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Problems and countermeasures of arc suppression coil in 10 kV distribution system

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Abstract: The arc suppression coil determines whether it can effectively extinguish the arc when it is grounded in the neutral non-effective grounding system. An artificial grounding test is an important way to verify its performance. In this study, 13 substations with the 10 kV system in the Ningxia area were selected and considered. Based on the artificial single-phase grounding test, the residual current, the compensation current and the off-resonance degree were measured in the arc suppression coil, and the performance of the arc suppression coil in the 10 kV system was verified. The experimental results show that the error of arc suppression coil automatic measurement is large, the off-resonance degree is large, the resistive component in the compensation current is excessive, the harmonic component exists in the compensating current and capacitive current. To solve these problems, this paper puts forward the corresponding countermeasures for reference.

Key words: arc suppression coil, capacitive current, artificial grounding fault test, neutral non-effective grounding system

1. Introduction

The arc suppression coil grounding is the main grounding mode of the 10–35 kV system in China. It has played the vital role for the distribution network safe movement relying on long time applications and mature technologies [1, 2]. In recent years, as the grid expands and the rate of cabling in urban areas is increasing, the system capacitance current increases continuously. In order to reduce the residual current of the fault point when the single-phase grounding occurs, many research institutes and power supply companies have done a lot of research and technical improvement on the arc suppression coil at present [3–5].

In the distribution network system, the grounding mode is mainly divided into the neutral point ungrounded, the neutral point with low resistance grounding and the neutral point with arc suppression coil grounding. The neutral point ungrounded can make the system continue to run in single-phase grounding. It is simple and economical, but it only applies to the case that the capacitance current of the system is less than 10 A. The neutral point with low-resistance grounding can use the simplest zero sequence over a current protection device to cut off the fault line selectively. Neutral point grounding with an arc suppression coil has been applied for nearly a hundred years as a mature technology. It was first invented by W. Petersen in Germany, also known as a ground fault neutralizer in the United States. The arc suppression coil can compensate the grounding capacitance current of the power network and extinguish the grounding arc itself when the single-phase ground fault occurs.

2. Theory and structure

The compensated network containing the arc suppression coil is shown in Fig. 1. If there is a ground fault on the k point of the A phase line, it can be an equivalent to the single phase direct ground fault ignoring the influence of the grounding resistance and arc resistance. At this time, the fault phase voltage of U_A reduces to zero, the neutral point voltage of U_0 shifts to U_A, the non-fault phase voltage of U_B and U_C rises to the line voltage of U'_B and U'_C. Although the neutral point of the power network has been displaced, the generator and power user do not respond to the single-phase ground fault. Under this condition, the compensation network is allowed to continue to run in a certain time.

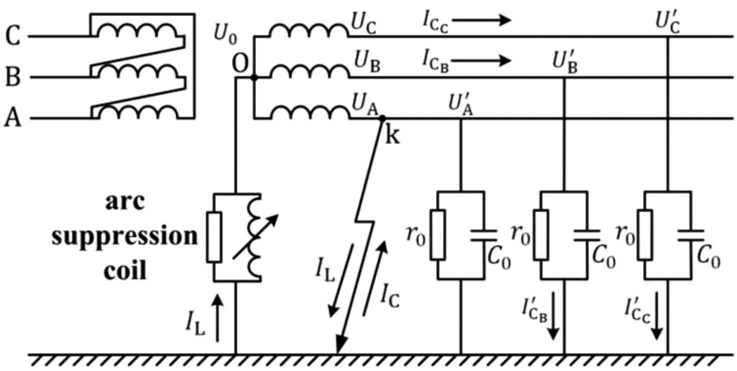

Fig. 1. Diagram of compensation network for single-phase grounding fault

The grounding residual current of the k point is I_δ. Its value is

$$I_\delta = I_R + j(I_C - I_L), \tag{1}$$

$$I_R = \frac{U_0}{R}, \tag{2}$$

$$I_C = 3\omega C_0 U_0, \tag{3}$$

$$I_L = \frac{U_0}{\omega L}, \tag{4}$$

where: I_R is the active component in the residual current, I_C is the grounding capacitance current of the power network, C_0 is the single-phase capacity, I_L is the compensating current of the arc suppression coil and L is the system inductance including arc suppression induction and line inductance. v is the off-resonance degree of the power network or the arc suppression coil.

$$v = \frac{I_C - I_L}{I_C} \cdot 100\%. \tag{5}$$

Because the inductor current of the arc suppression coil compensates the grounding capacitance current of the power network by adjusting inductance, the grounding current of the fault point becomes a residual current which is significantly reduced numerically, so the arc is easily extinguished when the residual current passes through zero.

