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An improved strategy for out-of-step oscillation separation devices based on apparent impedance angle applied to a series compensated line

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Abstract
Out-of-step oscillation separation devices based on apparent impedance angle trajectory are widely used in the power grid in China, and their reliability is of great importance. In this paper, the influence mechanism of series compensation on apparent impedance angle trajectory is analyzed. It reveals that series compensation capacitors reduce the equivalent impedance angle and consequently the apparent impedance angle cannot pass through all four zones, resulting in the risk of failure for the separation devices. A revised method of apparent impedance angle based on compensation principle is discussed, and then an improved out-of-step oscillation detection criterion is proposed. In view of the fact that the apparent impedance angle at the moment of maximum current is equal to the equivalent impedance angle during an oscillation process, a practical algorithm based on the compensated apparent impedance angle is proposed. RTDS tests are conducted to verify the effectiveness of the new criterion, considering transmission lines with a high series compensation level.

Keywords: Out-of-step oscillation separation, Series compensated line, Apparent impedance angle, Compensated impedance angle

1 Introduction

As the last defense in ensuring the stability of a power system, reliable operation of out-of-step oscillation separation devices is very important. Given their different acquisition methods, current out-of-step oscillation separation devices can be divided into wide area information-based and local information-based [1]. The out-of-step oscillation separation devices based on wide area information relay on the reliability of the communication system, while the security of communication information is still a thorny problem in the field of stability control [2–4]. Therefore, at present, out-of-step oscillation separation devices configured in China are still mainly based on local information, and the most widely used criteria are $U\cos\varphi$ trajectory principle and apparent impedance angle principle [5–7]. The out-of-step oscillation detection criterion based on the $U\cos\varphi$ trajectory can judge whether the system is out-of-step according to the voltage of the oscillation center during an oscillation process. It has the capability to accurately identify the time when the phase difference between equivalent generator electromotive forces at two ends swings to 180°, but it cannot judge the position of the oscillation center [6, 8]. The out-of-step oscillation detection criterion using apparent impedance angle calculates the phase angle difference between voltage and current at a point along the oscillation line. This indirectly reflects the variation of phase difference between the two equivalent generator electromotive

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forces, and then whether the system is out-of-step can be judged [7]. The premise of its correct application is that the line impedance angle is close to 90° in the traditional two machine equivalent system. However, when the criterion is applied to transmission lines with a high series compensation level, the previous boundary conditions are often difficult to meet. In particular, UHV transmission lines are often interconnected with two large power grids, so the equivalent system impedances of both sides are small while the series compensation level relative to the system impedances is very large. Therefore, the equivalent line impedance angle is far away from 90°, and thus, the reliability of out-of-step oscillation separation device based on apparent impedance angle trajectory will face challenges.

Series compensation is a common practice to reduces the electrical distance of transmission lines, and this is beneficial in improving the stability of a power grid. With the gradual promotion of UHV long-distance transmission in China, the application of series compensation is more and more extensive. Therefore, it is necessary to study the influence of series compensation on out-of-step oscillation characteristics and the reliability of out-of-step oscillation separation devices. At present, to solve the problems caused by the application of series compensation to the secondary equipment, power engineers around the world have undertaken a lot of theoretical and practical research. Most of it has focused on the field of relay protection [9–11], while there have been only few studies on the reliability of out-of-step oscillation separation devices.

In research on the out-of-step oscillation detection criterion based on apparent impedance angle, reference [7] points out that when a three-phase short circuit fault occurs in the opposite direction but subsequently disappears by itself, the criterion will fail to operate, and a relevant auxiliary criterion based on measured dynamic trajectory must be taken into account to improve the reliability of the criterion. In [12, 13], the criterion is improved by adding auxiliary conditions such as starting criterion and current trend criterion. In [14], an improved criterion using the threshold of voltage envelope as the unlocking condition is proposed, which can strictly distinguish between the process of short circuit and out-of-step oscillation. In [15], the influence mechanism of continuous commutation failure on the out-of-step oscillation detection criterion is analyzed, while [16, 17] consider the influence of the different voltage amplitudes and unit regulations at both sides on the oscillation center offset. However, the above studies cannot reduce the risk to the out-of-step oscillation separation device caused by the deviation of equivalent impedance angle from 90°.

