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# Fault location in the outer sheath of power cables

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## Abstract

With the development of power systems in recent years, the total amount of power cables in operation has increased greatly, and there are growing reports of cable failure. Cable failures may be due to various intrinsic or extrinsic factors and can lead to massive economic loss. With regard to high-voltage cables, such as 110 kV power cables, there are very few accurate reports on the actual fault observed. This article first analyses the possible causes of power cable outer sheath failure. It then introduces the bridge and step voltage methods, which are traditionally used for cable fault locating, and describes a new method for accurate fault locating in 110 kV cables, which uses the bridge method to pre-locate the fault and then the step voltage method to accurately determine the precise fault locating. Field testing confirms the applicability of the new method for accurate fault locating in 110 kV power cables. The results shown in this article may provide a good reference for the development of future research in related fields.

*Keywords:* Power cable outer sheath, Fault locating, Bridge method, Step voltage method

## 1. Introduction

Power cables are the major component of electric power grids, serving as a means of power transmission and distribution, and include outgoing lines from power plants, cross-river and cross-ocean underwater transmission lines, city underground grid systems and internal power supplies for industrial and mining enterprises. In recent years, city power grids have grown, and cables are used increasingly widely, playing an extremely important role in daily city life. As an example, the length of power cables in one city in China reached 725 km by the end of 2007, accounting for more than 40% of the entire 10 kV distribution network lines in that city [1]. Furthermore, in 2002, the length of cables carrying more than 10 kV in the power grid of Guangzhou City reached 3885 km [2]. By April 2010, the number of 110 kV and 220 kV power cables under the management of the cable section of the power distribution department of Shenzhen Power Supply Bureau reached 190 km, and the total length was 412 km [3]. Any damage to cables may result in blackouts or even more serious consequences. A typical example to illustrate this point is the power transmission failure that resulted from an oil leakage and subsequent pressure loss in the 500 kV oil-filled cable at Shajiao Plant C, which was caused by white ants [4]. This led to significant direct losses, as well as further in-

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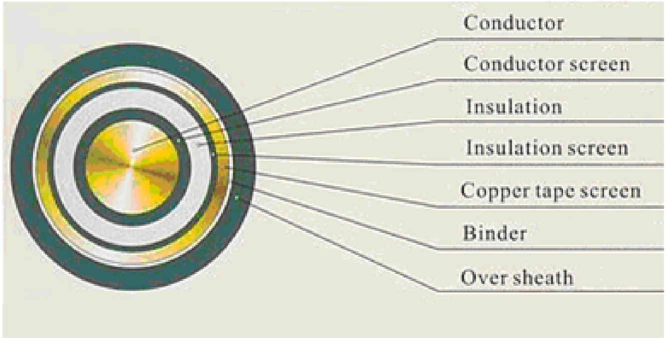


Figure 1: Structure of the single-core cable

calculable losses due to the subsequent blackout. In July 2012, a blackout at a pipe plant in Changzhou City, Jiangsu Province, resulted in a sudden shutdown of the processing and production line, and the furnace charge of that production batch was a total loss. Furthermore, components in the manufacturing plant cracked due to the sudden cooling, and the preliminary estimated economic loss amounted to more than 100,000 Yuan.

At present, the step voltage and bridge methods are commonly used to locate cable outer sheath faults [5–10]. The bridge method is based on the bridge balance principle, and it is applied by measuring the degree of deviation in resistance. The location of the fault can then be calculated based on the relationship between the resistance and the cable length. The step voltage method relies on measuring the degree of potential deviation between different points, with the location of the fault being determined according to the deflection and sway of the pointer.

In this article, the bridge method is first used to broadly pre-locate the fault in a 110 kV cable (Shuhui Transmission Line), and then the step voltage method is used to find the precise location of the fault. Through actual measurement, it has been confirmed that the pre-locating voltage method and the accurate fixed point step voltage method are both applicable to status evaluation and fault locating in 110 kV cable outer sheaths. The study described in this article can be used as a reference for future research.

