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Impact of Offshore Wind Power Integrated by VSC-HVDC on Power Angle Stability of Power Systems

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Abstract: Offshore wind farm connected to grid by VSC-HVDC loses frequency support for power system, so adding frequency control in wind farm and VSC-HVDC system is an effective measure, but it will change wind farm VSC-HVDC's transient stability on power system. Through theoretical analysis, concluding the relationship between equivalent mechanical power and electromagnetic power of two-machine system with the active power of wind farm VSC-HVDC, then analyzing the impact of wind farm VSC-HVDC with or without frequency control and different frequency control parameters on angle stability of synchronous machine by EEAC. The validity of theoretical analysis has been demonstrated through simulation in PSCAD/EMTDC.

1. Introduction

Offshore wind farm connected to AC grid by VSC-HVDC can save offshore platform space and reduce wind power fluctuations, so VSC-HVDC becomes the best way to transmit power from offshore wind farm to grid on land [1]. To guarantee the safety and stability of power system operation, we hope wind power can provide the ability of inertia and active/reactive power support [2]. However, HVDC decouples the offshore wind farm and AC grid on land, wind power can hardly provide frequency support. In order to solve this problem, author in [3] designed three frequency controllers to maintain the frequency stability on the AC bus of VSC, and compared the advantages and disadvantages of the three frequency controllers. In [4], a coordinated control strategy between GSVSC, WFVSC and wind turbine side was employed to make wind farm VSC-HVDC involve in frequency control initiatively.

At present, the transient stability of wind power accessed to grid on power system mainly focused on HVAC accessing, and less on VSC-HVDC. Author in [5] analysed different penetration of wind power impact on transient angle stability. Proposed a novel control strategy by changing the active power of DFIG in fault to improve transient stability of power system in [6]. Reference [7] adopted a supplementary control to coordinate the operation of wind turbines. Reference [8, 9] proposed a criterion to judge whether the wind power penetration was beneficial to the power system transient angle stability or not. Author in [10] analysed the effect of wind farm on transient stability by equalling the value of wind turbines power to the mechanical power of synchronous machine based on EEAC. Wind farm VSC-HVDC as a power electronic control system with multi-parameters, its process of electromechanical and electromagnetic transient is complex, and becomes more

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complicated after adding frequency control in the system. So it is necessary to take deep research on this problem.

This paper firstly built the models of wind farm and VSC-HVDC, then elicited the relationship between equivalent mechanical power and electromagnetic power of two-machine system with the active power of wind farm VSC-HVDC then analysing the impact of wind farm VSC-HVDC with or without frequency control and different frequency control parameters on angle stability of synchronous machine by EEAC.

2. System Models

2.1. Models of PMSG

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PMSG includes wind turbine, permanent magnet synchronous generator and full power converters. Mechanical power of wind turbine is:

$$P_w = 0.5\rho\pi R^2 v^3 C_p(\lambda,\beta) \tag{1}$$

P_w-mechanical power, ρ-air density, R-turbine radius, v-wind speed, C_p-rotor power coefficient, λ-tip speed ratio, β-pitch angle.

Mathematical model of PMSG in d-q coordinate system, the stator voltage equation is:

$$\begin{cases} \dfrac{di_d}{dt} = -\dfrac{R_a}{L_d} i_d + \omega_e \dfrac{L_q}{L_d} i_q + \dfrac{1}{L_d} u_d \\ \dfrac{di_q}{dt} = -\dfrac{R_a}{L_q} i_q - \omega_e \left(\dfrac{L_d}{L_q} i_d - \dfrac{1}{L_q} \psi_0 \right) + \dfrac{1}{L_q} U_q \end{cases} \tag{2}$$

i_d-d-axis current, i_q-q-axis current, L_d-d-axis inductance, L_q-q-axis inductance, R_a-resistance of stator, ω_e-electrical angular velocity, ψ_0-flux linkage, n_p-number of pole-pairs, u_d-d-axis voltage, u_q-q-axis voltage.

Electromagnetic torque equation of wind turbine is:

$$T_m = 1.5 n_p \left[\left(L_d - L_q \right) i_d i_q + i_q \psi_0 \right] \tag{3}$$

The main purpose of generator side control is to realize the active and reactive power decoupling. In Fig.1 (a), d-axis controls i_{dref}=0, q-axis employs active power control to track the maximum power of wind turbine.

