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A TRANSIENT PREVENTIVE CONTROL METHOD FOR WIND POWER-DC TRANSMISSION SYSTEM BASED ON PHASE TRAJECTORY ANALYSIS

Jia Fan[1], Zeng Yuan[1*], Chang Jiangtao[2]

1 Key Laboratory of Smart Grid of Ministry of Education, Tianjin University, Tianjin 300072, China
2 State Grid Shanxi Electric Power Company Maintenance Branch, Taiyuan, Shanxi Province 030000, China

ABSTRACT

In this paper, a transient preventive control method for wind power system, based on the information of generator power angle, angular velocity and voltage, is proposed. The objective function is the minimum of the total control amount. The required preventive control action can be efficiently solved via a linear programming model with the phase trajectory sensitivities-based constraints. The method aims to keep the online preventive transient stability with the wind power integration. The validity of the method is verified through 2DC system.

Keywords: Wind power, DFIG, Phase trajectory analysis, Transient stability preventive control strategy

1. INTRODUCTION

Compared with traditional power generation, wind power generation has many advantages. However, the fluctuation of wind energy itself and the electromechanical characteristics of wind turbines, which are different from thermal power units, have brought difficulties for large-scale wind power grid-connected. What's more, the long distance and large capacity DC transmission project has changed the traditional grid structure. So, the impact of wind power Grid-connected DC outgoing operation mode on system transient security has become a hot issue of current research.

[1] carried out a multi-time scale analysis of the wind power uncertainty, and proposed a kind of three lines of defense for power grid which considering wind power. [2] pointed out that wind power can be equivalent to power injection when corresponding conditions are satisfied and carried out some transient mechanism analysis on the basis of DC power flow model. In [3], an extended dual-machine system is proposed, and the effects of wind farm location, synchronous generator output adjustment and wind power permeability on the transient stability of the system are studied.

Researchers have also done a lot of research on HVDC transmission, and China State Grid Corporation has put some HVDC transmission technique into practical engineering applications. [4] has analyzed the mechanism of wind generations disconnection in high voltage bus caused by DC blocking fault and its countermeasures. Finally, an example of China Northwest wind-fire bundled DC transmission system is used to verify the effectiveness of the measures. [5] analyzed the influence of Hami-Zhengzhou UHVDC operation on the stability characteristics of Xinjiang-Northwest Power Grid, and proposed a kind of control strategy for improving wind power absorption capacity.

Most of the studies on transient stability of wind power grid-connected DC transmission system are concerned with the mechanism analysis of the system and the influencing factors of transient stability, and the proposed control strategy is relatively simple. Currently, there are few studies on how to improve the transient stability of hybrid systems in complex situations. In [6] and [7], the generator phase trajectory is used to judge the transient stability of the system in real time, which is simple and flexible. It provides a new idea for the transient problems under complex wind power access. However, most of the current studies only use the phase trajectory function to judge the transient stability directly. Few people pay attention to the transient margin information and sensitivity index contained in the phase trajectory function.

In this paper, using phase trajectory analysis, a transient preventive control strategy considering wind power-DC hybrid system is proposed.

2. AC/DC SYSTEM CONNECTED WITH WIND GENERATORS

Among many types of wind Generators, Doubly fed Induction Generator have become the most widely used wind Generators because of their advantages of flexible power control and low cost. The relationship between wind speed and mechanical power P_{mw} of wind generator is as follows [8]:

$$P_{mw} = \frac{1}{2P_B} \rho A v_w^3 C_p(\lambda, \beta) \tag{1}$$

ρ represents air density, A represents swept area of impeller, v_w represents wind speed, C_p represents power conversion coefficient, which is determined by tip velocity ratio λ and pitch angle β, and P_B represents power reference value. When the wind speed is determined, the mechanical power is determined by C_P.

In this section, a wind power connected three-area AC/DC hybrid equivalent system model is proposed as shown in Fig. 1. Area 1 contains generator G1, which is used to represent the equivalent power generating unit. Area 2 contains generator G2, which is used to represent an equivalent power receiving unit. Area 3 is the area of wind power access, which is used to represent the centrally connected wind farm after equivalent. Area 1 and area 3 are connected to G2 through AC/DC parallel lines.