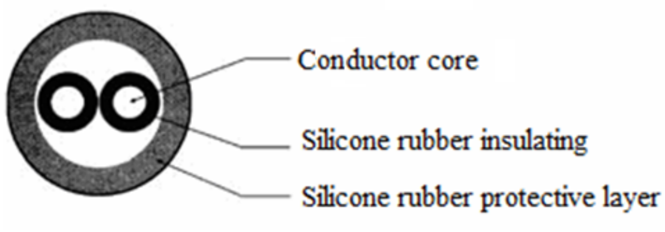


Figure 2: Structure of the twin-core cable

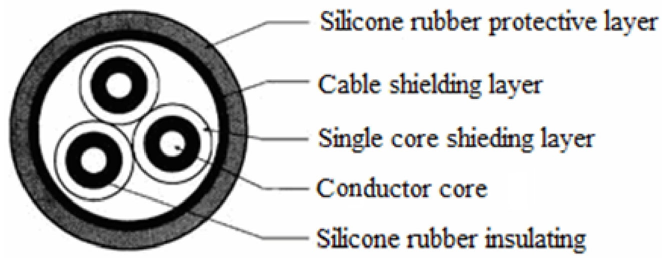


Figure 3: Structure of the three-core cable

## 2. Power cable outer sheath and its faults

Power cables are classified as single core or multi-core, depending on the type of conductor core [11], and the different structures are shown in Fig. 1...4. The power cable consists of a conductor core, a conductor shielding layer, a silicone rubber insulating layer, a silicon rubber insulating and shielding layer, a copper strip shielding layer, a non-woven fabric layer and the outer sheath layer, which varies with the number of cores.

As shown in the figures, the outer sheath is the outermost layer of the cable. As there may be electromagnetic induction when the cable is in use, a comparatively high induced voltage can be generated between the core and the metallic shielding layer of a long, high-voltage cable. To prevent the induced voltage from circulating in the metallic shielding layer [12], the insulating performance of the outer sheath has to be strengthened, and the cable must be

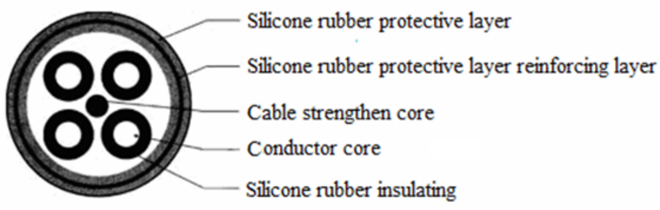


Figure 4: Structure of the four-core cable

Figure 5: Cables eroded by white ants

protected against mechanical damage and chemical corrosion. Therefore, the outer sheath has to be both insulating and provide adequate mechanical strength. Its constituent materials mainly include polyethylene (PE) and polyvinyl chloride (PVC).

There are many reasons for power cable faults. According to the Chinese National Standard GB/T11017-2002, after the completion of cable manufacture and installation, a high-voltage insulation test should be conducted. For the outer sheath of 110 kV cables, a DC test of 25 kV that lasts for 5 minutes should be conducted at the factory upon completion of manufacturing, and a DC test of 110 kV that lasts for 1 minute should be conducted upon completion of cable installation [13].

The main causes of power cable faults are described below.

1. Cable construction. For example, the Shenzhen Power Supply Bureau conducted a preventive test on the outer sheath of 150 of the 170 cables in its control between June 2004 and July 2009 [14], and only 64% of the high-voltage cable outer sheaths passed the test, with grounding faults being discovered in the outer sheath of 36% of the tested cables. The outer sheath had been damaged during cable laying—scratched or scored by hard articles, the sharp corners of laying tools, nails on the pre-cast template in the cable tunnels or supports in the cable duct.

