Analysis of Factors Influencing the Active Current on the Communication Channels between Regional Power Grids

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Abstract. This paper analyzes the changes of active power flow on the communication channel between regional power grids, summarizes the influencing factors affecting the active power flow, and provides a theoretical basis for the analysis of the combined loop conditions of the electromagnetic loop network between regional power grids. From the perspective of the power angle characteristics of the power system, the relationship between the active power and the power angle of the power supply of the two power networks is derived. The influence of the power angle change on the active power flow in the communication channel between the regional power grids is theoretically analyzed. The correctness of the derivation conclusion is verified by ETAP simulation modeling. Finally, the 35kV grid in Shou County, Huainan, is taken as an example to analyze the influence of power angle on the active power of the loop. The research results show that the change of power angle on the communication channel between regional power grids has a direct impact on the change of active power flow, and the power angle can be used as an important criterion for the electromagnetic ring network.

Key words: Electromagnetic loop; contact channel; power angle characteristics; active power flow

1. Introduction
At the first stage of the introduction of a new voltage level in the power grid, the structure cannot be very strong and the power flow of high-low loop network is little [1, 2]. In this case, it is reasonable to operate the power system with one or several electromagnetic loops to increase the power transmission capacity, improve the usage efficiency of the cheap resources and satisfy the increasing power demand [3-6]. However, with the development of high-level voltage grid and the integration of more power sources, the contradiction between the short-circuit current control in the electromagnetic loop network and the weak power supply capability and the transmission capacity of the power grid has become increasingly prominent [7, 8]. Therefore, it should be considered to break up the electromagnetic ring network and operate the power system in layering and partitioning mode [9, 10]. However, during the partition operation of the power grid, the tie line switching operation of the upper and lower levels of the communication channel is likely to form an electromagnetic loop, which may cause low voltage power flow crossing phenomenon [11-15], trigger the protection action leading to power outage. Thus, it is of vital importance to investigate the influential factors of the active power flow on the tie line.
between regional power grids to build a certain theoretical basis for the operation of the electromagnetic loop network and reduce the occurrence of power failures.

The existing literature focuses mainly on basic principles of decoupling electromagnetic loop networks and the optimization and decision for opening electromagnetic loop networks of specific power grids. In [3] the causes of electromagnetic loop networks are explained, and principles of determining the best opening time and position are proposed. Based on the concrete characteristics and long-term planning of the power grid in Hefei, a multi-stage multi-level electromagnetic loop networks decoupling strategy is proposed in [16]. To improve the efficiency of the 500kV/220kV power grid construction in Zhengzhou, the planning of power grid and the decoupling of the electromagnetic loop networks are combined in [17]. However, less contribution about the possible ring-closing operation on the tie line after the electromagnetic loop networks are opened has been reported. To some extent, this paper provides a theoretical basis for the research in this direction.

2. Power Angle Characteristic of Two Power Source Network

The power angle δ is a crucial parameter in the power system, which has a dual physical meaning.

1) The electrical meaning, i.e. it represents the phase angle difference between the terminal voltages of the generator and the receiving system.

2) The mechanical meaning, i.e. the angle δ can be regarded as the rotor angle difference between the sending and receiving generators when the infinite receiving system is equivalent to a generator with no internal impedance.

The two power grids can be simplified as two infinite systems after breaking up the electromagnetic loop, the equivalent two-machine power system is shown in Fig. 1.

\[
\begin{align*}
I_1 &= I_{11} - I_{12} = \frac{E_1}{Z_{11}} - \frac{E_2}{Z_{12}}
I_2 &= I_{21} - I_{22} = \frac{E_2}{Z_{21}} - \frac{E_1}{Z_{22}}
\end{align*}
\]

Equation (1), Z11 and Z22 represent the input impedances of the two power sources, Z12 and Z21 denote the transfer impedances between the two power sources.
Figure 3. Two power phase relationship

Figure 3 illustrates the phasor diagram of the two generator voltages, i.e. $\dot{E}_1$ and $\dot{E}_2$, and the voltage of the common connection point $\dot{E}_m$. Then, the output power of each generator can be deduced, for example the power of the first generator is expressed by

$$S_i = P_i + jQ_i = E_i I_i = \frac{E_i E_1}{Z_{11}} - \frac{E_i E_2}{Z_{12}}\angle(\delta_1 - \delta_2)$$  \hspace{1cm} (2)