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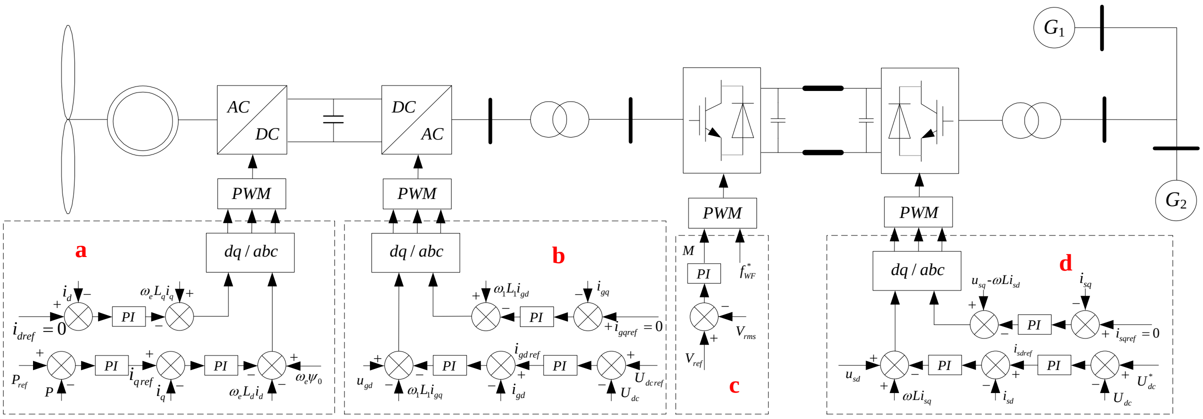

Figure 1. PMSG system of integrated by VSC-HVDC diagram

The mathematical model of converter of wind turbine in grid side is:

$$\begin{cases} U_{cd} = U_{gd} - \omega L i_{gq} - R i_{gd} - L\dfrac{di_{gd}}{dt} \\ U_{cq} = U_{gq} + \omega L i_{gd} - R i_{gq} - L\dfrac{di_{gq}}{dt} \end{cases} \tag{4}$$

The main purpose of converter in grid side is to stabilize the DC voltage and control reactive power in Fig.1 (b).

2.2. Model of VSC-HVDC

There is no load overseas, so WFVSC can work on the given voltage amplitude and frequency. In Fig.1 (c), M is voltage reference of wind farm converter side, f_{WF}^{*} =50Hz is frequency of the voltage. The mathematical model of GSVSC is similar to the converter in grid side of PMSG, and its control is in Fig.1 (d).

2.3. Frequency Control of Wind Farm VSC-HVDC

This paper uses the frequency control strategy in reference [4], the control was mainly divided into three parts shown in Fig.2:

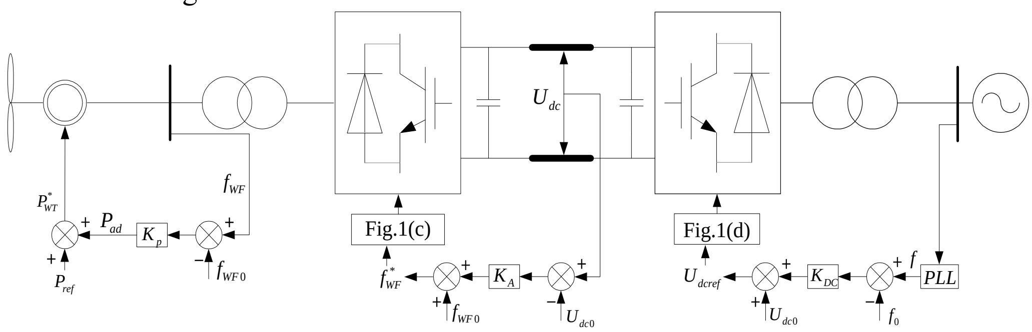

Figure 2. Frequency control strategy of wind farm and VSC-HVDC

I. Using the DC voltage of GSVSC side reflect the change of frequency of power system:

$$U_{dcref} = K_{DC}\Delta f + U_{dc0} \tag{5}$$

U_{dcref} -new DC voltage reference after frequency changes, K_{DC}-control parameter, Δf-frequency fluctuation value, U_{dc0}-balance value of DC voltage.