Figure 6: Cables damaged by theft

2. Technical inadequacy during construction. The semi-conducting layer and the grounding wire of the cable were not properly treated during construction of the cable accessories, resulting in an electric conduction path and insulation breakdown.
3. Ingress of water into the grounding box. There are three common kinds of grounding boxes: a direct grounding box for the cable sheath; a protective grounding box for the cable sheath; and a protective grounding sheath for the cross interconnection of cables. The grounding box for the cable sheath is used for direct grounding of the cable sheath, and the protective grounding boxes for the cable sheath and for cross interconnection of cables are used for protective grounding of the cable sheath. Ingress of water into the grounding box prevents the power cables from conducting electricity, and may result in a short circuit or an even more serious accident.
4. White ant erosion. In February 2004, the Guangzhou Power Supply Bureau assisted the municipal government with the construction of the Guangzhou Bridge Tunnel. During relocation of the cables from Yangji Station to Jiefang Road, 150 m of cables were recovered, and there were a total of 64 points where they were bitten through by white ants, as shown in Fig. 5.
5. Damage caused by theft after cable laying. The cables contain valuable metals such as copper,

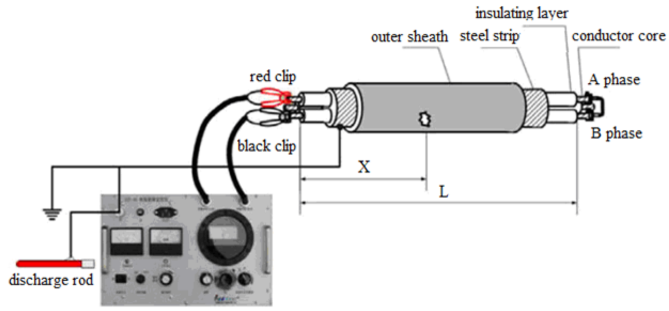


Figure 7: Detection principle of the bridge method connection diagram

and theft and attempted theft may cause damage to the cables (Fig. 6).

## 3. Fault detection methods for the outer sheath

Fault detection in the outer sheaths of power cables generally relies on both "rough" and “accurate” locating methods. The “rough" location methods are used to locate the fault point in the cable, and are also called the pre-locating methods for outer sheath faults. The most common "rough" location method is the bridge method, although for major cable insulation faults, the echo reflection method [15] may be applied for pre-location. Accurate location mostly relies upon the step voltage method, although the voice frequency method, the DC surge method and the comprehensive method can also be used.

$$\frac{r_i}{r_z} = \frac{R_i}{R_z} = \frac{X}{2L - X} \tag{1}$$

The detection principle of the bridge method—also called the Murray loop bridge—is shown in Fig. 7 and Fig. 8. Phase A and Phase B are connected, the cable resistance is equivalent to $r_i$, $r_z$, $R_i$ and $R_z$ in the bridge, and the resistance to ground of the fault point is equivalent to $R_p$. When the bridge balance is achieved, Formula (1) can be used to determine the location of the fault point. However, the insulating resistance of the fault point may vary with humidity and temperature, as well as with the damage to, and the materials of, the outer sheath. In addition, this method can be affected by various external factors [12], which is why it can only be used for "rough" location.

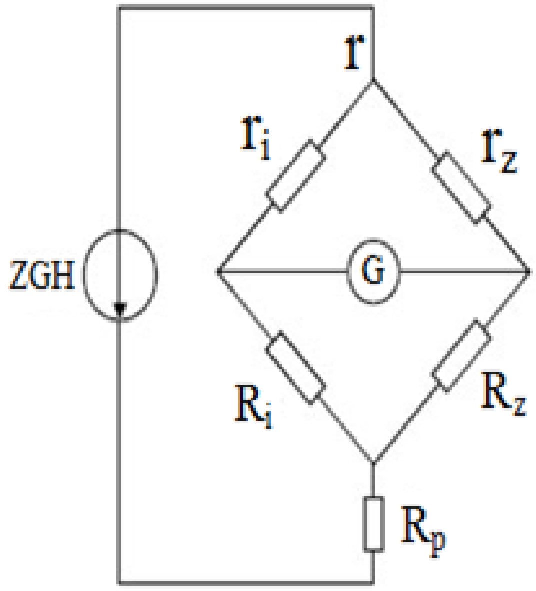


Figure 8: Detection principle of the bridge method

The principle of the step voltage method is shown in Fig. 9. It is applied by using a step voltage reflecting machine to send out voltage signals. As the outer sheath at the point of the fault is damaged, the cable will directly connect with the ground. The galvanometer on the step voltage receiver measures the potential of the circuit, and the pointer will point to the middle position when the galvanometer is just above the fault point, whereas when the galvanometer is located to the left of the fault, the pointer will deflect rightwards, and when the galvanometer is to the right of the fault, the pointer will deflect left-