But the arc suppression coil still has a lot of problems during the actual operation. However, due to the small amount of data, it is difficult to do statistical research. Besides, the available data are typically without a waveform and calibration measured in the arc suppression coil. The artificial grounding test help to study arc suppression coil performance because it can simulate the real grounding situation in the actual system and record the waveform [6].

3. Test

For the observation, 13 substations were selected in Ningxia. Through the artificial single-phase grounding test, the grounding residual current, compensation current and off-resonance degree of the arc suppression coil were measured, and the arc suppression coil performance in the 10 kV neutral non-effective grounding system was evaluated.

3.1. Test circuit

The artificial single-phase grounding test is shown in Fig. 2. The ground point was set on the 10 kV overhead line outside the substation. The overhead line and the test connection were connected with an insulated grounding rod. The lower end of the test connection was a fast switch in series with a HL28-12 type high voltage current transformer and an earth electrode with a grounding resistance less than 20 ohms. The ground current was recorded at the test site via a HIOKI 8861 transient parameter recorder. The bus voltage, the open triangle voltage and the compensation current in the arc suppression coil were recorded in the station via another HIOKI 8861 transient parameter recorder. The rated voltage of the fast switch is 40.5 kV, the rated current is 630 A, the closing time is less than 15 ms, the switching time is less than 5 ms and the accuracy level of the high voltage current transformer is 0.05.

3.2. Test process

First, the arc suppression coil was exited. In the case of complete safety measurements, the fast switch was closed to carry out the artificial direct grounding test, and the grounding current, the three-phase voltage and the open three-phase voltage were recorded by the transient parameter recorder. After 2 s, the fast switch was open. This test mainly measured the ground current to obtain the capacitance current value of the system.

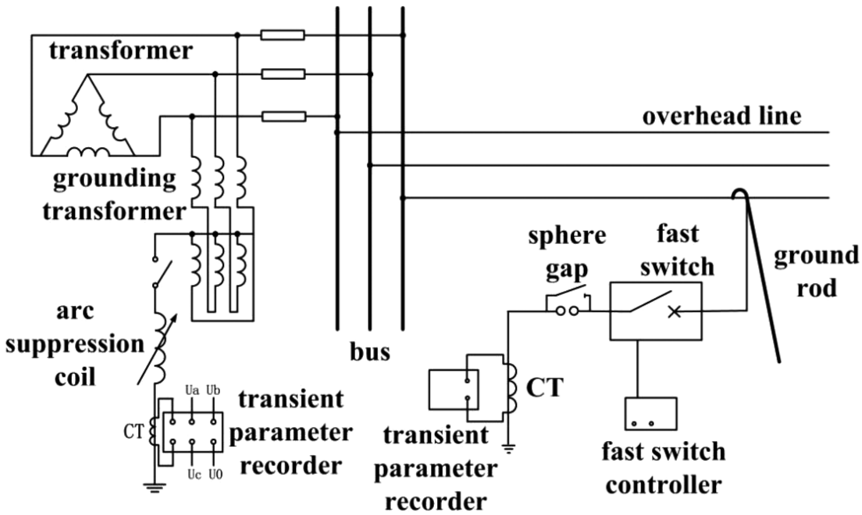

Fig. 2. Schematic diagram of single phase grounding test using fast switch

Then, the arc suppression coil was operated and the fast switch was closed to carry out the artificial direct grounding test. The grounding current, the three-phase voltage, the open three-phase voltage and the compensating current of the arc suppression coil were recorded by the transient parameter recorder. After 2 s, the fast switch was open. This test mainly measured the earth current, the residual current and the compensating current, while the off-resonance degree was calculated;

Finally, the artificial gap was inserted in the ground line. The artificial gap was made up of two adjacent metal spheres of equal diameters whose separation distance is 3 mm. The fast switch was closed to carry out the artificial arc grounding test by 2 s with measuring the grounding current, the three-phase voltage, the open three-phase voltage and the compensating current of the arc suppression coil. This test mainly observed the situation of arc.

During the test, the capacitance current, the compensation current, the residual current and the off-resonance degree of the arc suppression coil should be recorded at the station screen cabinet.