This paper investigates the influence of series compensation on the apparent impedance angle trajectory and out-of-step oscillation criterion, and an improved criterion is proposed to address the issues. The remainder of this paper is organized as follows. Section 2 introduces the out-of-step oscillation detection criterion using apparent impedance angle. This criterion is widely used in engineering practice. Section 3 analyses the influence of series compensation on the out-of-step oscillation separation device, and points out the risks. An improvement algorithm from the engineering application perspective is proposed in Sect. 4, while in Sect. 5, RTDS tests are carried out to verify the reliability of the proposed new criterion. Conclusions are drawn in Sect. 6.

2 Brief introduction of the out-of-step oscillation criterion based on apparent impedance angle

When an out-of-step oscillation happens in a two-generator system, the phase angle difference between voltages at two ends of the line varies periodically between 0° and 360°. Assuming that the line impedance distribution is uniform and the impedance angle is around 90°, the apparent impedance angle along the line varies periodically between 0° and 180° or 180° and 360°. This feature is implemented in the out-of-step oscillation separation device using apparent impedance angle to identify an out-of-step oscillation [7, 14]. In an actual power grid, because of the existence of transformers, reactive power compensation equipment and other components, these two assumptions are no longer justified. Thus, the apparent impedance angle φ does not strictly vary in the range of 180° during the out-of-step oscillation.

In view of the above, the impedance in the four-quadrant phase plane is divided into six zones as shown in Fig. 1. When φ varies by going through zones I–II–III–IV or I–VI–V–IV or I–IV, it can be considered that an out-of-step oscillation has occurred, and the direction of oscillation center can also be determined. At present, the boundaries of the zones are set as $\varphi_1 \in (50°, 60°)$

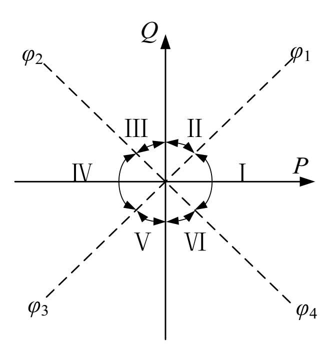

Fig. 1 Zone division of apparent impedance angle

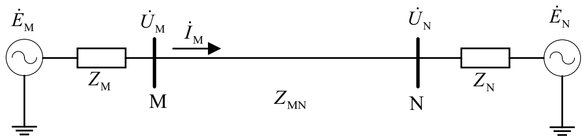

Fig. 2 Schematic diagram of two-generator equivalence system

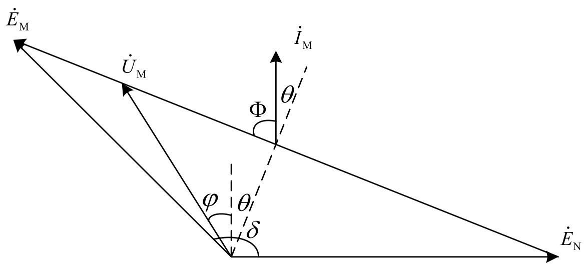

Fig. 3 Phasor diagram of voltage and current on the tie-line

and $\varphi_2 \in (120°, 130°)$ in engineering practice. This is based on large amounts of field operational experience and sufficient experimental verification. It can also well be adapted to the situation where the actual line impedance angle is close to 90°.

3 Influence of series compensation on the out-of-step oscillation separation device

3.1 Relationship between apparent impedance angle and equivalent impedance angle

For the two-generator system shown in Fig. 2, assuming the out-of-step oscillation separation device is installed at point M. $\dot{E}_M$ and $\dot{E}_N$ represent the two equivalent generator electromotive forces, Z_M and Z_N are the internal impedances, $\dot{U}_M$ and $\dot{U}_N$ are the voltages at both sides of the line, $\dot{I}_M$ is the current of point M, and Z_{MN} represents the line impedance.

The electromotive force amplitude difference of the two generators is ignored while it is assumed that the impedance angles of the whole system are the same. The phasor diagram of voltage and current on the tie-line is shown in Fig. 3, where δ is the phase angle difference of generator electromotive forces at the two ends, Φ is the equivalent line impedance angle, and θ is the complementary angle of Φ.

