Frequency deviation peak calculation of sending-end network in large asynchronous interconnected power grid

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Abstract: The asynchronous connection by high-voltage direct current (HVDC) links optimises the power angle stability of the large area power grid. However on the side of the sending-end, the loss of DC links causes high frequency, of which the frequency deviation peak is an important index in the study of the power grid frequency stability. In this study, the method to calculate the peak value of frequency deviation based on the change rate of the frequency deviation is obtained by analysing a single-machine system. Then, the application of method is extended to the actual power system to study HVDC additional control and generator tripping. Finally, the single-machine power grid and Yunnan Power Grid are simulated, respectively, to verify the accuracy and the feasibility of the method. The simulation results show that the method is accurate and applicable to the actual power grid, which has practical value of engineering.

1 Introduction

In China Southern Power Grid, the power grid comprises sending end and receiving end. When AC lines between the sending end and receiving end are deleted, the power can only be transmitted through DC lines so that the area grids are interconnected asynchronously. Due to the asynchronous interconnection, the power angle stability issues on both sides are no longer closely related. Even if the DC power fails under bipolar blocks, the change of the power flow distribution will not do damage to the power angle and frequency stability of the main power grid [1, 2]. For the sending-end network, the DC fault will cause considerable surplus power while the grid governor fails to respond rapidly [3, 4]. As a result, the frequency will exceed the limit and jeopardise the stability of the system frequency.

In 2016, China Southern Power Grid, serving as the main grid, is asynchronously connected with Yunnan Power Grid, the sending-end network. To transmit power from Yunnan Power Grid to Southern Power Grid, there are six DC lines, such as Line Nuozhadu and Line Chusui, which connect two area grids asynchronously to build a typical large-scale power system [5]. For the stability of asynchronously interconnected power grids, the post-fault frequency deviation peak is an important index, which plays an essential role in the designing of the stability control scheme.

At present, literatures about frequency stability problems in large-scale interconnected power grids mostly focus on the research of low-frequency load shedding [6, 7]. However, for over-frequency problems in the sending-end network, a formulation of the frequency deviation of single-machine system is deduced in [8] and a generator-tripping scheme of over-frequency in Central China Power Grid is studied in [9]. With HVDC systems of islanding operation mode attended, methods to improve the frequency stability of the sending end by DC additional control has been systematically studied in [10, 11]. However, the grid frequency deviation peak is an important indicator of grid frequency stability and a basis for designing control schemes, whether for generator tripping or DC additional control. Thus, the calculation of frequency deviation peak is imperative to the research of the sending-end frequency stability.

Based on the frequency deviation response characteristics of a single-machine system, this paper obtained the relationship between the change rate of the frequency deviation and the peak value of frequency deviation. More specifically, the frequency deviation peak can be calculated directly by the change rate of the frequency deviation. Considering the fact that the actual grid cannot be accurately equivalent to a single-machine system, several relevant countermeasures are proposed. The calculation of grid frequency deviation applied in DC additional control and generator-tripping stability control is also illustrated in detail. Finally, through the simulation test of the single-machine system and Yunnan power grid, conclusions are carried out in this paper.

2 Calculation of frequency deviation peak in a single-machine system

In a sending-end network that is asynchronously interconnected, the grid frequency deviation in response to the change of outgoing DC power can be approximately equivalent to that in a single-machine system with load. The dynamic process of the overall system frequency can be indicated by the block diagram as shown in Fig. 1.

In Fig. 1, \( M \) is the inertia constant of the single-machine system; \( D \) is the regulation constant of the system load; \( K \) is the constant of the static characteristic of power and frequency; \( T \) is the integration constant of the governor. \( \Delta P_e \) is the value of the active power change, which is the change of the outgoing DC power. \( \Delta P_L \) is the value of the load power change caused by the change of the active power. From Fig. 1, the transfer function can be formulated as

\[
\Delta \omega(s) = \frac{\Delta P_e(s)}{\Delta P_L(s)} = \frac{1}{sM} + \frac{K}{sT + 1} + \frac{sT + 1}{MT^2 + (M + DT)s + (D + K)}
\]

