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New finding on out-of-step separation configuration of large-scale power systems*

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Abstract: In this paper, two new concepts—“main out-of-step mode” and “minor out-of-step mode”—are proposed for power system reliability analysis. Large-scale power system studies found that out-of-step generator groups may have characteristics of the main out-of-step mode and the minor out-of-step mode. The generator groups with main out-of-step modes can determine the out-of-step interface of the large-scale power system, while generators with the minor out-of-step modes cannot play such a role. Therefore, the method of capturing the out-of-step interface by seeking the lowest voltage point (the out-of-step center) can only group the generators with the main out-of-step modes, and may fail to combine the generators with the minor out-of-step modes into proper coherent generator groups. Thus, it is necessary in engineering applications to equip the generators that are likely to have the characteristics of the minor out-of-step modes with separation devices based on off-line simulation studies in order to reduce the risk of further accidents caused by these generators after system separation.

Key words: Out-of-step center, Out-of-step interface, Separation device, Main out-of-step mode, Minor out-of-step mode
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INTRODUCTION

With the interconnection of the western grid and the eastern grid, the electrical power grid of China has developed into a long-distance and huge capacity interconnected system with AC and DC transmission lines in parallel. With the persistent expansion of the power systems, some severe system contingencies may cause huge losses (Billinton and Allan, 1996; Pourbeik *et al*., 2006). In reliability analysis of bulk power system, the most important thing is how to prevent power-system collapse and large-scale blackouts (Wang *et al*., 1995; Novosel *et al*., 2004; Sulzberger and Gallagher, 2004). As the last defensive strategy against system collapse, system separation is widely used in power systems all around the world (Yuan, 1999; Hou and Tziouvaras, 2004; Paunescu *et al*., 2004; Bai *et al*., 2006).

System separation can be defined as follows: when the system is out-of-step, it should be separated into several parts by selecting proper separation points such that the oscillations between two or more parts of it due to different frequencies can be eliminated and further impacts of accidents can also be avoided (Han, 1995; Tziouvaras and Hou, 2004). The out-of-step center (i.e., the oscillation center) is located in the electrical connection of the out-of-step generator groups. Therefore, the separation points are usually selected in the following steps in engineering applications (Ohura *et al*., 1990; Kosterev *et al*., 1996; Cong *et al*., 2002; Teng *et al*., 2002; de Villiers and van Coller, 2004):

(1) Find the out-of-step center through transient

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simulation.

(2) Determine the out-of-step interface, which is defined as a group of tie-lines around the out-of-step center.

(3) Separate the system from the out-of-step interface.

Two new concepts—“main out-of-step mode” and “minor out-of-step mode” are presented in this paper. Large-scale power system studies found that out-of-step generator groups may have two different characteristics: the main out-of-step mode and the minor out-of-step mode. Not like generator groups with the main out-of-step modes, the generators with minor out-of-step modes cannot determine the out-of-step interface of large-scale power system. They may be coherent with different generator groups due to different types of disturbances they are exposed to. However, the system out-of-step interface will not change no matter which generator group they are coherent with. Therefore, the method of capturing the out-of-step interface by seeking the lowest voltage points may only be able to group the generators with the main out-of-step modes, while the generators with the minor out-of-step modes may cause potential accidents after system separation if they are not partitioned into proper system islands. Thus, in engineering applications, it is necessary to equip the generators that are likely to have the characteristics of the minor out-of-step modes with separation devices based on off-line system analysis. Otherwise, these generators may cause further accidents after system separation.

ANALYSIS METHOD AND TEST SYSTEM

Framework of the China Northwest Power Grid in 2010

In this paper, the China Northwest Power Grid (CNPG) in 2010 is studied. It is the first UHV project in China. The framework of the 750 kV lines is shown in Fig.1. There are totally thirteen 750 kV lines, among which there are two double-circuit lines: Guanting to Lanzhou and Lanzhou to Pingliang.

The CNPG can be divided into Eastern Part (includes the power network of Shanxi province) and Western Part (includes Gansu, Ningxia and Qinghai). The framework of the 330 kV system is shown in Fig.2.