In Equation (2), $\theta_{11}$ and $\theta_{12}$ are the impedance angle of $Z_{11}$ and $Z_{22}$, respectively. By further expanding Equation (2) into real and imaginary parts, the output active power is calculated by

$$P_1 = \frac{E_1^2}{Z_{11}} \cos \theta_{11} - \frac{E_1 E_2}{Z_{12}} \cos(\delta_{12} - \theta_{12})$$ \hspace{1cm} (3)

Define $\alpha = 90^\circ - \theta$ is the complementary angle of $\theta$, the output active power can also be represented by

$$P_1 = \frac{E_1^2}{Z_{11}} \sin \alpha_{11} - \frac{E_1 E_2}{Z_{12}} \sin(\delta_{12} - \alpha_{12})$$ \hspace{1cm} (4)

Basically, two power angle characteristics of the two-machine power system can be concluded from Equation (4).

The output power of each generator is influenced by the voltage magnitude and voltage angle difference of all the generators in the system. In other words, changing the operation status of an arbitrary generator can move the other generators to a new operation point.

The power angle characteristic of each generator is a multi-variable function of the rotor angle difference between the generator itself and the others.

The two power grids can be treated as two separated infinite power system when the electromagnetic loop is broken up. If the electromagnetic loop network is operated in the closed loop operation mode, the system should be modelled as a two-machine power system shown in Fig. 2. According to Equation (4), the output active power of each generator is determined by the magnitude and power angle $\delta_{12}$ of the generator voltages $\dot{E}_1$ and $\dot{E}_2$. The voltage magnitudes $E_1$ and $E_2$ experience just small deviations under the normal operation scenario, therefore, the output power is mainly influenced by the power angle $\delta_{12}$.

3. Influence of power angle on active power flow in communication channel — Simulation analysis

The simulation model shown in Fig. 4 is built using ETAP to verify the correctness and effectiveness of the theoretical analysis and investigate the effects of the power angle on the active power flow.
As demonstrated in Fig. 4, the power sources are modelled as infinite buses in the two-machine power grid ETAP simulation model. The network has three voltage levels, i.e. 220kV, 110kV and 35kV. By changing the phase angle of the voltage at one infinite bus, the power angle of the simulation system is varied from 0° to 50° to investigate its effects on the active power flow active power of the looped loop. The simulation results are given in Table 1.

### Table 1. The effect of the power angle of two power networks on the active power flow active power of the looped loop

| Power angle of the infinite bus | 220kV | 110kV | 35kV |
|---------------------------------|-------|-------|-------|
| Power angle before close loop operation | Power angle before close loop operation | Active power flow on the tie line [MW] | Power angle before close loop operation | Active power flow on the tie line [MW] | Power angle before close loop operation | Active power flow on the tie line [MW] |
| 0° | 0° | 0 | 0° | 0.01 | 0° | 0.04 |
| 10° | 10° | 171.7 | 10° | 15.2 | 10° | 1.1 |
| 20° | 20° | 341.6 | 20° | 29.9 | 20° | 2.2 |
| 30° | 30° | 504.7 | 30° | 43.6 | 30° | 3.2 |
| 40° | 40° | 655.9 | 40° | 55.6 | 40° | 4.6 |
| 50° | 50° | 790.8 | 50° | 65.3 | 50° | 4.6 |

It can be observed from Table 1 that the line active power at each voltage level is gradually increased as the power angle of the busbar during the open loop operation is increased. The relation can be approximated by a sinusoidal function. Moreover, when the power angle before the close loop operation remains the same, the higher the voltage level is, the greater the active power of the ring line is. The simulation results reveal the critical impacts of the power angle on the active power flow of the communication channel, which is consistent with the theoretical analysis.

4. Real test case analysis – power grid in Shou country

The substation voltages before and after the electromagnetic loop closing of the 35kV power grid in Shou country during the peak load period of 2016 and 2017 are analyzed in this section to verify the effects of the power angle on the loop closing active power flow.