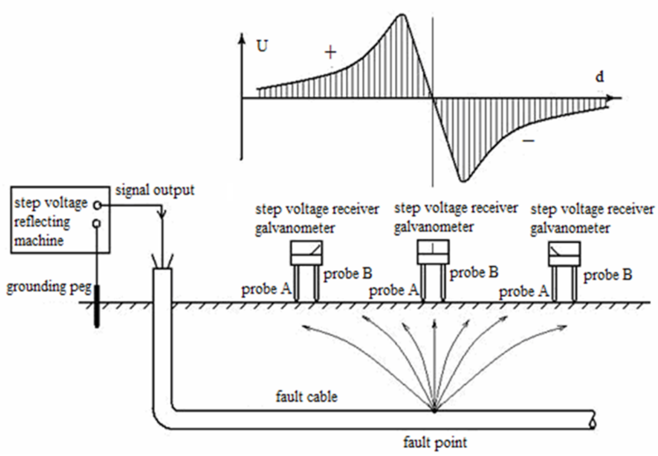


Figure 9: Principle of the step voltage method

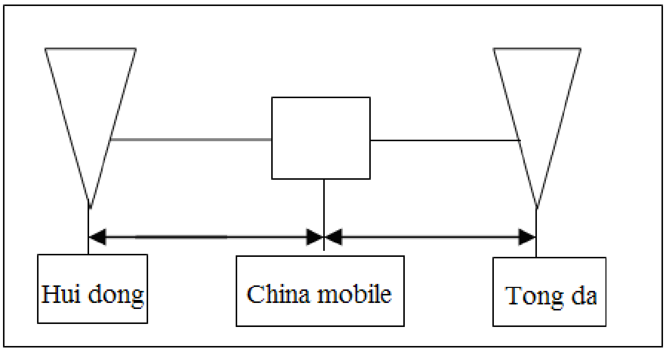


Figure 10: Schematic diagram of the 110 kV extra-high-voltage power cable line in Zigong (Shuhui Line)

wards. In theory, the larger the angle of deflection is, the further the distance is from the fault. This method requires no reading or calculation, and it is very simple to use—and the result is more accurate.

The audio frequency locating method is based on a similar principle to the step voltage method, but is less intuitive. The comprehensive locating method is used in some complicated circumstances, and the measurements required are also quite complicated.

## 4. Actual measurement for outer sheath fault locating

To study the accurate location of power cable outer sheath faults in a better way, a location test was conducted on the outer sheath fault of a 110 kV cross-linking power cable (Shuhui Line). As required by Zigong Power Supply Co., Ltd. of the State Grid Sichuan Electric Power Company, Bartsu Instrument Supply (Shanghai), Ltd. carried out a de-energized test for fault locating in the outer sheath of a 110 kV power cable (Shuhui Line), and accurately located the fault on the outer sheath between the direct grounding box of China Mobile and the protective grounding box of Huidong Substation.

### *4.1. Insulation resistance test on the outer sheath*

#### *4.1.1. Test conditions*

1. Rated voltage of the cable: 64/110 kV (Fig. 10).
2. Cable model: YJLW02-64/110 kV 1×400 mm$^2$.
3. Cable manufacturer: Jiangsu Baosheng Prysmian Co., Ltd.
4. Number of cable accessories: two groups of cable terminals, respectively located at Huidong Substation and #31 steel pipe pole along the Shuhui Line (both JB protective grounding boxes); one group of straight joints, located at China Mobile (the JD direct grounding box was fixed on the wall of the cable duct at the gate of China Mobile).
5. Installation of the cable accessories: Changlan Electric Technology Co., Ltd (Changsha Cable Accessories Co., Ltd.).
6. Overall length of the cable: 1,33 km, divided into two sections: the first section was 683 m long (from Huidong Substation to China Mobile); the second section was 650 m long (from China Mobile to the #31 steel pipe pole of Shuhui Line). They are shown in Fig. 11 and Fig. 12.

