q-axis component of rotor current can adjust its power output to respond to the fluctuation of system frequency, the process can be described as:

\[ \Delta I_q = K_f \Delta f \]  

(14)

\[ I_q = I_{q0} + \Delta I_q \]  

(15)

where \( \Delta I_q \) is the deviation of the q-axis component of the rotor current of VSSC, \( K_f \) is the proportion of \( \Delta I_q \) and the power system frequency deviation, \( I_{q0} \) is the initial value of the current control.

3. Wide-area inertia control strategy

Different resources use the acquired local frequency signals to participate in the frequency regulation, but for a large power system, different geographical locations will result in differences in frequency variation between different regions of the system when disturbance occurs. In order to eliminate the limitation of local signals, this paper proposes a control mechanism based on the wide-area information, which can reflect the overall dynamic characteristics of the power system.

The wide area monitoring system (WAMS) can grant a uniform time standard to the collected data with high accuracy, but the PMU is expensive and can only be configured on key buses of the system. Based on the slow homology principle in reference [7], the generators of the power system are clustered and the dominant generators in the cluster are extracted as the PMU mounting targets. Setting the number of system slow homology groups as \( r \), the frequency obtained by PMU at the dominant unit of the i-th cluster is \( f_i \), and the frequency signal of the whole system can be shown as:

\[ f_w = \sum_{i=1}^{r} g_i f_i \]  

(16)

where \( f_w \) is the frequency signal of the whole system based on the wide-area information and \( g_i \) is the weighting coefficient of the i-th slow homology generator group relative to the whole power system which satisfies the equation shown as:

\[ g_i = \frac{\sum_{j=1}^{k_i} T_{ij} S_{Nj}}{\sum_{j=1}^{k_i} \sum_{j=1}^{Nj} T_{ij} S_{Nj}} \]  

(17)

where \( k_i \) is the number of units in the i-th slow coherency generator group, \( T_{ij} \) is the inertial time constant of the j-th generator in the i-th slow coherency generator group, and \( S_{Nj} \) is its rated capacity.
The key of the synthetic inertia control mechanism shown in 2.1. is to make the voltage of DC capacitance respond to the change of system frequency. According to the equation (6), the voltage deviation of the DC voltage slip control based on the wide-area information can be expressed as:

$$\Delta U_{ZW} = K_{ZW} \Delta f_w$$  \hspace{1cm} (18)

where $K_{ZW}$ is the Wide-area control parameter decided by the equivalent inertial time constant value of the PSVSC.

When the disturbance occurs in the power system region connected to the VSC-HVDC, the local frequency signal is highly fluctuated but the wide-area signal obtained is relatively weak. If only the wide-area signal is adopted, the inertial support provided by VSC-HVDC will not be able to respond to the active fluctuation better. Therefore, the local signal and the wide-area signal are both required to participate in the frequency regulation, and the DC voltage slip control of PSVSC will be modified:

$$U_{ZW}^* = g_a K_z \Delta f + h_a K_{ZW} \Delta f_w + U_{Z0}$$  \hspace{1cm} (19)

where $g_a$ is the weighting coefficient of the a-th slow coherence group connected with VSC-HVDC, and $h_a$ satisfies $h_a = 1 - g_a$, $U_{Z0}$ is the initial value of the DC voltage.

Similar to the wide-area inertia control of VSC-HVDC, the wide-area synthetic inertia control of DFIG can also be designed. The $P_{AD}$ in equation (11) will be revised as:

$$P_{AD}^* = g_b \frac{d \Delta f_{WS}}{dt} + K_{df} h_b \frac{d \Delta f_w}{dt} + K_{pf} g_b \Delta f_{WS} + K_{pfw} h_b \Delta f_w$$  \hspace{1cm} (20)

where $g_b$ is the weighting coefficient of the b-th slow coherence group connected with the DFIG, $h_b$ satisfies $h_b = 1 - g_b$, $\Delta f_{WS}$ is the local frequency deviation of WSVSC, $\Delta f_w$ is the acquired wide-area frequency signal deviation.

For the wide-area inertia control of VSSC, the proportional controller is used to make the current control of VSSC respond to both the local and wide-area frequency signals. Based on the equation (14), the current deviation in VSSC wide-area inertia control can be modified as:

$$\Delta I_{rW} = K_{CW} \Delta f_w$$  \hspace{1cm} (21)

where $K_{CW}$ is the control parameter of the proportional controller. Referring to the equations (4), (5) and (15), the modified VSSC current control reference value is expressed as:

$$I_{rW}^* = g_c \Delta I_r + h_c \Delta I_{rW} + I_{V0}$$  \hspace{1cm} (22)

where $g_c$ is the weighting coefficient of the c-th slow coherence group collected with the VSSC and $h_c$ satisfies $h_c = 1 - g_c$, $I_{V0}$ is the initial reference value of the current control of VSSC.

The wide-area synthetic inertia control diagram of the three resources is shown in Figure 2, which adopts both the local and wide-area frequency signals.

![Figure 2. Wide-area coordinated control diagram](image-url)
4. Simulation results

4.1. DFIG participating in primary frequency control

The simulation model on the PowerFactory which consists of two DFIGs with rated power of 2.5MW respectively, a synchronous generator with automatic voltage regulator and governor, and its rated capacity is 8MW, load 1 with rated power of 10 MW, and load 2 is 1.5WM. Load 2 is disconnected at t=5s. The control parameters are adjusted to study the influence of the frequency control of DFIG.

![Figure 3](image1.png)

**Figure 3.** Output of DFIG with frequency control

![Figure 4](image2.png)

**Figure 4.** Frequency of system with different $K_{df}$

As shown in Figure 3 and 4, the active power output of DFIG is obviously reduced when load 2 is cut out so that the frequency fluctuation of the system is significantly reduced. What’s more, the effect of frequency modulation of DFIG is related to the droop coefficient.

4.2. Wide-area synthetic inertia control

New England 39-bus test system is built in PowerFactory. VSSC with rated power of 350MW is connected with bus 5, the wind farm with rated active power of 650MW formed by 20 DFIGs is connected with the 35-th bus through VSC-HVDC, which replaces the 6-th synchronous generator set. The topology diagram of the simulation case is shown as:

![Figure 5](image3.png)

**Figure 5.** Schematic of New England 39-bus test system

The validity of the wide-area synthetic inertia control strategy to improve the stability of the system is verified as shown in figure 6. The 4-th synchronous generator is cut out at t=2s. The simulation results will verify the validity of wide-area synthetic control on frequency fluctuation suppression under different control conditions. Figure 6 verifies the effectiveness of wide-area synthetic inertial control, Figure 7, Figure 8 and Figure 9 studies the effect of the wide-area synthetic inertia control with different control parameters of $K_{CW}$, $K_{pfw}$ and $K_{ZB}$, respectively.
5. Conclusion
A wide-area synthetic inertia control strategy for multiple resources is proposed in this paper. DFIGs, VSC-HVDC and synchronous condensers are equipped with synthetic inertia control, respectively. Wide-area frequency signal is employed to overcome the limitation of local signal. Primary frequency control support by DFIGs is incorporated to improve the control effect of the strategy. Simulations show that the primary frequency modulation of DFIG and the wide-area synthesis control strategy have improved the stability of the system, and the influence of different control parameters on the control effect is also studied.

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