The apparent impedance angle of point M is:

$$\varphi = \arg\left(\frac{\dot{U}_M}{\dot{I}_M}\right) = \arg\left(\frac{1}{1-e^{-j\delta}}Z_\Sigma - Z_M\right) \tag{1}$$

where $Z_\Sigma = Z_M + Z_{MN} + Z_N$.

Assuming $Z_\Sigma = kZ_M$, the following result can be obtained:

$$\varphi = \arg\left(\frac{k-2}{2} - j\frac{k}{2}\cot\frac{\delta}{2}\right) + \Phi \tag{2}$$

If point M is near the oscillation center (i.e., k = 2), then:

$$\varphi = \pm 90° + \Phi \tag{3}$$

Otherwise, φ can be expressed as:

$$\varphi = \arctan\left[\frac{k}{k-2}\tan\left(\frac{\delta}{2} - 90°\right)\right] + \Phi \tag{4}$$

That is:

$$\varphi = \begin{cases} \frac{\delta}{2} - 90° + \Phi & k > 2 \\ -\frac{\delta}{2} + 90° + \Phi & 2 > k > 1 \end{cases} \tag{5}$$

From (3) and (5), φ varies with δ, but is also affected by Φ and the position of point M. If the oscillation center lies in the forward direction of point M, φ varies between $(-90° + \Phi)$ and $(90° + \Phi)$, and passes through the angles of 0° and 90°. Alternatively, if the oscillation center lies in the backward direction of point M, φ still varies between $(-90° + \Phi)$ and $(90° + \Phi)$, but passes through the angles of − 180° and − 90°. If the oscillation center lies near point M, φ also varies between $(-90° + \Phi)$ and $(90° + \Phi)$. In summary, regardless of where the oscillation center is, the maximum value of φ is $(90° + \Phi)$. If Φ is less than 90°, the maximum value of φ will be less than 180°.

3.2 Influence of series compensation on the out-of-step oscillation separation device

Clearly, the series compensation capacitor of the transmission line further reduces the value of Φ, as well as the measurement of the maximum value of φ. In severe cases, if $\varphi_{max} = (90° + \Phi) < \varphi_2$, φ will not go through all the four zones during the oscillation process. This will cause the failure of the separation device. With the different Φ and compensation proportion k_C, the value of φ_{max} is shown in Table 1.

The boundary between zones III and IV is (120°–130°) in engineering practice. It can be seen from the figures in Table 1 that, when there is a high series compensation level, the out-of-step oscillation separation device based on the apparent impedance angle principle has the risk of failure. The higher the compensation level, the greater the risk. The compensation level of UHV AC lines in China is generally less than 40%, but in other countries, the compensation ratio can reach 70%, so the influence of series compensation cannot be ignored.

Table 1 Value of φ_{max} under different conditions

$\Phi \backslash k_C$	40%	50%	60%	70%	80%	90%
60°	136°	131°	124°	117°	109°	100°
70°	149°	144°	138°	130°	119°	105°
80°	164°	161°	156°	150°	139°	120°
85°	171°	170°	168°	164°	156°	139°

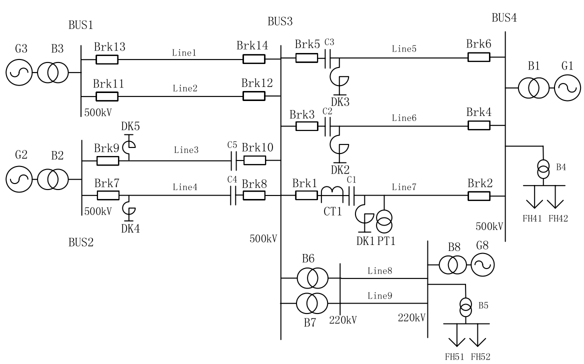

Fig. 4 Equivalent model of a regional power grid in North China

3.3 Experimental verification for the influence of series compensation

Table 2 Parameters of the generators

Generator	Un/kV	Sn/MVA	Xd/pu	Xd′/pu	Xq/pu	Xq′/pu	Power factor
G1, G2	20	3530	2.047	0.299	1.93	0.418	0.851
G3	20	1334	2.156	0.301	2.1	0.448	0.851
G8	20	706	1.836	0.228	1.79	0.379	0.851

Using practical parameters of a regional power grid in North China, an RTDS test verifies the risk mentioned above. Figure 4 shows the equivalent system model. The initial values of loads FH41, FH42, FH91 and FH92 in the system are 300 + j186 MVA, and the maximum capacities are 1000 + j1000 MVA. The series compensation capacitors are C1 = C2 = C3 = 12 μf, C4 = C5 = 212.4 μf, while the compensation ratios of Line 5–7 are 50%. Other main parameters are shown in Tables 2, 3 and 4.