By Laplace transformation, a step disturbance to the active power can be expressed as \( \Delta P_L/s \). Substituting the step disturbance into the transfer function of the frequency dynamic characteristic in (1),
the time-domain solution of the frequency deviation is given by (2)

\[ \Delta \omega(t) = \frac{\Delta P_e}{D + K} \left[ 1 - e^{-\alpha t} \left( \cos bt - \frac{(a + c)}{b} \sin bt \right) \right] \]

where

\[ a = \frac{M + DT}{2MT}; \quad b = \sqrt{\frac{D + K}{MT} - \left( \frac{M + DT}{2MT} \right)^2}; \quad c = \frac{KT - M}{MT}; \]

\[ A = \sqrt{1 + \left( \frac{a + c}{b} \right)^2}; \quad \varphi = \arctan \left( \frac{a + c}{b} \right) \]

The derivative with respect to \( t \) is given by

\[ \frac{d\Delta \omega}{dt} = \frac{\Delta P_e}{D + K} \left[ Aa e^{-\alpha t} \cos bt + Ab e^{-\alpha t} \sin bt + (a + c) b \sin bt \right] \]

\[ = \frac{\Delta P_e}{D + K} A e^{-\alpha t} \left[ a + b \sin bt + \arctan \left( \frac{a + c}{b} \right) \right] \]

From (3), when \( t = 0 \)

\[ \frac{d\Delta \omega}{dt} = \frac{\Delta P_e}{M} \]

From (4), when the disturbance occurs, the change rate of system frequency deviation is proportional to the value of disturbance and inversely proportional to the system inertia constant.

According to the extremum theorem, when system frequency deviation reaches the peak value, the change rate of the frequency deviation is 0. We obtain

\[ t_{\max} = \frac{n\pi - \varphi - \theta}{b}, \quad n = 0, 1, 2, \ldots \]

where \( \alpha \) is the proportionality coefficient of \( \Delta \omega_{\max} \) and \( \Delta P_e \). In fact, when the disturbance occurs in the power grid, the value of the disturbance \( \Delta P_e \) is difficult to be determined, so the frequency deviation peak of the power grid cannot be directly calculated by (6). However, the change rate of the system frequency deviation can be swiftly measured after disturbance. Equation (7) is derived from the combination of (4) and (6)

\[ \Delta \omega_{\max} = \alpha M \left| \frac{d\Delta \omega}{dt} \right|_{t=0} \]

From (7), the peak value of the frequency deviation can be calculated by the change rate of the frequency deviation immediately after the disturbance occurs. In reality, the over-frequency problems of the sending end are usually caused by the DC blocking failure in an asynchronously connected power grid. Since a DC blocking failure in a single-machine system can be regarded as a step disturbance, it is reasonable to calculate the frequency deviation peak through (7).

### 3 Research of the calculation of the frequency deviation peak in actual power grids

For systems whose sending end and receiving end are asynchronously connected, the change of frequency deviation in different parts of the area is basically the same when the outgoing DC power of the sending end changes. Therefore, a single-machine system by equivalence can be used to calculate the peak value of the grid frequency deviation. Still, there are three issues worth attention.

#### 3.1 Grid equivalence

Actually, there are a portion of sending-end networks with a large number of generators, varieties of grid governors and uncertain load regulation effect. Even if the actual grid can be equivalent to single-machine system, the result of the equivalence is not accurate, neither is the analysis of the grid dynamic frequency characteristic. However, from (4), (6), and (7), when the frequency deviation characteristic of the power grid is equivalent to that of a single-machine system, the relationship between the disturbance value, the change rate of the frequency deviation and the peak value of frequency deviation is obviously proportional, leaving the proportionality coefficients undetermined. Once the coefficients are determined, it is quite reasonable to obtain the peak value of frequency deviation through the change rate of the frequency deviation. To acquire the coefficient in actual power grids, actual network tests and off-line simulations are two practical methods.

As far as actual grids are concerned, if the structure of the grid is too complex to be equivalent, where the method of simulation is impractical, the proportionality coefficient in (7) can also be obtained directly through the actual test. As a result, whenever the outgoing DC power changes, the peak value of the frequency deviation can be calculated through the change rate of the frequency deviation.