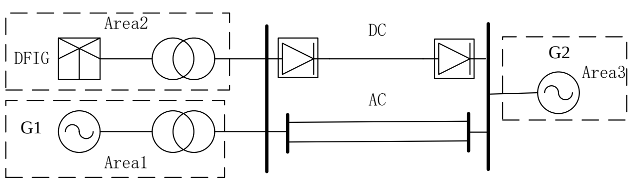

Fig. 1 Three-area AC/DC system

3. PHASE TRAJECTORY ANALYSIS METHOD

3.1 Single machine phase trajectory

In an ideal single machine infinite bus system, if the damp is neglected and the effects of regulators and governors are not taken into account, the equation of motion of the single machine infinite bus system can be expressed as

$$\begin{cases} \dot{\delta} = \omega \\ \dot{\omega} = \dfrac{1}{T}(P_m - P_{e\max} \sin\delta) \end{cases} \tag{2}$$

δ represents the angle of the generator, ω represents the angular velocity deviation of the generator relative to the synchronous electric angular velocity; T represents the inertial time constant; P_m represents the mechanical power of the generator; P_{emax} represents the maximum electromagnetic power of the generator. The phase trajectory of the generator at different fault clearance times is shown in Fig. 2.

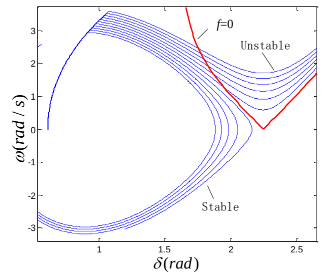

Fig. 2 Stable/unstable phase trajectory

As shown in Fig. 2, there is a clear demarcation line which affects the trend of k_1. It divides the phase plane into two parts, the left part of the second derivative $k_2 < 0$, and the right part of the second derivative $k_2 > 0$.

3.2 AC/DC system trajectory

In the AC/DC system shown in Fig. 2, the instability caused by large disturbances is dominated by the swing of the angle of the sending end generator relative to the rest of the units.

$$\begin{cases} \dot{\delta} = \omega \\ \dot{\omega} = \dfrac{1}{T}(P_m - P_D - \dfrac{EU}{X}\sin\delta) \end{cases} \tag{3}$$

The parameters represented by δ, ω, T and P_m are the same as those in section 3.1. E represents the internal potential of the generator; U represents the bus voltage where the generator is connected to the power grid; X represents the equivalent impedance between the two potential; P_D represents the transmission power of the DC system.

Compared with the pure AC connection system, the rotor equation of the system not only increases the DC power, but also introduces the bus voltage. In the case of large disturbance, the power of DC system controlled by power electronic components changes rapidly, and the reactive power compensation ability of the system is required to be higher. Therefore, the bus voltage of DC terminal will fluctuate dramatically, so the influence of voltage must be considered. In addition, the bus voltage stability will be further deteriorated when the wind turbine is connected to the bus at the sending end which is also one of the reasons for considering the voltage. Considering U as a function of time, the first derivative k_1

and the second derivative k_2 of the phase trajectory are as follows

$$k_1 = \frac{d\omega}{d\delta} = \frac{(P_m - P_D - \frac{EU}{X}\sin\delta)/T}{\omega} \tag{4}$$

$$\begin{aligned} k_2 &= \frac{dk_1}{d\delta} \\ &= -\frac{\frac{EU^{'}}{TX}\omega\sin\delta + \frac{EU}{TX}\omega^2\cos\delta + [(P_m - P_D - \frac{EU}{X}\sin)/T]^2}{\omega^3} \end{aligned} \tag{5}$$

The transient stability criterion formula based on the phase trajectory is as follows

$$f = -\{\frac{EU^{'}}{TX}\omega\sin\delta + \frac{EU}{TX}\omega^2\cos\delta + [(P_m - P_D - \frac{EU}{X}\sin)/T]^2\} \tag{6}$$