An out-of-step oscillation separation device is installed at BUS3 to monitor the oscillation condition of Line 5. Its parameter related to oscillation center direction is set to allow action, regardless of whether the oscillation center lies in the positive or negative direction. The lowest threshold value of the voltage profile used to judge the control action zone is set to 80 V.

During the test, all series compensations are put into operation. When Line7 is disconnected without fault, an out-of-step oscillation occurs. The oscillation center is between BUS3 and BUS4, and the equivalent impedance angle is about 68°. Some electrical quantities at the installation point of the out-of-step oscillation separation device are shown in Fig. 5, where "Phase angle difference" refers to the voltage phase angle difference between BUS3 and BUS4.

It can be seen that in the first out-of-step period the maximum value of φ measured by the out-of-step oscillation separation device is 123.79°. If the set value of φ_2 is greater than 124°, φ cannot complete the crossing from zone I to zone IV, and consequently the separation device cannot identify the out-of-step oscillation. Only in the second out-of-step period can the device identify effectively and the action time is delayed by about 500 ms.

In summary, the results of theoretical analysis and dynamic simulation both show that when an out-of-step oscillation occurs on a series compensated transmission line, the apparent impedance angle cannot accurately reflect the variation of phase angle difference between generator electromotive forces at two ends because the equivalent impedance angle no longer meets the requirement of approaching 90°. For this reason, the out-of-step oscillation separation device based on local apparent impedance angle has the risk of failure.

4 Improvement of the criterion

4.1 Principle of apparent impedance angle compensation

To accurately reflect the variation of phase angle difference between generator electromotive forces at the two ends of the line during the oscillation process, the apparent impedance angle must be revised. As shown in Fig. 3, for any Φ, $\varphi + \theta$ can accurately reflect the variation law of δ. Therefore, $\varphi' = \varphi + \theta$ can be used to identify the out-of-step

Table 3 Main parameters of the transformers

Transformer	Sn/MVA	Wiring group	Ratio	Uk%
B1, B2	3700	dy0	20/550	14.32
B3	1440	dy0	20/525	13.91
B6	801	y/y	536/233	13.20
B7	750	y/y	500/233	14.30
B8	800	dy0	20/230	14.0

Table 4 Unit parameters of the transmission lines

Line	Length/km	R/(Ω/km)	X_L/(Ω/km)	X_C/(Ω/km)
Line 1, 2	202.4	0.01936	0.1987	0.1878
Line 3, 4	154.23	0.0282	0.2745	0.2356
Line 5–7	208.17	0.02927	0.2762	0.2197
Line 8, 9	86.53	0.02122	0.1491	0.5086

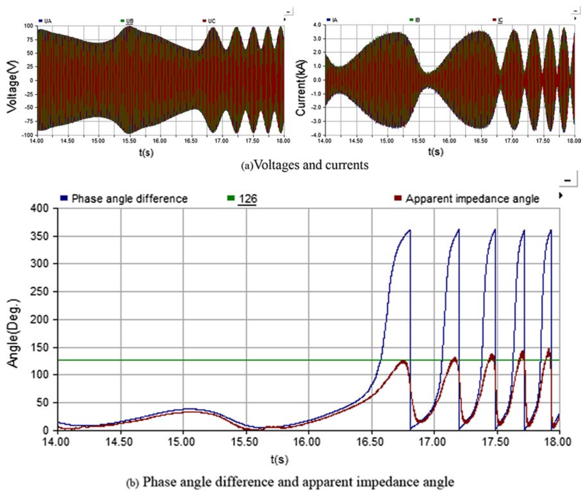

Fig. 5 Related electric quantities of the device installation point

oscillation instead of φ, where θ is defined as the compensation impedance angle. The value of Φ can be obtained from field measurement, and can also be calculated according to the structural parameters of the power grid. Assuming the system equivalent impedance is $R + jX$, $\Phi = \arctan(X/R)$ and the compensation impedance angle is:

$$\theta = 90^\circ - \Phi = 90^\circ - \arctan(X/R) \tag{6}$$

Considering the series compensation capacitor, the calculation of Φ can be modified as:

$$\Phi = \arctan\frac{(1-k_C)X}{R} \tag{7}$$

In this way, the apparent impedance angle can be compensated as:

$$\varphi' = \varphi + \theta = \varphi + 90^\circ - \arctan\frac{(1-k_C)X}{R} \tag{8}$$

Using the compensated apparent impedance angle to identify the out-of-step oscillation can avoid the failure due to the inaccurate assumption.