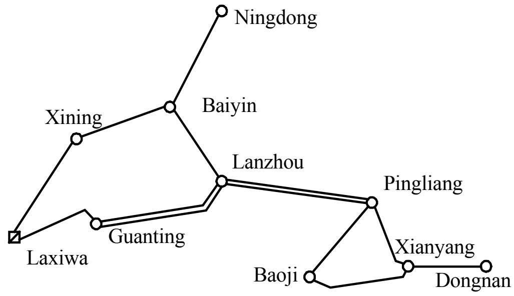


Fig.1 The first edition of the 750 kV line framework of the China Northwest Power Grid in 2010

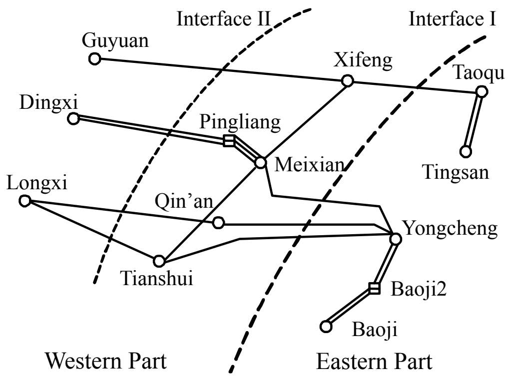


Fig.2 The 330 kV East-West framework of the China Northwest Power Grid

As shown in Fig.2, there are mainly two power flow transmission interfaces in the 330 kV system. Interface I contains the following transmission lines: Xifeng to Taoqu, Meixian to Yongcheng, Qin’an to Yongcheng, and Tianshui to Yongcheng. Interface II contains the following transmission lines: Guyuan to Xifeng, Dingxi to Meixian, Longxi to Qin’an, and Longxi to Tianshui. Interface I is the electrical connection center of the eastern and western parts of the CNPG.

Introduction of the analysis method

The out-of-step center is the lowest voltage point on the out-of-step interface during an out-of-step process. Therefore, the out-of-step interfaces are usually determined by seeking the lowest voltage points (out-of-step center) in engineering applications (Han, 1995; Hou and Tziouvaras, 2004).

Generally, the strongest voltage and power oscillations can be observed at the out-of-step center, and the closer to the out-of-step center, the stronger the electrical oscillation will be. The locus of the phase-angle difference between two sides of the out-of-step center varies from 0° to 360° continuously and periodically (Ohura *et al*., 1990; Han, 1995; Ota *et al*., 2000).

All the simulation analysis in this paper is implemented with the transient stability simulation software package BPA (Bonneville Power Administration) (Wang and Ravindran, 2002). The following methods are adopted to locate the electrical interface:

(1) Based on the transient stability simulation results, find the buses with the lowest voltage profiles in each AC transmission corridor when oscillation occurs, and the out-of-step center is located near these buses.

(2) Calculate the phase-angle differences between two ends of the lines connected to these buses. If the phase-angle difference between two ends of a certain line varies continuously and exceeds ±180°, the out-of-step center of the AC corridor lies exactly on this line.

(3) Determine the coherent generator groups based on the loci of generator rotor angles; in fact, the electrical connection interface between the out-of-step generator groups is exactly the out-of-step interface (Ohura *et al*., 1990).

The detailed study and analysis in the paper may inspire further improvement to the method of selecting separation points that is widely used in engineering applications nowadays.

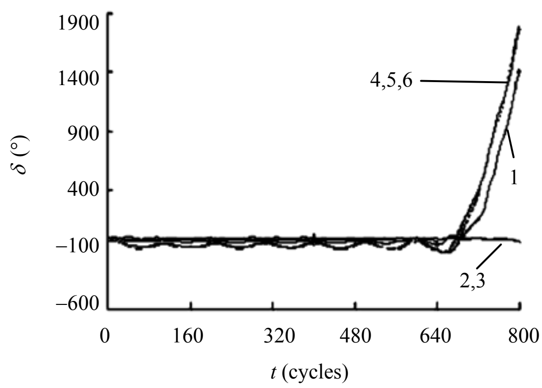
RESEARCH ON OUT-OF-STEP OPERATION BETWEEN EASTERN AND WESTERN PARTS OF CNPG

According to the power grid expansion plan of the CNPG, the network structure and transmission capacity in the year 2010 will be remarkably strengthened, and power system stability will also be greatly improved. The system will remain stable unless contingencies occur on the main 750 kV transmission lines. As shown in Fig.1, once the double-circuit lines from Lanzhou750 to Pingliang750 are dropped, the 750 kV system will be separated into two parts, which will greatly impact the system stability and security. Therefore, the outage of the double-circuit line is selected in this paper as the study case for the out-of-step oscillation research of the CNPG.