Figure 11: Shuhui Line cable termination, the 122 equipment interval of Huidong Substation

#### *4.1.2. Test results*

The test results of the outer sheath insulation resistance, according to the 110 kV Cable (Shuhui Line AC Voltage Withstand Test Report) of 21 June 2013, are given in Table 1. The testing organization was the Anzhao Debugging Branch of Luzhou Special Transformer Co., Ltd.

According to the Power Safety Specification, electricity testing and ground sealing were carried out on Huidong Substation and #122 and #31 poles of the Shuhui Line at 8:30 am on 30 November 2013. The

Table 1: Outer sheath insulation resistance test table

| Voltage application point | Phase A | Phase B | Phase C | Remarks |
|---|---|---|---|---|
| Insulation resistance, MΩ | 50 | 0 | 0 | Megameter: 2500 V |
| Insulation resistance, MΩ | ∞ | 18 | 2.2 | Measurement by digital multimeter |
| Test results | Pass | Insulation resistance unqualified | Insulation resistance unqualified | / |

Table 2: Ground insulation resistance test table for various metallic protective layers

| Voltage application point | Phase A | Phase B | Phase C | Remarks |
|---|---|---|---|---|
| Insulation resistance, MΩ | 25 | 3 | 0 | Megameter: 2500 V |
| Insulation resistance, MΩ | ∞ | ∞ | 0.002 | Measurement by digital multimeter |

cable conductor cores on the two sides were separated from the system. At 9:30 am, a 2.5 kV megameter (model: ZC-11, manual) and a digital multimeter were used to measure the ground insulation resistance of each metallic protective layer. The results are given in Table 2.

According to Table 1, the entire cable line passed the major insulation voltage test; the insulation resistances of outer sheaths B and C were 0 MΩ and required testing again after inspection.

According to Table 2, the insulation resistance of Phase B and Phase C cable outer sheaths failed the test and required testing again after inspection. The outer sheath of Phase A could be used as the comparatively better phase.

### 4.2. *Outer sheath fault pre-location test*

#### 4.2.1. *Test conditions*

At 10:30 am on 30 November 2013, the wrinkled copper sheath of Phase C and the conductor cores of Phase A and Phase C were short circuited and suspended on pole no. 31, with pole no. 31 as the far end of the voltage method (Fig. 13).

Actual measurement and grounding were at 11:15 am on 30 November, and the Bartsu MFM10 main machine was placed in the interval of 122 Equipment at Huidong Substation. Then, once it was ensured that the conductor cores and metallic protective layers of Phases A, B and C were all grounded, the metallic layers of the three phases were short circuited and suspended at the cable terminals of China Mobile, with the metallic protective layer of China Mobile as the far end of the voltage method (Fig. 14).

At 11:45 am on 30 November, as shown in Fig. 15, an auxiliary phase voltage method was applied, considering the metallic protective layer of Phase A as the auxiliary phase and ignoring the conductor core of Phase C. Then, MFM10 was connected with the metallic protective layers of Phases A and C. Thus, the overall input length was 1.33 km (683 m + 650 m).

#### 4.2.2. *Test results*

The test conducted at 10:30am showed that the broken metallic protective layer of Phase C was not conductive, based on the proximal measurements. The metallic protective layers of Phases A and B were then checked and shown to be broken and incapable of conducting electricity. It was also confirmed that the installation of the direct grounding box of China Mobile was defective, with non-straight joints having been used. A further defect in the equipment was discovered, and reconstruction was deemed necessary during the next power-down maintenance.

The results of the test conducted at 11:45 am indicated that the outer sheath fault distance was 460 m.

Figure 12: Shuhui Line 110 kV cable termination, pole #31 of Tongda farm produce market

### 4.3. *Outer sheath accurate fault locating test*

#### 4.3.1. *Test conditions*

The step voltage method was applied to precisely locate the fault of the outer sheath. The step voltage pinpoint principle of the MFM10 system is shown in Fig. 16. The MFM10 was connected between the metallic protective layer of the cable and the system, and the operation mode was turned to DC pulses.