4.2 Practical algorithm of the compensated apparent impedance angle

The calculation of φ' requires the equivalent impedance angle information, but a power system oscillation is complex and volatile, which increases the difficulty in the setting in real applications. In addition, the series compensation capacitors may be switched on/off or adjusted at any time during operation. The out-of-step oscillation separation device needs to be adjusted with the compensation parameters in real time according to the change of operational mode. This increases the risk of operation mismatch in application.

As can be seen from Fig. 3, when the power angle swings to 180°, Φ is equal to φ, which is also the time when the line current reaches its maximum. Therefore, in the process of oscillation, the out-of-step oscillation separation device can record the apparent impedance angle $\varphi_{i\,\max}$ at the point of maximum current, and the complementary angle can be acquired by $\theta = 90^\circ - \varphi_{i\,\max}$. Consequently, the compensated apparent impedance angle φ' can be calculated according to (8), and the out-of-step oscillation separation device can be adapted to the real operational condition based on the trajectory of φ'.

For the previous RTDS test, Fig. 6 shows the apparent impedance angle trajectory after compensation. It can be seen that the compensated apparent impedance angle gradually increases to 145° in the first out-of-step period, goes through zones I-II-III-IV, and the separation device can identify the occurrence of out-of-step oscillation in time.

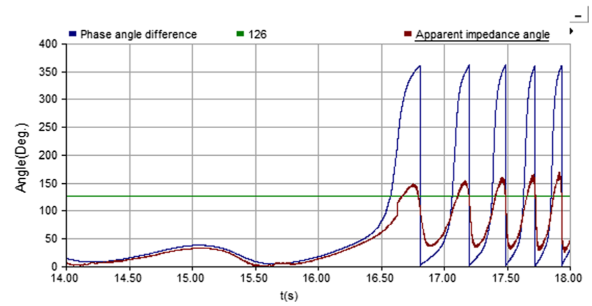

Fig. 6 Apparent impedance angle trajectory after compensation

5 Verification tests of the new criterion

In order to further verify the reliability of the improved out-of-step oscillation identification criterion, further tests are conducted based on the previous RTDS model in Fig. 4. The tests are designed according to the requirements raised by relevant standards [18] and by taking into consideration practical operational environments, such as synchronous and out-of-step oscillations, various types of short circuit faults and other disturbance scenarios. There are four out-of-step oscillation separation devices, namely D1, D2, D3 and D4. D1 and D2 are installed on the left and right sides of Line3, whereas D3 and D4 are installed on the left and right sides of Line5. The tests and performance of the devices are presented below.

Table 5 Performance of the devices in test scenario 1

Oscillation center position	On/off strategies of series compensation capacitor	Device performances (action or not)				Results
		D1	D2	D3	D4	
BUS2–BUS3	All entry	Y	Y	N	Y	Correct
	C1–C3 Exit	Y	Y	N	Y	Correct
	C4, C5 Exit	Y	Y	N	N	Correct
	All exit	Y	Y	N	N	Correct
Near BUS3	All entry	Y	Y	Y	Y	Correct
	C1–C3 exit	Y	Y	Y	Y	Correct
	C4, C5 exit	Y	Y	Y	Y	Correct
	All exit	Y	Y	Y	Y	Correct
BUS3–BUS4	All entry	Y	N	Y	Y	Correct
	C1–C3 exit	N	N	Y	Y	Correct
	C4, C5 exit	Y	N	Y	Y	Correct
	All exit	N	N	Y	Y	Correct

5.1 Out-of-step oscillation

Out-of-step oscillations are simulated under different on/off strategies of series compensation capacitors.

(1) Complete phase oscillation.

Scenario 1: The parameters related to oscillation center direction are set to allow action only when the oscillation center lies in forward direction. The performance of the four devices is shown in Table 5.