Differentiation of f diagonal δ is as follow

$$\begin{aligned} \frac{df}{d\delta} &= \frac{\partial f}{\partial\delta} + \frac{\partial f}{\partial\omega}\frac{d\omega}{d\delta} \\ &= \frac{EU^{'}}{TX}\sin\delta\frac{(P_m - P_D - \frac{EU}{X}\sin\delta)/T}{\omega} + \frac{EU}{TX}\omega^2\sin\delta \\ &= \frac{E}{TX}\sin\delta[U^{'}\cdot k_1 + U\omega^2] \end{aligned} \tag{7}$$

In transient process, $U^{'}<0$, $k_1<0$, $U\omega^2>0$, so $f' > 0$. That is, the f function increases monotonously with the increase of δ. When_ω decreases monotonously, f increases monotonously. Suppose that when $t = t_0$ $\omega=\omega_{\min}$, then f function has a maximum $f(t_0)$ Then the transient stability constraints based on phase trajectory can be obtained:

$$f(\delta, \omega_{\min}) \le 0 \tag{8}$$

When the system is stable, $f(t_0)$ is as follow:

$$f(t_0) = -[(P_m - P_D - \frac{EU}{X}\sin\delta)/T]^2 \tag{9}$$

Phase trajectory sensitivity of generator output is shown as

$$\begin{aligned} &\frac{df(\delta_r, 0, P_m)}{dP_m} \\ &= -2(P_m - P_D - \frac{EU}{X}\sin\delta_r)(1 - \frac{E}{X}\frac{dU}{dP}\sin\delta_r + \frac{EU}{X}\cos\delta_r \cdot \frac{d\delta_r}{dP_m}) \end{aligned} \tag{10}$$

3.3 Preventive control model based on phase trajectory

If the system is transient unstable, we usually use DC power emergency control first, because the control cost of DC is much less, and then adopted the measures of generator cut-off and load reduction. [9] pointed out that the DC power emergency control can achieve the stable control effect of cutting generator or load by rapidly increasing or reducing DC power. The transient preventive control strategy of generator output adjustment can be converted into the following linear programming problem.

$$\begin{cases} \min\limits_{\Delta P_{Gi}} - \sum\limits_{i \in S^+} \Delta P_{Gi} \\ \text{s.t.} \begin{cases} \Delta P_{Gi} \le 0, \; i \in S^+ \\ \Delta P_{Gj} \ge 0, \; i \in S^- \\ -0.5P_{D0} \le \Delta P_D \le 0.1P_{D0} \\ \sum\limits_{i \in S^+} \Delta P_{Gi} + \sum\limits_{i \in S^-} \Delta P_{Gj} = 0 \\ P_{Gk}^{\min} \le P_{Gk}^0 + \Delta P_{Gk} \le P_{Gk}^{\max}, \forall k \in \{S^- \cup S^+\} \end{cases} \\ \sum\limits_{i \in S^+} \Phi(f, t_0, P_{Gi}, P_{D0} + \Delta P_D)\Delta P_{Gi} + \\ \sum\limits_{i \in S^-} \Phi(f, t_0, P_{Gj}, P_{D0} + \Delta P_D)\Delta P_{Gj} < -f(t_0) \end{cases} \tag{11}$$

ΔP_{Gi} is the change of generator output, S^+ and S^- are the group of positive and negative sensitive factor generators respectively. P_{Gk}^0 represents the basic operating point of generator k. $\Phi(f,t_0,P_{Gi})$ represents the sensitivity of generator i to equivalent phase trajectory at t_0; $P_{Gk}^{\max}$ and $P_{Gk}^{\min}$ represent the upper and lower output limits of generator k; the upper limit of DC transmission power is 110% rated power, and the lower limit is 50% rated power.

4. TRANSIENT PREVENTIVE CONTROL WITH WIND POWER

In China, it is generally preferred to accept wind power in full. Wind power output has the characteristics of fluctuation, intermittence and uncertainty, so how to adjust the output of generator to balance the power difference caused by the fluctuation of wind power output is a problem that needs to be solved in the transient preventive control strategy.

When adjusting synchronizer to prevent control strategy to balance the fluctuation caused by wind power grid connection, we need to consider the economy of control strategy. Therefore, the objective function is set up to minimize the adjustment cost of generator.

$$\min F = \sum_i C_i \bullet \Delta P_{Gi} \tag{12}$$

F represents the cost of generator adjustment, i represents the generator label, C_i represents the cost of generator adjustment, and ΔP_{Gi} represents the amount of generator output adjustment.