#### 3.2 Geographical difference

For a large-scale area grid, frequency of different locations changes differently under the same disturbance because of the geographical difference, which requires the consideration of the place to detect grid frequency deviation. In an asynchronously interconnected network, the over-frequency problem is mainly caused by the change of the outgoing DC power. The peak value of the frequency deviation can be obtained through the change rate of the frequency deviation because the frequency deviation changes immediately the DC power changes. However, except for the fault of DC power, the load power itself changes at any time, causing the fluctuation of the change rate of the frequency deviation. Thus, during the calculation of the peak value of the frequency deviation, the DC power signal requires attention due to its function of confirming the change source, so the device for frequency detection should be set at the DC converter bus. Consequently, the peak value of grid frequency deviation can be obtained so that the measures for stability control can be determined in time.

In addition, when the power from different DC systems reduces by the same amount, the frequency deviation of different part of the grid varies because of the geographical difference. Hence, DC systems at different locations need to be individually tested to obtain the proportionality coefficient between the peak value and the change rate of the frequency deviation.

#### 3.3 Effects of the governor

Specifically, the sending-end surplus power under a bipolar block failure exceeds so much that the opening level of the grid governor gate may reach the limit, so the regulation ability of the governor is worse than that under a unipolar block failure. Accordingly, the peak value of frequency deviation under a bipolar block failure is larger than twice the peak value of frequency under unipolar block failure. When calculating the peak value of the bipolar block frequency deviation, an extra compensation factor >1 is required, of which the specific value can be obtained through simulation tests in actual grids.

In addition to the three issues above, the change rate of the frequency deviation at a non-zero time also satisfies to calculate the frequency deviation peak. As it is illustrated in (3) that the change rate of the frequency deviation at any time is proportional
to the magnitude of the disturbance, as well as the peak value of grid frequency deviation.

For the issue of the frequency stability in actual grids, not only does the peak value of the frequency deviation need attention, but also the stable value of the grid frequency deviation. Supposing that the variable \( t \) in (2) tends to infinite, we obtain

\[
\Delta \omega_t = \Delta P_e D + K
\]

From (8), the stable value of the grid frequency deviation is proportional to the value of the disturbance just like the peak value, thus it can be calculated by the change rate of the frequency deviation.

4 Application of the calculation of frequency deviation peak

Until now, there are two solutions to the high-frequency problems in the sending-end network. The first solution is the DC additional control, which means to increase the outgoing power to suppress the grid frequency from going too high. When a DC line breaks down, the other serviceable DC lines share the power that was transmitted by the faulty line. The second solution is the arrangement of generator tripping, which means to reduce the surplus power in the sending-end network by tripping generators. Taking both the source side and the load side into consideration, the two methods above contribute greatly to the stability of sending-end network frequency. In the following of this paper, the application of frequency deviation peak calculation in these two aspects is introduced.

4.1 Application of the frequency deviation peak calculation in DC additional control

The DC frequency limit controller (FLC) is used to suppress the over-frequency in the sending-end network, of which the structure is shown in Fig. 2. As can be seen in Fig. 2, the proportionality coefficients of the controller in the FLC have major influence on the control effect. If we analyse the controller irrespective of the dead zone and the limiter, the effect of FLC on the grid can be approximated as an increase of constant \( D \), which represents the system load regulation effect constant. Therefore, for the dynamic frequency deviation characteristic of a power grid with FLC, the peak value and the change rate of the grid frequency deviation are approximately linear. If the FLC has been configured, the frequency deviation peak of the power grid decreases, suggesting a decrease of the proportionality coefficient in (7), which can be obtained through the simulation test.

For different FLC input schemes, the corresponding proportionality coefficient will also be different; thus affecting the peak value of grid frequency deviation. Conversely, the FLC input scheme can also be determined by the peak value of frequency deviation. When a DC fault occurs in the grid, the frequency deviation peak responding to different FLC input schemes is determined by both the proportionality coefficient of the scheme and the frequency deviation change rate measured. Then the appropriate FLC input scheme is selected for execution. The specific process is shown in Fig. 3.