Scenario 2: The parameters related to oscillation center direction are set to allow action, regardless of whether the oscillation center lies in the positive or negative direction. The performance of the four devices is shown in Table 6.

(2) Incomplete phase oscillations caused by circuit breaker single phase tripping. In these scenarios, all four out-of-step oscillation separation devices do not act. These results satisfy the relevant specification requirements

The above tests show that the performance of the out-of-step oscillation separation devices based on the principle of compensated apparent impedance angle are consistent with the design principle.

5.2 Other disturbances

(1) Various short-circuit faults at different fault points.

The fault scenarios include: temporary and permanent single-phase-to-ground faults, phase-to-phase faults and three-phase faults at various locations along Line1, Line5 and Line9, while system faults disappear spontaneously with no change of network topology (simulating faults occurring at and cleared by other lines).

(2) Synchronous oscillations of the system and short circuit faults occur during a synchronous oscillation.

The fault scenarios in this test include: complete and incomplete phase oscillations, fault occurrences during an oscillation including short circuit at single point and successive alternate faults at the forward and backward directions of the device.

(3) Manual switching on a discharged line or a fault line.

The fault scenarios include manually switching on the line circuit breaker of the discharged line where the device is located, and manually switching on the line circuit breaker of the fault line where the device is located.

(4) TV and TA broken wires.

TV/TA single-phase or three-phase broken wires are simulated.

(5) Switching on/off the device power supply.

Under the above five disturbance scenarios, all four out-of-step oscillation separation devices operate correctly.

All the test results demonstrate that the functions and electrical performance of the out-of-step oscillation separation device based on the compensated apparent impedance angle meet the requirements of relevant technical specifications and standards.

6 Conclusion

In this paper, the influence mechanism of series compensation on the apparent impedance angle trajectory and out-of-step oscillation criterion is discussed. An improved criterion from the engineering application perspective is proposed. The effectiveness and validity of the proposed criterion have also been extensively tested using RTDS simulation. The conclusions of this investigation are summarized as follows:

(1) When an out-of-step oscillation happens in a two-machine system, the series compensation capacitor reduces the equivalent impedance angle while the maximum value of apparent impedance angle at each end of the line is less than 180°, and the higher the proportion of compensation, the smaller maximum value of apparent impedance angle. In severe

Table 6 Performance of the devices in test scenario 2

Oscillation center position	On/off strategies of series compensation capacitor	Device performances (action or not)				Results
		D1	D2	D3	D4	
BUS2–BUS3	All entry	Y	Y	Y	Y	Correct
	C1–C3 exit	Y	Y	Y	Y	Correct
	C4, C5 exit	Y	Y	Y	N	Correct
	All exit	Y	Y	Y	N	Correct
Near BUS3	All entry	Y	Y	Y	Y	Correct
	C1–C3 exit	Y	Y	Y	Y	Correct
	C4, C5 exit	Y	Y	Y	Y	Correct
	All exit	Y	Y	Y	Y	Correct
BUS3–BUS4	All entry	Y	Y	Y	Y	Correct
	C1–C3 exit	N	Y	Y	Y	Correct
	C4, C5 exit	Y	Y	Y	Y	Correct
	All exit	N	Y	Y	Y	Correct

cases, if the apparent impedance angle cannot pass through all four zones continuously, the separation device will not be able to identify the out-of-step oscillation.

(2) In order to avoid the risk of failure, a method of compensating the apparent impedance angle is proposed. An improved out-of-step oscillation criterion based on compensated apparent impedance angle trajectory is then presented to identify the out-of-step oscillation, regardless of the line equivalent impedance angle.

(3) Furthermore, as the apparent impedance angle at the moment of maximum current is equal to the equivalent impedance angle during an oscillation process, the compensated apparent impedance angle can be easily calculated in real time by separation devices. Therefore, the improved out-of-step oscillation criterion based on compensated apparent impedance angle is a good prospect for application. RTDS tests also verify that the new criterion is not affected by the system operational mode and has good reliability.

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Author contributions
HX as the first author and corresponding author, performed the simulation, analyzed the data, and wrote the paper. YC, XQ and ZD helped to revise the manuscript. All authors read and approved the final manuscript.