All adjustable generators $\Delta \boldsymbol{P} = [\Delta P_{G1}, \Delta P_{G2}, \ldots, \Delta P_{Gn}]$ constitute preventive control vectors. When the wind power fluctuation is ΔP_w, the other generators need to adjust $\sum \Delta P_{Gi} = \Delta P_w$ to ensure the power balance of the system. The adjusted transient stability constraints are expressed in the form of phase trajectories as follows.

$$\sum \Phi(f,t_0,P_{Gi})\Delta P_{Gi} + \Phi(f,t_0,P_w)\Delta P_w < -f(t_0) \quad (13)$$

If the system is transient unstable at the basic operating point, a stable operating point should be obtained according to algorithm mentioned in section 3.4. The mathematic model of transient preventive control for system transient stability and DFIG output fluctuation is as follows.

$$\begin{cases} \min \sum_{i \in S^+} C_i \Delta P_{Gi} \\ \text{s.t.} \begin{cases} \sum \Delta P_{Gi} + \Delta P_w = 0 \\ P_{Gk}^{\min} \le P_{Gk}^0 + \Delta P_{Gk} \le P_{Gk}^{\max} \end{cases} \\ \sum \Phi(f,t_0,P_{Gi})\Delta P_{Gi} + \Phi(f,t_0,P_w)\Delta P_w < -f(t_0) \end{cases} \quad (14)$$

C_i represents the output adjustment cost of generator i; ΔP_w represents the output fluctuation of DFIG; and the constraint equation coordinates the output limitation of generator and the transient stability constraint equation based on the sensitivity of phase trajectory from top to bottom. For the rest of the symbolic meanings, see formula (11).

5. CASE STUDY

The proposed control strategy is applied to the AC/DC system shown in Fig. 3 to verify the effectiveness. The system is a calculation example provided by BPA software. Generators' output are shown in Tab. 1.

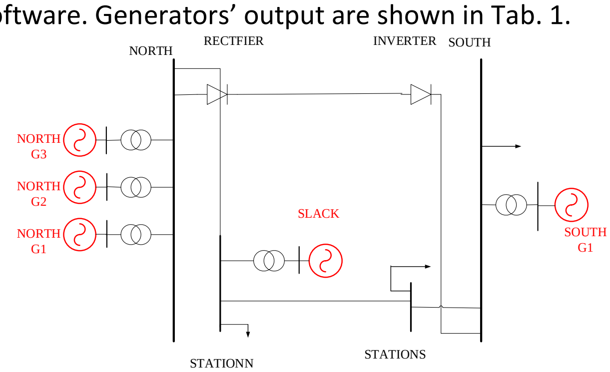

Fig. 3 AC/DC system

Tab. 1 Generators' output

Generators	P(MW)
NORTH G1	950
NORTH G2	950
NORTH G3	950
SLACK	1054
SOUTH G1	2000

5.1 Case1

In order to verify the validity of the algorithm, the fault is selected as NORTH-STATIONN three-phase grounding short circuit, and the fault line is removed after 0.04s. SLACK is a balanced unit. The instability power angle curve of the system is shown in Fig. 4. From the instability power angle curve, it can be seen that the generators NORTH G1, NORTH G2 and NORTH G3 are the leading groups.

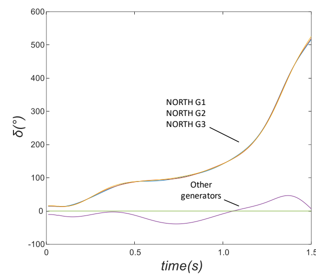

Fig. 4 Power angle curve

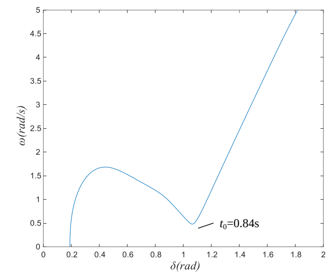

Fig. 5 Phase trajectory curve

As shown in Fig. 5, according to the analysis in Section 3.2 the f function increases with the decrease of angular velocity. When the angular velocity reaches the minimum value $\omega_{AB}=\omega_{\min}$ and t_0=0.84s, the phase trajectory function $f(t_0)$=2.3421($p.u$) reaches the maximum value.