Simulation studies

The simulation process is as follows: when t=0, a permanent three-phase grounding fault occurs on one of the double-circuit lines from Lanzhou750 to Pingliang750, with the fault point being near the Pingliang750 bus side; after 100 ms, the double-circuit lines are dropped, and out-of-step oscillation occurs between generator groups of the eastern and western parts of the system.

The loci of the rotor angles of the following generators, Pingliang, Qinling2, Shiquan1, Hami, Liujx1 and Pucheng, are shown in Fig.3. The Longyangxia generator is selected as the reference unit.



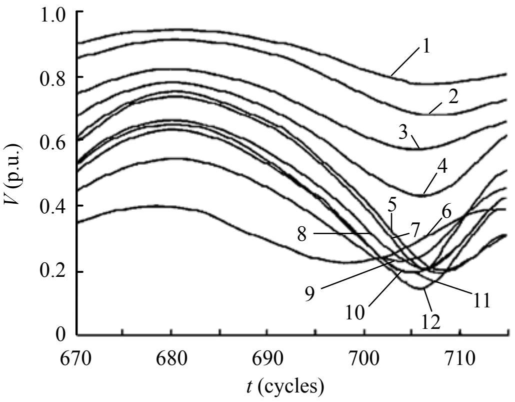
1: Pingliang; 2: Hami; 3: Liujx1; 4: Qinling2; 5: Shiquan1; 6: Pucheng

Fig.3 Locus of rotor angles of generators of simulation

It can be seen from Fig.3 that although the Pingliang generator belongs to the western part of the system, it is incoherent with the other generators in the western part of the system (Hami, Liujx1). On the contrary, it is coherent with generators in the eastern part of the system (Qinling2, Pucheng, Shiquan1). Based on this, a preliminary conclusion can be drawn that the out-of-step interface should be on the west side of the Pingliang generator.

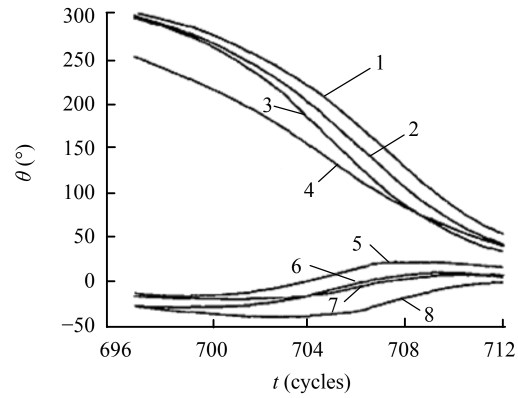
For convenience, Interfaces I and II are defined as shown in Fig.2.

As mentioned above, the strongest oscillation occurs at the out-of-step center. The closer to the out-of-step center, the stronger the electrical oscillation will be. The loci of bus voltage magnitudes of the following twelve 330 kV buses: Guyuan, Xifeng, Taoqu, Dingxi, Meixian, Yongcheng, Longxi, Qin'an, Tianshui, Lanzd, Pingliang, Shetang, are shown in Fig.4.



1: Lanzd; 2: Dingxi; 3: Guyuan; 4: Longxi; 5: Pingliang; 6: Taoqu; 7: Meixian; 8: Tianshui; 9: Yongcheng; 10: Xifeng; 11: Qin'an; 12: Shetang

Fig.4 The loci of the bus voltage magnitudes



1: $\theta_{Meixian}-\theta_{Yongcheng}$; 2: $\theta_{Tianshui}-\theta_{Yongcheng}$; 3: $\theta_{Qin'an}-\theta_{Yongcheng}$; 4: $\theta_{Xifeng}-\theta_{Taoqu}$; 5: $\theta_{Longxi}-\theta_{Qin'an}$; 6: $\theta_{Guyuan}-\theta_{Xifeng}$; 7: $\theta_{Longxi}-\theta_{Tianshui}$; 8: $\theta_{Dingxi}-\theta_{Meixian}$

Fig.5 Locus of the phase-angle differences between two line-ends

After 704 cycles, the system bus voltage magnitudes that reflect the system oscillation strength decrease to the bottom values. As shown in Fig.4, the voltage magnitude of the above 12 buses can be sorted in descending order from 1 to 12 in sequence. Referring to Interfaces I and II defined in Fig.2, we can draw the conclusion that the out-of-step center should be in Interface I. This means that the system out-of-step center lies on the east side of the Pingliang generator, with this conclusion contradicting the previous one.