A DC pulse signal of 0...1.8 kV was applied between the faulty Phase C and the earth, with a signal frequency of 1:3, which means that the signal was sent out repeatedly at an interval of 3 s. The ESG NT step voltage accurate locater was used as the receiver at the damaged point of the cable outer sheath to measure the step voltage generated by the grounding current flowing to earth (Fig. 17). The voltage measurement value dropped or increased sharply at the fault point, with the step voltage polarity reversing at the point of damage. Hence, the location of the damaged point on the cable outer sheath could be determined with an accuracy of ±50 mm.

#### 4.3.2. *Test results*

According to the cable path distribution diagram of the Shuhui Line (Huidong Substation—straight joint of China Mobile), the step voltage value shown on the ESG NT was about 63 mV when it reached the gate of the Zhongxin Teahouse in Zigong City, which is on the opposite side of Lanying Garden and 215 m from China Mobile, and the polarity was reversed. After the ESG NT was moved out of this area, the step voltage value dropped sharply to 0.2 mV or less. The step voltage value increased as the ESG NT was moved closer to the fault, indicating that the cable in that area was faulty. Through further measurement and inspection, the fault was found to be located at the gate of the Zhongxin Teahouse. When checked, it was confirmed that the fault was caused by outer sheath insulation failure (Fig. 18). The test results show that the step voltage method is satis-

Figure 13: Pole no. 31 was distal, the metallic layers were suspended

Figure 14: China Mobile was distal, the metallic protective layers were all short circuited and suspended

Figure 15: A phase metallic protective layer was the auxiliary phase, MFM10 voltage method predetermining rigid displacement

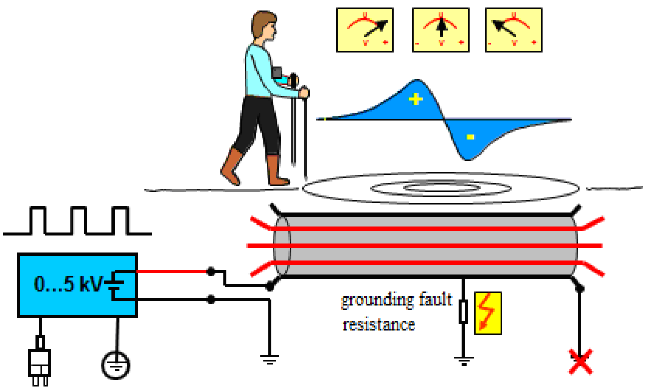


Figure 16: Step voltage pinpoint principle graph of the MFM10 system

factory for accurate fault locating of a 110 kV cable outer sheath.

## 5. Conclusions

According to the requirement specified in Chapter 5.15 of Regulations of condition-based maintenance & test for electric equipment (Q/GDW168-2008 of China) [16], applying a DC withstand voltage of 5 kV to the metallic protective layer of the extra-high-voltage cable for 1 minute each year is an important means of testing the condition of the outer sheath of the cable. Condition-based maintenance should be carried out on the 110 kV cable of the Shuhui Line according to the Regulations, so


Figure 17: Pinpointing the fixed point; the ESG NT automatically displays the step voltage value and direction

Figure 18: Fault points of single core cable outer sheath layer discolored by heating

as to monitor the operational state of the extra-high-voltage cable equipment. In this article, the following conclusions have been drawn through theoretical analysis, actual measurement and condition analysis of the point of the fault.

1. The outer sheath layer is the outermost layer of the extra-high-voltage cable and serves to segregate the induced voltage of the metallic protective layer, as well as preventing external damage to the cable and the ingress of moisture.
2. If the cable outer sheath to extra-high-voltage cable equipment is neglected for an extended period of time, a significant grounding current will be generated, and much heat will be produced at the damaged point on the outer sheath.

If the heat cannot be radiated away, it will be transferred to the major insulation layer of the cable, melting the cross-linked polyethylene of the cable, which will ultimately result in sudden power failure.

3. A new method for accurate fault locating in the 110 kV cable, using the bridge method for fault pre-location and the step voltage method for the accurate fault locating, has been presented. Through insulation resistance measurement and fault locating conducted on the outer sheath of a 110 kV cable (Shuhui Line), it has been confirmed that the new method is applicable to status evaluation and accurate fault locating for 110 kV cable outer sheaths.

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