4. Test results and analysis

According to the test plan, artificial single-phase grounding tests were done in the 10 kV system of 13 substations in the Ningxia area. The main parameters of the arc suppression coil is shown in Table 1, covering the arc suppression coil mainstream manufacturers, main parameters, main compensation principle and operation date. According to the analysis of the test results, the following problems were found:

Table 1. Technical parameters of arc suppression coil

Substation	**Capacity kVA**	**Tap number**	**Current regulation range/A**	**Type**	**Commissioning date**
A	630	15	20–105	control inductance	2014.04
B	400	17	10–66	control capacitance	2005.11
C	800	19	5–110	control capacitance	2011.08
D	1 100	19	50–181	control inductance	2014.11
E	1 100	19	50–181	control inductance	2014.11
F	1 000	19	50–165	control inductance	2013.09
G	1 200	19	25–200	control capacitance	2011.11
H	450	19	5–75	control capacitance	2010.05
I	315	9	15–50	control inductance	2015.12
J	400	16	0.5–67.4	control inductance	2014.12
M	315	15	15–50	control inductance	2014.11
L	630	15	20–105	control inductance	2015.03
N	1 000	19	45–160	control capacitance	2012.11

4.1. The error of arc suppression coil automatic measurement

To obtain the proper off-resonance degree, the arc suppression coil, in this study, needs to adjust the corresponding gear according to the capacitive current measured by the equipment before being grounded [7]. The proper off-resonance means the difference between the variable coil inductance value and the actual capacitive current is less than 10 A. This method is called arc suppression coil automatic measurement. Therefore, the correct system capacitance current measurement before grounding is the key to see whether the coil can perform arc suppression and ensure the system safety.

According to the performance test of the arc suppression coil, the capacitance current value was measured automatically and the corresponding calculated value of the ground residual current was compared with the actual value, as shown in Table 2. The relative error δ_I is

$$\delta_I = \frac{I_D - I_M}{I_M} \cdot 100\%, \tag{6}$$

where: I_D is the current value displayed from the arc suppression coil automatically, I_M is the current value measured from a single-phase grounding test.

In addition to substations A, J, M, L, other stations arc suppression coil capacitance current measurements, whose relative error was over 20%, showed that the actual values were significantly different. The substations B, E and N showed that the capacitance current value was 0, and the arc suppression coil could not completely calculate the off-resonance degree, which made it impossible to adjust the gear according to the change. Due to the automatic measurement error of a capacitive current, the expected grounding residual current and the actual residual current would be greatly difference.

Table 2. Automatic measurement value and actual value of arc suppression coil

Substation	Capacitive current/A			Ground residual current/A		
	Measured value	Display value	Relative error	Measured value	Display value	Relative error
A	59	50.76	−14.0%	6.0	14.6	143.3%
B	356	0	−100.0%	269	0	−100.0%
C	403	106.9	−73.5%	294	55.1	−81.3%
D	187	24.6	−86.8%	136	24.4	−82.1%
E	388	0	−100.0%	304	0	−100.0%
F	265	192.36	−27.4%	112	24.36	−78.3%
G	655	111.4	−83.0%	398	6.5	−98.4%
H	296	20	−93.2%	280	1.4	−99.5%
I	2.3	19.5	747.8%	12.4	4.2	−66.1%
J	75	72.8	−2.9%	10.9	8.2	−24.8%
M	22.1	22.82	3.3%	13.2	2.87	−78.3%
L	12	13.66	13.8%	5.0	5.27	5.4%
N	374	0	−100.0%	226	0	−100.0%

4.2. The off-resonance degree

The index value of the arc suppression coil in the performance test was shown in Table 3. In addition to substations I and L, other substations were under compensated at the experimental

Table 3. The value of arc suppression coil in performance test

Substation	Current regulation range/A	Measured capacitive current/A	Compensating current/A	Tap position	Grounding residual current/A	Off-resonance degree
A	20–105	59	53	11	6	10.2%
B	10–66	356	62.5	16	269	82.4%
C	5–110	403	57	16	294	85.9%
D	50–181	187	51	1	136	72.7%
E	50–181	388	84	12	304	78.4%
F	50–165	265	153	19	112	42.3%
G	25–200	655	121	16	398	81.5%
H	5–75	296	16	2	280	94.6%
I	15–50	2.3	12.7	1	12.4	−452.2%
J	0.5–67.4	75	64	1	10.9	14.7%
M	15–50	22.1	16.7	7	13.23	24.4%
L	20–105	12	17.3	1	5	−44.2%
N	45–160	374	139	18	226	62.8%

stage. Because the deviation between the automatic measuring value of a capacitive current and the actual value was small in the A station, the grounding residual current was in the 10 A range when the gear was under offset, and the arc could normally extinguish in the test. However, the other substations were characterized by a large off-resonance degree and poor compensation, and there was a large arc of a continuous current in the artificial arc grounding test. If this situation occurs in the actual operation stage, it will further expand the fault to a certain degree, resulting in a two-phase short-circuit, tripping, even explosion of cable accessories and other accidents.