Figure 5 demonstrates the active power flow of the 35kV power grid in Shou country during the peak load period of 2016 under the Anfeng Station – Yanzhong Station closing loop operation mode. The power station voltages before and after the loop closing are listed in Table 2.
It can be observed from Table 2 that the voltage amplitude and phase angle differences of the grids on both sides of the 35kV Anfeng Station-Yinzong Station are relatively large during the peak load period of 2016. The voltage phase angle decreases from Anfeng Station to Yinzong Station. After closing the electromagnetic loop, the voltage amplitude difference and the phase angle difference become smaller, and the direction in which the voltage phase angle decreases is the same as the power flow direction as shown in Fig. 5. However, the power flow exceeds the secure operation capacity of the tie line which is likely to cause a power failure.

Table 2. Voltage comparison of 35kV Anfeng Station in the summer of 2016

| Number | Name of the Station | Station voltages before closing loop | Station voltages after closing loop |
|--------|---------------------|--------------------------------------|-------------------------------------|
|        |                     | 110kV 35kV Phase angle               | 110kV 35kV Phase angle              |
| 1      | Shouzhou            | 108.3 ---- -89.9                     | 108.1 ---- -90.1                    |
| 2      | Baoyi               | 107.4 34.6 -93.4                     | 106.8 34.3 -96.6                    |
| 3      | Anfeng              | ---- 34.4 -93.6                      | ---- 34.0 -97.1                     |
| 4      | Yinzong             | ---- 32.7 -101.0                     | ---- 33.7 -97.4                     |
| 5      | Yanliu              | 101.0 32.7 -101.0                   | 102.01 33.5 -97.6                   |
| 6      | Guangyan            | 101.1 ---- -100.0                   | 102.0 ---- -97.4                     |

The active power flow of the 35kV power grid in Shou country during the peak load period of 2017 under the Anfeng Station-Yinzong Station closing loop operation mode is shown in Fig. 6. The power station voltages before and after the loop closing are listed in Table 3.

As shown in Table 3, the voltage amplitude and phase angle differences of the grids on both sides of the 35kV Anfeng Station-Yinzong Station are relatively small during the peak load period of 2017. The voltage phase angle decreases from Yinzong Station to Anfeng Station. After closing the electromagnetic loop, the voltage amplitude difference and the phase angle difference become smaller, and the direction in which the voltage phase angle decreases is the same as the power flow direction as shown in Fig. 6. The power flow remains within the secure operation capacity of the tie line, and the low voltage power flow crossing phenomenon does not happen.

Table 3. 2017 summer peak 35kV Anfeng station - Yinzong station before and after the ring voltage comparison

| Number | Name of the Station | Station voltages before closing loop | Station voltages after closing loop |
|--------|---------------------|--------------------------------------|-------------------------------------|
|        |                     | 110kV 35kV Phase angle               | 110kV 35kV Phase angle              |
| 1      | Shouzhou            | 107.2 ---- -25.1                     | 107.7 ---- -25.2                    |
| 2      | Baoyi               | 104.9 33.6 -29.9                     | 106.8 35.2 -29.0                    |
| 3      | Anfeng              | ---- 33.5 -30.1                      | ---- 35.2 -29.3                     |
| 4      | Yinzong             | ---- 36.2 -28.9                      | ---- 35.4 -29.5                     |
| 5      | Yanliu              | 111.7 36.2 -28.8                    | 111.0 35.5 -29.3                    |
| 6      | Guangyan            | 111.8 ---- -28.1                    | 111.1 ---- -28.3                     |
The simulation results and the comparison between different operation scenarios of the real power grid reveal the fact that the active power flow on the tie line is mainly determined by the voltage phase angle difference of the two grids before closing the electromagnetic loop. Large power angle will result in a large active power flow on the tie line. Under severe situation, the low voltage power flow crossing phenomenon can appear and easily cause a power failure. Therefore, the power angle can be used as an important technical indicator before the lower-level grid switching operation.

5. Conclusion
In this paper, the low voltage power flow crossing problem that may be caused by the switching operation of the low-level power grid under the opening operation mode of the electromagnetic loop network is analyzed. The critical influential factors of the active power flow on the tie line between the reginal power grids are analyzed. The following conclusions can be drawn through theoretical analysis, simulation verification, and the practical power grid analysis.

(1) The change of the power angle on the tie line between regional power grids has a direct impact on the change of active power flow.

(2) After the electromagnetic loop is closed, the direction of the power flow is the same as the direction in which phase angle of the voltage decreases. The larger the power angle under the open loop operation mode is, the larger the active power flow on the tie line when the loop is closed.

(3) The power angle can be used as an important technical indicator before the lower-level grid switching operation.

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