The sensitivity of the phase trajectory at $f(t_0)$ and the sensitivity after DC modulation are both shown in the Tab. 2. The coordinated control schemes obtained by formula (11) without DC modulation are $\Delta P_{N\text{-}G1}$=-27MW, $\Delta P_{N\text{-}G2}$=-27MW, $\Delta P_{N\text{-}G3}$=-27MW, $\Delta P_{S\text{-}G1}$=81MW. When DC modulation is preferred, the DC power is increased by 1%, the coordinated control schemes obtained by formula (11) are $\Delta P_{N\text{-}G1}$=-22MW, $\Delta P_{N\text{-}G2}$=-22MW, $\Delta P_{N\text{-}G3}$=-22MW, $\Delta P_{S\text{-}G1}$=66MW.

Tab. 2 Generators' phase trajectory sensitivity in different strategies

Generators	Sensitivity1	Sensitivity2
NORTH G1	0.02928	0.03717
NORTH G2	0.02928	0.03717
NORTH G3	0.02928	0.03717
SLACK	Slack Bus	Slack Bus
SOUTH G1	-0.00119	-0.00129

It can be seen that after adjusting DC, the adjusting amount of synchronous machine has been significantly reduced, which also verifies the effectiveness of the method proposed in this paper.

5.2 *Case2*

In this case, the wind farm with the maximum output of 225MW is connected to the NORTH bus, and the fault is selected as NORTH-STATIONN three-phase grounding short circuit, and the fault line is removed after 0.04s.The fluctuation of the DFIG in a day is selected from the data of a domestic wind farm as shown in Tab. 3.

Tab. 3 Active power output of wind farm in one day

T (h)	P (MW)	T (h)	P (MW)	T (h)	P (MW)
1	21.24	9	92.89	17	35.26
2	15.36	10	48.20	18	50.12
3	19.67	11	29.09	19	65.51
4	18.86	12	66.46	20	80.61
5	33.70	13	94.39	21	108.9
6	18.54	14	36.26	22	158.0
7	21.31	15	9.50	23	180.5
8	12.11	16	30.64	24	185.2

The DFIG output at time 1 is selected as the initial operating point and the DC power is increased by 1%.

The phase trajectory sensitivity calculated at $f(t_0)$ is shown in Tab. 4

Tab. 4 Generators' phase trajectory sensitivity considering DFIG integrated

Generators	Sensitivity
NORTH G1	0.0192
NORTH G2	0. 0192
NORTH G3	0. 0192
SLACK	Slack Bus
SOUTH G1	-0.0031
DFIG	0.0378

For different time, we adopt such preventive control scheme: if the fluctuation of DFIG output increases, first increase DC power and improve system stability, and then three generators at the sending end, NORTH G1, NORTH G2 and NORTH G3, are selected to track the fluctuation of wind power and bear the corresponding power deviation. If the fluctuation of DFIG output decreases, first reduce DC power to improve system stability, and then select SOUTH G1 to balance power deviation. The *f*-function value considering the above preventive control scheme in one day is shown in Fig. 6.

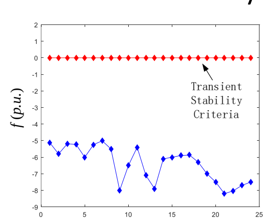

Fig. 6 *f*-function value curve

In Fig. 6, it can be seen that the real-time preventive control method proposed in this paper can guarantee the transient stability of the system when the DFIG output fluctuates in one day, and it can play a good role in the purpose of the transient preventive control. Moreover, the value of the *f* function reflects the transient stability margin and can be provided to the dispatchers to analyze the transient stability of the system in real time.

6. CONCLUSIONS

Based on the phase trajectory analysis method, a transient preventive control strategy based on phase trajectory sensitivity is proposed in this paper. Cases show that the calculated transient preventive control scheme is still very scientific in AC/DC systems. Finally, this paper proposed a system transient preventive control method considering wind power fluctuation, which can provide reference for dispatchers to select generators in real time and formulate control strategies.

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