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II. Make relation between DC voltage and frequency of WFVSC side:

$$\Delta f_{WF} = K_A \Delta U_{dc} \tag{6}$$

$$f_{WF}^{*} = \Delta f_{WF} + f_{WF0} \tag{7}$$

Δf_{WF}, f_{WF} and f_{WF0} is frequency deviation value, frequency reference value and initial frequency value of WFVSC respectively, K_A-control parameter.

III. Changing the active power of wind turbine according to the frequency of WFVSC:

$$P_{ad} = K_P\left(f_{WF} - f_{WF0}\right) \tag{8}$$

$$P_{WT}^{*} = P_{ad} + P_{ref} \tag{9}$$

K_p-control parameter, f_{WF}-real-time frequency of wind farm side.

2.4. Equivalent Model of Grid

For a power system without wind power, the synchronous machines can be divided into two parts (G_1 and G_2) after the power system subjected to a large disturbance, and the two parts follow the motion equations:

$$\begin{cases} \dfrac{M_1}{\omega_0}\dfrac{d^2\delta_1}{dt^2} = P_{m1} - P_{e1} \\ \dfrac{M_2}{\omega_0}\dfrac{d^2\delta_2}{dt^2} = P_{m2} - P_{e2} \end{cases} \tag{10}$$

Furthermore, the two parts can be equivalent to one machine infinite system (OMIS):

$$\frac{d^2\delta}{dt^2} = \frac{\omega_0}{M}\left(P_m - P_e\right) \tag{11}$$

And

$$\begin{cases} M = \dfrac{M_1 M_2}{M_1 + M_2} \\ P_m = \dfrac{M_2}{M_1 + M_2}P_{m1} - \dfrac{M_1}{M_1 + M_2}P_{m2} \\ P_e = \dfrac{M_2}{M_1 + M_2}P_{e1} - \dfrac{M_1}{M_1 + M_2}P_{e2} \end{cases} \tag{12}$$

M_1-inertial time constant of G_1, M_2-inertial time constant of G_2, ω_0-grid frequency, P_{m1}, P_{e1}-mechanical power and electromagnetic power of G_1, P_{m2}, P_{e2}-mechanical power and electromagnetic power of G_2, M-inertial time constant after equivalent, P_m- mechanical power after equivalent, P_e-electromagnetic power after equivalent.

3. Mechanism analysis of transient stability analysis

Make wind farm VSC-HVDC connected to two-machine system in Fig.3, and neglect the resistance of the transmission line, P_W is the active power of wind power VSC-HVDC, P_L is the load, X_W is the reactance between wind power VSC-HVDC to G_1, X_L is the reactance between load to G1, and $K_L=X_L/X$.

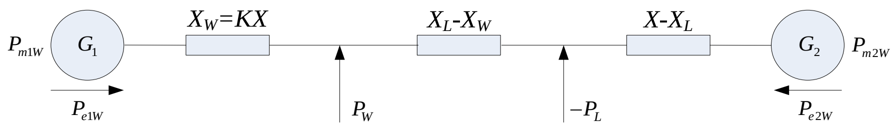

Figure 3. Wind power VSC-HVDC access to two-machine system

The angle difference of the two synchronous machine is:

$$\delta_W = P_{e1W} X - P_L\left(1-K_L\right)X + P_W\left(1-K\right)X \tag{13}$$

So

$$P_{e1W} = \delta_W / X - P_W\left(1-K\right) + P_L\left(1-K_L\right) \tag{14}$$

As $P_{e1}+P_{e2}+P_W = P_L$, there is:

$$P_{e2W} = -\delta_W / X + K_L P_L - K P_W \tag{15}$$

Put equation (14) and (15) into (12):

$$P_{eW} = \delta_W / X + \left(1-\alpha-K_L\right)P_L - \left(1-K-\alpha\right)P_W \tag{16}$$