The poor compensation cause of the arc suppression coil is that, on the one hand, as shown in the 2.1 section, the arc suppression coil could not properly measure the actual capacitive current, resulting in the gear position adjustment not in line with the actual demand. On the other hand, with the current actual capacitance increasing with the system line and other reasons, it is far higher than the design value when the arc suppression coil is put into operation, and it leads to the compensating range beyond the arc suppression coil. The arc suppression coil still cannot compensate efficiently in the most advanced tap position.

In addition, the off-resonance degree of substation I was more than 100%, because the station was the new power plant investment and the actual operation of the transmission line was less. As the capacitance current was low, the arc suppression coil should quit operation, or even in the lowest tap position, the grounding residual current would still exceed 10 A. It caused continuous arc whose current waveform was shown in Fig. 3.

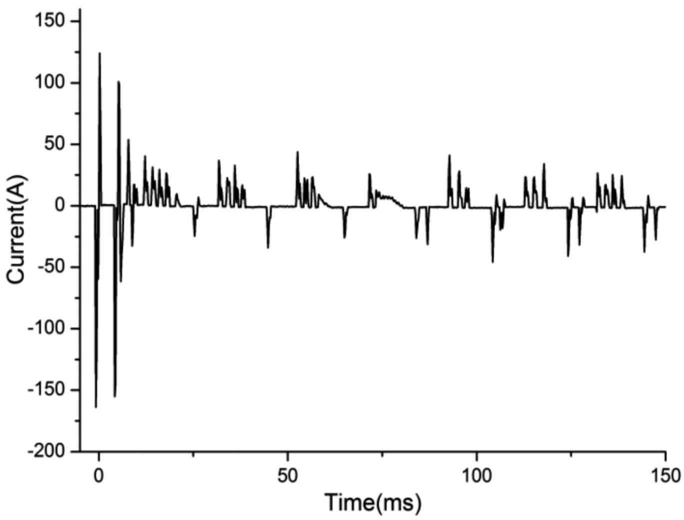

Fig. 3. Arc grounding current waveform of substation I

4.3. Resistive component in the compensation current

In this test, the phase relation between the neutral point current and the voltage was obtained through the arc suppression coil and the resistive component in the compensating current was calculated. Table 4 is the resistance current parameter of the arc suppression coil compensation current of 8 substations which meet the measurement conditions.

Table 4. Resistive component in the compensation current of arc suppression coil

Substation	Compensating current/A	Resistive component/A	Resistive component ratio	Tap position
A	53	3.3	6.2%	11
B	62.5	7.8	12.5%	16
G	121	20	16.5%	16
I	12.7	6.1	48.0%	1
J	64	8	12.5%	1
M	16.7	3.1	18.6%	7
L	17.3	1.1	6.4%	1
N	139	21.7	15.6%	18

The resistive component of the arc suppression coil of substation G and N exceeded 20 A, which caused the residual current to be excessive in the compensation. Thus, even if the arc suppression coil inductance fully compensates the capacitive current of the system, the arc cannot be extinguished. There might be two reasons for this. On the one hand, the arc suppression coil damping resistance was not shorted when the line was single-phase grounded, and, on the other hand, the coil had too high DC resistance.

4.4. Harmonic component in the compensating current

When the substation J carried on the direct and the arc grounding tests, the neutral point current (compensating current) in the arc suppression coil possessed the odd harmonic component, as shown in Figs. 4 and 5. Its harmonic characteristic is shown in Fig 6. Although the residual