There is another criterion for locating the out-of-step center, which is "if the phase-angle difference between the two ends of a certain line varies continuously and exceeds ±180°, the out-of-step center of the AC corridor lies exactly on this transmission line" (Yuan, 1996; Tziouvaras and Hou, 2004; Bai *et al*., 2006). The loci of the phase-angle differences between two ends of lines on the electrical connection interface of the eastern and western parts of the system are shown in Fig.5.

Fig.5 shows that for the lines that belong to Interface I, the phase-angle differences between their two ends vary continuously and get beyond 180° smoothly (as shown by Curves 1~4). However, the phase-angle differences of the lines belonging to Interface II do not change too much (as shown by Curves 5~8). Thus, we can confirm that the out-of-step center is right on Interface I.

From the loci of generator angles, it is concluded that the out-of-step center should be on Interface II. However, the out-of-step center is actually on Interface I. This case indicates that for large-scale power system, the method of capturing the out-of-step interface by seeking the lowest voltage points (out-of-step center) may fail to combine some out-of-step generators into the proper groups.

In the above case, the fault occurs on the tie-line from the Lanzhou750 bus to the Pingliang750 bus, near the Pingliang750 bus side. Further simulation analysis showed that, if the same type of fault occurs far away from the Pingliang generator, for example, happens on the same tie-line but near the Lanzhou750 bus side, the Pingliang generator will experience relatively small transient energy impacts, and it will be coherent with the subsystem with smaller frequency. However, in the above case, the fault point is near the Pingliang generator, and it experiences more transient energy impacts, which accelerates the generator out-of-step process and finally makes the generator coherent with the subsystem with larger frequency. Compared with the equivalent internal impedances of the eastern and western parts of the CNPG, the internal impedance of the Pingliang generator is relatively large. This kind of feature results in the fact that the out-of-step interface of the whole system will not be changed no matter which subsystems the Pingliang generator is coherent with.

Conclusions and the practical value

As shown in the above case, the Pingliang generator is coherent with the generator group of the system's eastern part. However, the out-of-step center of the whole system is still on the electrical connection Interface I that contains the transmission lines of Taoqu to Xifeng, Meixian to Yongcheng, Qin'an to Yongcheng, and Tianshui to Yongcheng, and separates the Pingliang generator from the system's Eastern Part.

It can be seen that the eastern and western out-of-step generator groups have decisive effects on the out-of-step interface tie-lines where the out-of-step center is located, and they can be defined as generator groups with the main out-of-step modes. However, the Pingliang generator cannot determine the out-of-step interface tie-lines, and is the generator with the minor out-of-step mode. Simulation results also showed that the generators with the minor out-of-step mode are most likely located near the electrical center of the whole system, and there will be certain electrical distance between them and the generator groups with the main out-of-step modes.

In the interconnected power systems, it is very important to restrict the out-of-step operation since the out-of-step generators will have critical impacts on the system stability and security and they may even cause system collapse (Gomes, 2004; Horowitz and Phadke, 2006). Nowadays, out-of-step separation devices are normally equipped on the interface tie-lines where the out-of-step center is located. That means attention is only paid to the generator groups with the main out-of-step modes. However, the simulation analysis in this paper indicated that we also need to pay attention to the generators with the minor out-of-step mode and to equip them with separation devices, since these generators may continue to disturb the system and cause further accidents after system separation.

CONCLUSION

In this paper, analysis of large-scale power system found that the out-of-step generator groups may have characteristics of the main out-of-step mode and the minor out-of-step mode. The generator groups with the main out-of-step modes can determine the out-of-step interface of the system, while the generators with the minor out-of-step mode cannot affect the system out-of-step interface. However, they may cause further accidents if they are not partitioned into the proper system islands after system separation. Therefore, it is suggested that the generators that are likely to have characteristics of the minor out-of-step mode should be equipped with the out-of-step separation devices based on off-line simulation studies in order to reduce the risk of further accidents caused by these generators after system separation.

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