With regard to mechanical power of synchronous, there is:

$$P_{m1W} = P_{e1} - \beta P_W \tag{17}$$

$$P_{m2W} = P_{e2} - \left(1-\beta\right)P_W \tag{18}$$

P_{e1}, P_{e2} is the electromagnetic power of G_1 and G_2 before the wind power VSC-HVDC accessed to grid, β-power distribution coefficient of synchronous, put equation (17) and (18) into (12), and there is:

$$P_{mW} = P_{e1} - \alpha P_L + \left(2\alpha-\beta\right)P_W \tag{19}$$

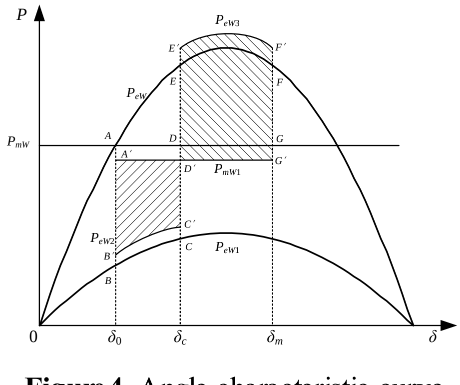

Figure 4. Angle characteristic curve

For the wind power VSC-HVDC with frequency control, active power surplus will result in higher frequency after the fault in power system, and compared with wind power VSC-HVDC without frequency control, wind power with frequency control will automatically reduce active power output based on higher frequency. In equation (16) and (19), if $1\text{-}K\text{-}\alpha>0$ and $2\alpha\text{-}\beta>0$, the equivalent electromagnetic power will increase and the equivalent mechanical power will decrease after the fault, and can be showed in Fig.4.

The accelerate area and decelerate area can be described as A-B-C-D-A and D-E-F-G-D in wind power VSC-HVDC without frequency control after fault; in wind power VSC-HVDC system with

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frequency control, the equivalent electromagnetic power of synchronous machine changed from P_{eW1} to P_{eW2} and mechanical power from P_{mW} to P_{mW1} during the fault, and during the period of recovery after the fault, the equivalent electromagnetic power changed from P_{eW} to P_{eW3}, the equivalent mechanical power can still described as P_{mW1} approximately, so the accelerate area decreased from A-B-C-D-A to A'-B'-C'-D', and the decelerate area increased from D-E-F-G-D to D'-E'-F'-G'-D'. It can be seen that wind power VSC-HVDC with frequency control can improve the transient stability of power system by decreasing the accelerate area and increasing the decelerate area at the same time.

4. Simulation and Analysis

4.1. Effect on the stability of power angle by frequency control

Set up a simulation model showed in Fig 1 in PSCAD/EMTDC, and parameters are α=0.5, β=0.6 and K=0.2. So 1-K-α>0 in equation (16) and 2α-β>0 in equation (19).

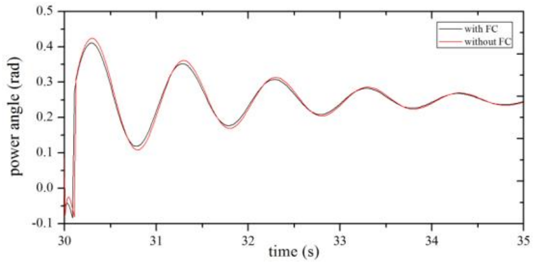


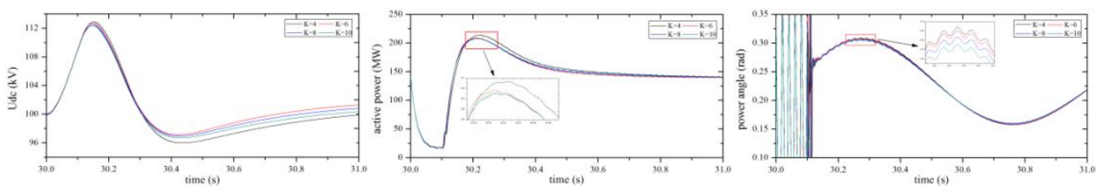
Figure5. Power angle of with and without FC after fault

In Fig.5, the fluctuating margin of wind power VSC-HVDC with FC is less than that without FC, it indicates that wind power VSC-HVDC with FC can improve the transient stability of power system, and the effectiveness of the analysis above.

4.2. Impact of FC parameters on power angle stability

The FC mentioned in 1.3 has three main parameters, GSVSC parameter K_{DC}, WFVSC parameter K_A and WT parameter K_p. This chapter mainly analyses the impact of the three parameters on power angle stability.

4.2.1 GSVSC parameter. Set WFVSC parameter K_A=0.1, WT parameter K_p=-0.8, change the parameter K_{DC} of GSVSC, K_{DC}=4, 6, 8 and 10, compare the effect on the stability of power angle by different K_{DC}.