4.2 Application of the frequency deviation peak calculation in stability-control generator tripping

After a DC fault, the surplus power can be decreased by generator tripping, in order to keep the stability of the sending-end network frequency. The main concern of the generator tripping schemes is how much to cut, which is determined by the time of tripping. The sooner generator tripping functions, the fewer generators are to be tripped. However not every DC fault requires generator tripping, for the peak value of the frequency deviation is still within the limitation of frequency. So it depends on the specific situation to make sure whether to trip generators.

The specific realisation of the process is shown in Fig. 4. After receiving the fault signal, the peak value of the grid frequency deviation is obtained by calculation. Then whether to trip generators as well as the scheme of generator tripping is determined based on the peak value of the grid frequency deviation. Different schemes of generator tripping are made in advance according to different frequency deviation peaks. Since the DC frequency deviation peak can be immediately obtained, the generator tripping scheme can be implemented in time, thus reducing the generator tripping volume as a result.

5 Case study and simulation verification

5.1 Case 1: single-machine system

A simply structured sending-end network with not many generators is closely connected inside; thus it can be equivalent to a single-
machine system shown in Fig. 1. This paper builds a power system with two areas asynchronously interconnected on the electromechanical transient simulation tool PSS/E (power system simulator/engineering), which is shown in Fig. 5.

In Fig. 5, area 1 is the sending-end network, from which the power is transmitted to area 2 through two DC lines. Area 1 is equivalent to a single-machine system, of which the parameters are as follows. \( M = 10, \; K = 20, \; T = 5, \; D = 2 \). Equation (9) is derived from (4)

\[
\frac{\Delta \omega}{dt} \bigg|_{t=0} = \frac{\Delta P_e}{10} \tag{9}
\]

From (5), we obtain \( t_{\text{max}} = 2.48 \) s. Substituting \( t_{\text{max}} \) into (2), we obtain

\[
\Delta \omega_{\text{max}} = 0.133 \Delta P_e \tag{10}
\]

Equation (11) is derived from (9) and (10).

\[
\Delta \omega_{\text{max}} = 1.33 \frac{\Delta \omega}{dt} \bigg|_{t=0} \tag{11}
\]

Based on (11), the peak value of grid frequency deviation in Fig. 5 can be obtained when the outgoing DC power changes.

In this paper, a blocking simulation is implemented on one of the DC lines at 1 s. The initial change rate of grid frequency deviation is 1.1 Hz/s, and the peak value of frequency is calculated to be 1.46 Hz by substituting the change rate into (11). In Fig. 6, the actual curve of simulation is displayed and the peak value of the frequency deviation is around 1.465 Hz. The comparison of the simulated value and the calculating value proves the correctness of the method to obtain the frequency deviation peak based on the change rate of frequency deviation.

5.2 Case 2: actual grid

In Fig. 7, Yunnan Power Grid is asynchronously connected with South Power Grid through six DC lines. As the sending-end network, Yunnan Power Grid transmits power to the South Power Grid that serves as the load center. This actual grid is inappropriate to be equivalent to a single-machine system displayed in Fig. 1 because of its complexity, so more research is required for further analysis.

In this paper, the calculation of the frequency deviation peak in Yunnan Power Grid is based on PSS/E. For example, in the research of the Chusui DC lines, the DC power of 5000 MW is transmitted from Yunnan Chuxiong to Guangdong Suidong. Assuming Chusui DC power down to 4500 MW at 1 s, the frequency deviation at the rectifying-side converter station is shown in Fig. 8.

According to the simulation of Yunnan Power Grid, the change rate of frequency deviation at 1.2 s is 0.04 Hz/s and the frequency deviation peak is 0.062 Hz. Thus the proportionality coefficient between the frequency deviation peak and the change rate of frequency deviation is 1.55 s. Column 3 in Table 1 is obtained by the calculation of the frequency deviation peak based on the coefficient 1.55 s.

From Table 1, when the DC power loss varies within 2500 MW, the coincidence of the calculated value and simulation value proves the correctness of the calculation method.

Next, bipolar block is set on Chusui DC line to simulate a DC power loss of 5000 MW. Theoretically, if we neglect the influence of the limit of the governor in the grid, the frequency deviation response curve of bipolar block should be two times the response curve of the unipolar block. However in reality, the comparison of the two situations is displayed in Fig. 9.