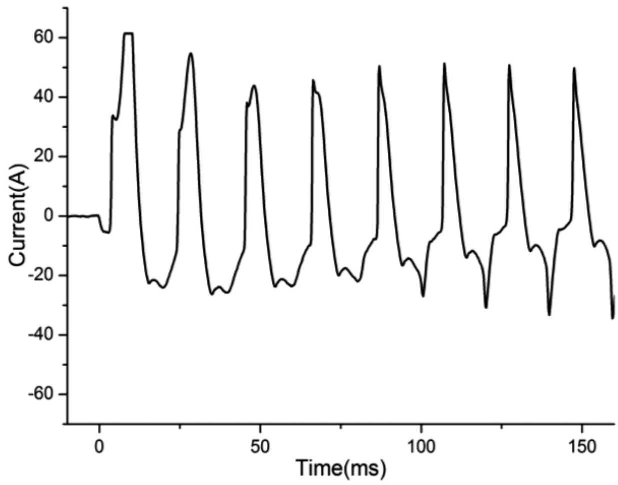

Fig. 4. Compensation current of substation J in direct grounding test

current was 10.9 A and the amplitude was small, there was still a continuous arc current in the arc grounding test, as shown in Fig. 7. Part of the reason why the arc couldn't be extinguished was that the harmonic component was introduced by the compensation current, and this harmonic component was due to the saturation of the arc suppression coil. This situation should be avoided as much as possible.

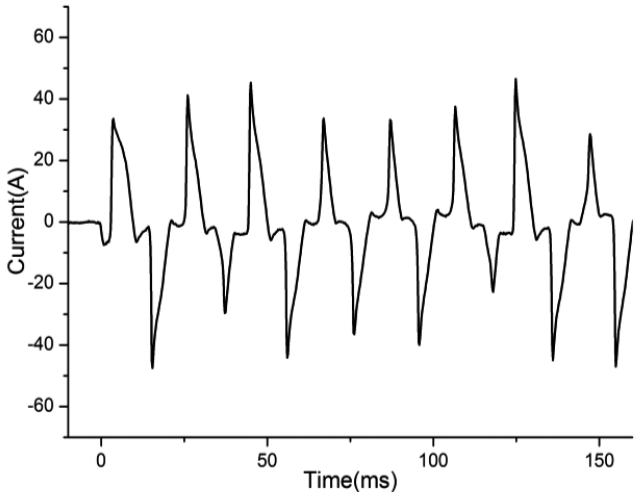

Fig. 5. Compensation current of substation J in arc grounding test

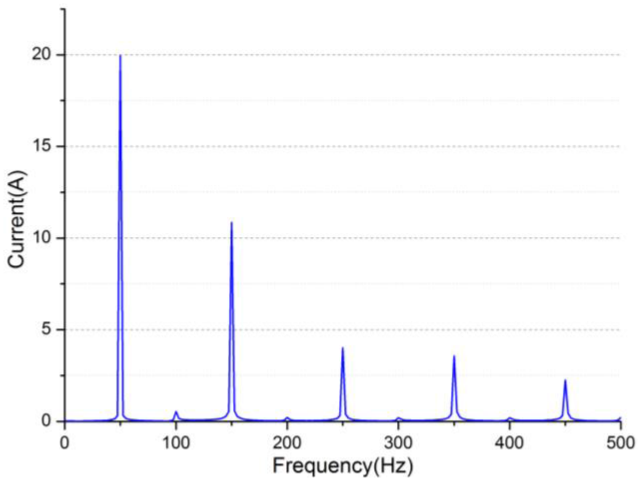

Fig. 6. Harmonic characteristics of compensation current in substation J

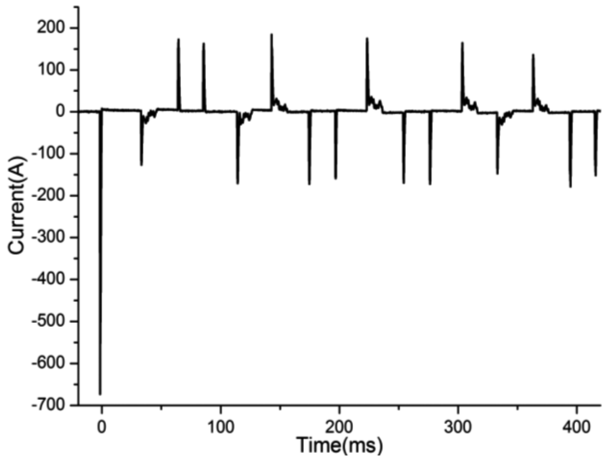

Fig. 7. Arc grounding current waveform of substation J

4.5. The harmonic component in the capacitive current

In the artificial grounding test of substation D, there was a rich harmonic set in the ground current, as shown in Fig. 8 and the harmonic characteristic is shown in Fig. 9. It was seriously polluted by the harmonic ;pollution in the 10 kV system, especially some harmonics exceeding the standard of the 5 harmonic. Because the harmonic frequency of waveform tends to be $K = 6$ N ± 1, it is suspected that it is caused by a three-phase six-pulse full-wave rectifier, which may come from wind, photovoltaic power plants or new energy vehicle charging stations.