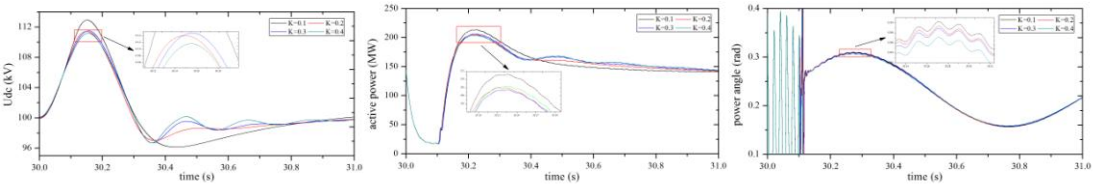


(a) DC voltage (b) Active power (c) Power angle

Figure6. Impact of GSVSC parameters on power system

From Fig.6 we can see, when K_{DC} increases, on the one hand, actual value of DC voltage also will increase, part active power transmitted from wind power are saved in the DC capacity; on the other hand, the wind turbine will decrease active power according to higher DC voltage, and then improve the power angle stability. So, under certain conditions, increasing K_{DC} can enhance transient stability of power system.

4.2.2 WFVSC parameter. Set GSVSC parameter K_{DC}=5, WT parameter K_p=-0.8, change the parameter K_A of WFVSC, K_A=0.1, 0.2, 0.3and 0.4, compare the effect on the stability of power angle by different K_A.

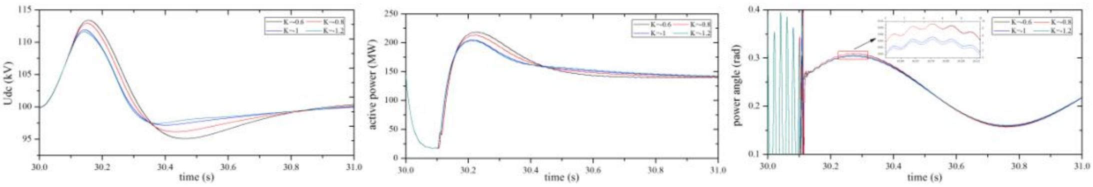


(a) DC voltage (b) Active power (c) Power angle

Figure7. Impact of WFVSC parameters on power system

In Fig.7, the frequency and the DC voltage reference will increase with fault, WFVSC frequency reference increases with the increase of coefficient of K_A and DC voltage, and the wind turbine will decrease more active power, at the same time, the real value of DC voltage will be reduced. The power angle stability improved by the lower active power from the wind turbine. So, in some condition, increasing K_A can enhance transient stability of power system.

4.2.3 WT parameter. Set GSVSC parameter K_{DC}=5, WFVSC parameter K_A=0.1, change the parameter K_P of WT, K_P=-0.6,-0.8,-1.0and-1.2, compare the effect on the stability of power angle by different K_P.



(a) DC voltage (b) Active power (c) Power angle

Figure8. Impact of WT parameters on power system

In Fig.8, After the fault, with the decreasing of K_P, the active power of wind turbine will reduce more, and the DC voltage is the same. The power angle stability improved by the lower active power from the wind turbine. So, in some condition, decreasing K_P can enhance transient stability of power system.

5. Conclusion

This paper built the model of wind power VSC-HVDC with frequency control, elicited the relationship between equivalent mechanical power and electromagnetic power of two-machine system with the active power of wind farm VSC-HVDC and analysed the impact of wind farm VSC-HVDC with or without frequency control and different frequency control parameters on angle stability of synchronous machine. Several conclusions are achieved as follows:

(1) Compared with wind power VSC-HVDC without frequency control, wind power VSC-HVDC with frequency control can improve the transient stability of power system. The main reason is that after the fault, wind power VSC-HVDC with FC automatically decreases the active power itself, it can reduce the decelerate area and at the same time increase the accelerate area.

(2) Different FC parameters can affect transient stability of power system. Under certain conditions, increasing K_A and K_{DC} and decreasing K_P can enhance transient stability of system, the effects of control parameters on stability mainly reflect on different control parameters change the active power output of wind turbine and the energy saved in DC capacitors, these behaviors changed the wind power VSC-HVDC grid-connected power result in the variation of power angle of synchronous.

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