As can be seen in Fig. 9, the two curves are basically coincident at the beginning, but overall, the frequency deviation peak under bipolar block is larger than twice the peak value under unipolar block due to the governor limit. When the opening level of the governor gate under the bipolar block reaches the maximum, the ability of the governor's frequency modulation is worse than that
under unipolar block. Hence, during the calculation of the frequency deviation peak under bipolar block failure, the original proportionality coefficient should be multiplied by a compensation factor >1. In this example, the peak value of frequency deviation corresponding to the bipolar block is 0.653 Hz, so the value of the compensation factor for bipolar block is around 1.05.

6 Conclusion

In this paper, we studied the frequency deviation peak of the sending-end network in a large-scale asynchronously interconnected power system. The main conclusions are as follows.

i. The proportionality between the peak value of frequency deviation and the change rate of frequency deviation is deduced theoretically. Also the simulation based on the single-machine system and Yunnan Power Grid proves the correctness of the proportional relationship. The frequency deviation peak can be directly derived from the change rate of frequency deviation in actual grids.

ii. Considering the problems of grid equivalence, geographic differences and governor limit in actual large-scale area power grids, a method of obtaining the proportionality coefficient and compensation coefficient by actual tests is proposed to calculate the frequency deviation peak quickly.

iii. A scheme of determining FLC input and generator tripping according to the frequency deviation peak is addressed, which reduces the generator tripping volume and suppresses the peak value of frequency deviation, thus improving the frequency stability of the sending-end network.

7 References

[1] O'Sullivan, A.R.: ‘Studying the maximum instantaneous non-synchronous generation in an island system-frequency stability challenges in Ireland’, IEEE Trans. Power Syst., 2014, 29, (6), pp. 2943–2951
[2] Zhou, C.H.: ‘Study of backbone structure change from synchronous to asynchronous in China southern power grid’, Proc. CSEE, 2016, 36, (8), pp. 2084–2092
[3] Wei, P., Liu, J., Zhou, Q., et al.: ‘Research on impacts of bipolar blocking in Jinsu UHVDC on stability of receiving-end system’. 2015 5th Int. Conf. Electric Utility Deregulation and Restructuring and Power Technologies (DRPT), 2015, vol. pp, no. 99
[4] Wen, Y., Chung, C., Ye, X.: ‘Enhancing frequency stability of asynchronous grids interconnected with HVDC links’, IEEE Trans. Power Syst., 2018, 33, pp. 1800–1810
[5] Fairley, P.: ‘Why southern China broke up its power grid’, IEEE Spectr., 2016, 53, (12), pp. 13–14
[6] Wu, Y., Ye, G., Chang, L., et al.: ‘Capacity determination of a dynamic energy storage system in an island power system with high renewable energy penetration’. 2017 Int. Conf. Applied System Innovation (ICASI), 2017
[7] Tang, Y., Zhao, P., Li, W., et al.: ‘Load shedding control strategy for power system voltage regulation in distribution networks’. 2017 IEEE Conf. Energy Internet and Energy System Integration (EI2), 2017, pp. 1–5
[8] Zhang, Z., Xu, Y., Yuan, R., et al.: ‘Frequency characteristics of power grid at sending end of split large-scale interconnected regional power grid and corresponding over-frequency generator-tripping scheme’, Power Syst. Technol., 2015, 39, (1), pp. 288–293 (in Chinese)
[9] Song, Z., Lin, Y., Liu, C., et al.: ‘Review on over-frequency generator tripping for frequency stability control’. 2016 IEEE PES Asia-Pacific Power and Energy Engineering Conf. (APPEEC), 2016
[10] Wang, S., Wang, Y., Ma, J.: ‘Study of frequency and voltage characteristics of islanded HVDC system and the corresponding control strategy’. 2014 Int. Conf. Power System Technology, 2014, pp. 2247–2251
[11] Liang, Z., Qin, Q., Guo, Q., et al.: ‘Frequency control for islanded system at sending terminal of HVDC power transmission from China to Mongolia’, Power Syst. Technol., 2008, 12, (21), pp. 22–25 (in Chinese)