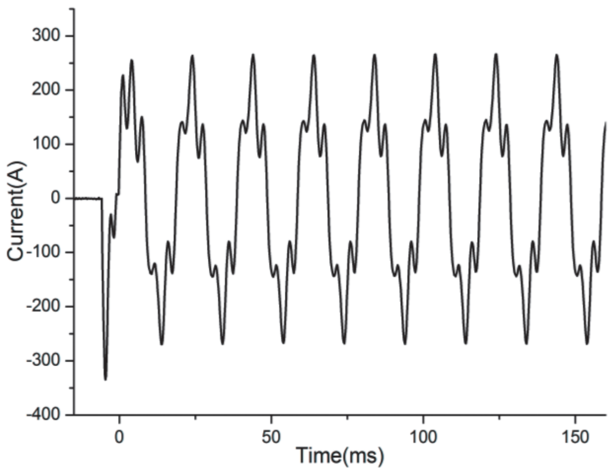

Fig. 8. Direct grounding current waveform of substation D

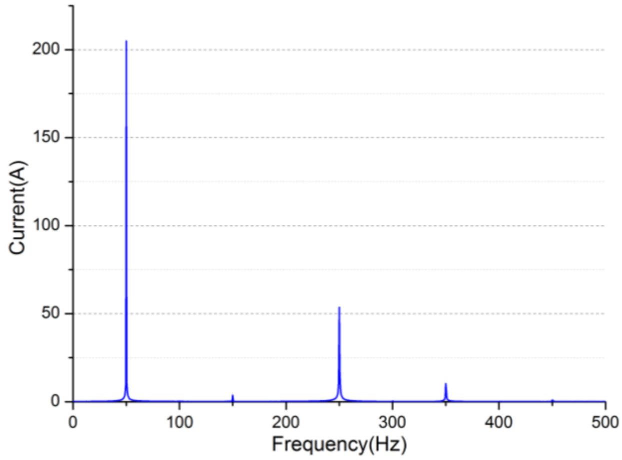

Fig. 9. Harmonic characteristics of direct grounding current in substation D

When serious harmonics appear in the system, on the one hand, it will cause great influence on the measurement of a capacitance current, such as the measurement in the D substation. The relative error is −86.8%, causing the error of arc suppression coil position adjustment. On the other hand, the arc suppression coil cannot compensate a harmonic component that results in a large grounding residual current.

5. Countermeasures

According to the problems arising from the arc suppression coil performance test, the following countermeasures are put forward:

1) Strengthen the arc suppression coil acceptance, operation, test and maintenance management. The indication of a capacitance current, line selection and arc suppression coil action should be checked periodically. The display value of 0 should be promptly repaired.

2) Follow the tracks of a capacitance current variation trend. For the distribution network with a wide range and high cable rate, the checking period of the capacitance current should be shortened. If the capacitance current exceeds the arc suppression coil capacity, the system should be upgraded in time.

3) As a result of the popularisation of cable lines, in comparison to overhead ones in large agglomerations, the modernization activities of compensation systems should be synchronized with design works and the implementations of the network expansion with new connections. It requires the joint efforts of the planning, design, construction and management departments of the distribution network.

4) The enhance research and application of a new arc suppression device. For example, the full current compensation technique is necessary for systems with large resistance components and large harmonic components. For an excessive capacitor current system (more than 150 A), an active intervention arc suppression device (arc suppression cabinet) is recommended. For the distribution network system with upgrade capability, a variety of arc suppression devices can be installed in a distributed manner.

6. Conclusion

In this observation, the artificial grounding tests of arc suppression coils of the 10 kV distribution system in 13 substations in the Ningxia area was carried out, and the following conclusions are drawn:

1) The artificial grounding test combined with the fast grounding switch could effectively and safely verify the performance of the arc suppression coil.

2) In addition to the normal arc suppression coil operation, there are different problems: the error of arc suppression coil automatic measurement is large, the off-resonance degree is large, the resistive component in the compensation current is excessive, the harmonic component exists in the compensating current and capacitive current. These problems will affect the arc suppression coil, so that the distribution system cannot extinguish the arc in the grounding, and further expand the fault.

3) To ensure the safe and reliable operation of a distribution network system for the related problems exposed in the arc suppression coil performance, acceptance, operation, test and maintenance management should be strengthened, the tracks of the capacitance current variation trend need following, the research and application of new arc suppression device should be enhanced.

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