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Availability of data and materials
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Declarations

Competing interests
The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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References

1. Fang, Y. J., Liu, F. S., & Li, B. J. (2017). A review of out-of-step oscillation islanding control of large-scale power systems. *Proceedings of the CSEE, 37*(18), 5256–5265. (in Chinese).
2. Zhang, S., & Zhang, Y. X. (2016). A novel out-of-step splitting protection based on the wide area information. *IEEE Transactions on Smart Grid, 8*(1), 41–51.
3. Cai, M. M. (2017). Research on characteristics and controlled islanding strategy of the out-of-step power system based on multi-source information. *Southeast University* (in Chinese).
4. Lin, Z., Xia, T., Ye, Y., Zhang, Y., Chen, L., Liu, Y., Tomsovic, K., Bilke, T., & Wen, F. (2013). Application of wide area measurement systems to islanding detection of bulk power systems. *IEEE Transactions on Power Systems, 28*(2), 2006–2015.
5. Tealane, M., Kilter, J., & Pill, K. (2021). Real-time testing of out-of-step protection devices. In: *2021 IEEE PES Innovative Smart Grid Technologies Europe (ISGT Europe)*.
6. Zong, H. L., Ren, Z. Y., Zheng, Y. P., Shao, X. J., & Sun, G. H. (2003). An out-of-step splitting device based on the changing track of the voltage of oscillation. *Automation of Electric Power, 27*(19), 83–85. (in Chinese).
7. Fang, Y. J., Xu, H. B., & Li, X. M., et al. (2009). Application of UFV-200F out-of-step oscillation islanding control device in the first 1000 kV ultra high voltage AC power transmission demonstration project. In: *International conference on UHV power transmission*. Beijing, China.
8. Zheng, C., Chen, Y. H., Lu, S. Z., et al. (2021). Correction of oscillation center location by Ucosφ and wide area out-of-step splitting control. *Power System Technology, 45*(4), 1518–1526. (in Chinese).
9. Xie, H., Pan, L., Zhao, Q. C., et al. (2017). Research on the effect of UPFC and SC on line protection. *Power System Protection and Control, 36*(4), 137–142. (in Chinese).
10. Srivani, S. G., & Vittal, K. P. (2010). Adaptive distance relaying scheme in series compensated transmission lines. In: *International conference on power electronics, drives and energy systems (PEDES) and 2010 power India* (pp. 1–7). IEEE.
11. Od, N., Pradhan, A. K., & George, N. (2021). A hybrid time-domain protection scheme for series compensated transmission lines. *IEEE Transactions on Power Delivery, 37*, 1823–1833.
12. Dong, X. J., Zhao, J., Ling, C., Li, X. M., Li, H. J., Zhang, Z. Q., & Zhang, C. Y. (2010). Research on out-of-step oscillation criterion mechanism based on

principle of phase angle. *Power System Protection and Control, 38*(7), 1–6. (in Chinese).
13. Ren, J. F., Ding, Y. W., Fu, L., Chen, X., & Li, X. (2011). An improved strategy for out-of-step oscillation separation based on phase angle principle for 1000 kV ultra-high voltage AC power grids. *Automation of Electric Power, 35*(10), 104–107. (in Chinese).
14. Qu, Y. X., Shi, B. N., Liu, Z. C., et al. (2020). Improvement of out-of-step oscillation separation criterion based on apparent impedance angle. *Power System Protection and Control, 48*(5), 181–187. (in Chinese).
15. Wang, L. X., Fang, Y. J., Xu, H. B., Hou, Y. Q., & Zheng, Y. P. (2016). Mechanism analysis of successive commutation failures influence on out-of-step splitting criterion based on phase angle. *Automation of Electric Power Systems, 40*(9), 71–77. (in Chinese).
16. Tang, F., Liu, J., Liao, Q., Liu, Y., Xiao, G., & Wang, C. (2018). Location and migration laws of out-of-step center under multi-frequency oscillation based on voltage phase angle trajectory. In: *2018 IEEE power and energy society general meeting (PESGM)*. IEEE.
17. Liu, F. S., Fang, Y. J., & Wu, X. L. (2015). Adapt-ability and countermeasures of splitting criterion based on phase angle in complex scenarios. *Automation of Electric Power Systems, 39*(16), 71–75. (in Chinese).
18. DL/T 993-2019 (2008). *General specification for power system out-of-step oscillation separation equipment*. Beijing: China Electric Power Press (in Chinese).