Case study on application of digital radiography in cable

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Abstract. Because of the frequent occurrence of power cable fault, rapid and accurate fault diagnosis is an important subject in this field. In this paper, the DR detection cases of cables and related components with different voltage levels are described and analyzed based on the research work of radiographic detection carried out by our research group in the field of cables and their accessories in the recent three years. The results show that the technology can effectively detect and analyze the internal damage of cable outer breaking point, the ablative defect of cable buffer layer, the size and position deviation of cable joint. Due to the large number of cable layers and material types, the paper also gives some solutions to the problem of shielding copper core and some examples of abnormal image identification. Cable ontology, cable joints and other accessories produced by different manufacturers have certain structural differences due to numerous processes and procedures. It is necessary to continue to carry out research on DR testing for cable engineering structural parts of different types, establish relevant standard comparison atlas and provide reference for the application of DR technology in the field of cable testing.

1. Introduction

In recent years, power interruption and fire accidents caused by power cable failure occur frequently, which has a serious impact on the national economy[1-2]. As the power cable has been in harsh natural conditions for a long time, its insulation ability affected by environmental effects, poor construction technology, external construction and excavation and other factors, would cause local heating or discharge, which eventually leads to breakdown and even fire accidents resulting in losses[3]. However, the domestic cable structure, production and installation process are complicated, and there are many types of defects in the operation of the cable and the causes are not clear, which makes it difficult to carry out the investigation of cable defects hidden dangers. How to diagnose cable defects accurately and quickly is still an important topic.

X-ray digital imaging technology has achieved good results in inspecting the internal defects of overhead transmission line structures such as tensioning clamp[4], connecting pipe and installation[5] of transformer GIS adsorbent cover. Our research group has carried out some exploratory work in the field of cable by referring to its relevant technology.

Combined with the DR detection research and field engineering application cases carried out by our research group in the field of cable and its accessories in the past 3 years, the paper analyzed and expounded various detection conditions, in order to provide reference for the subsequent field application of digital radiographic technology in the investigation of cable defects and hidden dangers.
2. Radiographic digital imaging detection technology

Digital Radiography (DR) is a nondestructive transmission imaging detection technology that replaces conventional film imaging with digital detector array (plate detector) based on the principle of X-ray detection\(^6\). Using ray machine devices to generate rays, through the sensitive digital detector array will be invisible ray light signals into digital signals, after computer signal processing, the formation of digital images can be stored and optimized processing.

There are many regular structural layers in high-voltage power cables and each layer made of different materials. When X-ray passes through the cable radially, the image of inconsistent gray levels of each structural layer will be presented due to the difference in ray attenuation capacity and thickness of structural layer of each layer. When the geometrical size of cable structure changes and the materials of different structural layers react with each other to produce different density materials, the imaging changes of digital ray images will be caused. Therefore, we can carry out ray digital imaging detection for cable engineering-related problems.

![Fig.1 Detection principle of ray digital imaging](image)

3. Application of DR technology in cable engineering

3.1 External construction damage detection of XLPE cable

In 2020, the excavation of a municipal engineering construction site caused disturbance to 110 kV directly buried cable, resulting in damage to an outer sheath of the cable line and bending of a cable after external pressure. The power cable model was YJLW04-64/110KV-1 ×400, which was XLPE insulated aluminum sheathed and PE sheathed, with conductor nominal area 400mm\(^2\) and cable insulation nominal thickness 17.5mm.

Operation and maintenance personnel insulated wound the damaged outer sheath after the accident, but as the damaged structure inside the cable was unknown, digital radiography technology was used for detection. GE DXR250V constant frequency ray machine was used for detection, the focal length was 600mm and the exposure condition was 70KV-2MA-17s. The X-ray detection image, as shown in Fig.1, could be seen that there was an obvious bulge at the wrapping of the external insulation repair and serious deformation of the internal aluminum sheath nearby. However, the boundary of the main insulation layer in the figure was clear without obvious abnormality and the main insulation not damaged by the external damage.

Similarly, on-site digital ray detection was carried out at the bending point of the externally damaged cable, and the results were shown in Fig.2. The image was imported into image measurement software for proportional measurement, and it was found that its bending radius did not meet the requirements of "the minimum bending radius of corrugated aluminum sheathed and metal plastic composite sheathed cable is 20 times of cable diameter" in GB/T 11017.2-2014 "XLPE insulated Power Cables and Accessories part 2: Cables". At the same time, it could be seen that the outer sheath and aluminum sheath were seriously deformed in the bending compression area, and the inner aluminum sheath structure produced large compression deformation.
3.2 Ablative detection of buffer layer of XLPE cable
In 2019, buffer layer ablation failure occurred in a 110 kV cable. The sample of the fault section was taken for DR detection. The detection image was shown in Fig.3 and normal cable detection in Fig.4. It was found that the images of all structural layers of the normal cable were uniform, while the defective cable had obvious uneven high-density shadow within the structure range of the buffer layer, which was the "ablation" trace.

3.3 Defects in weld construction of main insulation of cable fusion joint
Cable fusion joint is a new power cable construction connection technology. Fig.5 is the digital radiographic detection image of 110 kV fusion joint after the main insulation layer restored. It was found that the copper core was geometrically bent and the main insulation layer not equal in thickness in the process of making the fusion joint.

4. Discuss and differentiate cable imaging examination
Due to variety of cable layers and materials, there're inspection precautions and imaging abnormalities identification problems in digital radiography, which will be discussed in the following sections.

4.1 Processing method of copper core shielded problem
Because the copper core is in the innermost layer of the structure, and the copper absorption of rays is large and difficult to penetrate. Therefore, the part blocked by the copper core in primary ray penetration won’t be able to identify whether there is abnormal damage, which may lead to defect detection. We name it the copper core shielded problem. Some literatures had given the detection angle formula of two different angle tests covering the whole circumference detection range, as shown...
in Equations (1) and (2). The radius of the cable conductor is ‘d’, the outer diameter of the cable body is ‘D’, \( \alpha_1 \) is the minimum included Angle without copper core shielded during two radiographic detections, while \( \alpha_2 \) the maximum included Angle. For the detection of one station, two detection methods should be adopted, and the two included Angles \( \alpha \) should meet \( \alpha_1 < \alpha < \alpha_2 \). It can be seen from the table that the Angle of the two tests should be assured to be between 45.9° and 134.1°, so as not to be blocked by copper core. Therefore, the site is often through vertical two detection to solve the problem of shielding copper core. When the site conditions can’t meet the vertical irradiation, using other angles in the range.

\[
\alpha_1 = 2 \times \arcsin \left( \frac{d}{D} \right) \quad (1)
\]

\[
\alpha_2 = 180^\circ - 2 \times \arcsin(d/D) \quad (2)
\]

| Cross-sectional area S/mm² | Diameter d/mm | Out diameter D/mm | \( \alpha_1 \)/° | \( \alpha_2 \)/° |
|----------------------------|---------------|-------------------|-----------------|-----------------|
| **110kV**                  |               |                   |                 |                 |
| 400                        | 23.8          | 92.3              | 29.9            | 150.1           |
| 630                        | 30.0          | 96.9              | 36.1            | 143.9           |
| 800                        | 34.0          | 99.9              | 39.8            | 140.2           |
| 1200                       | 42.6          | 109.4             | 45.9            | 134.1           |
| **220kV**                  |               |                   |                 |                 |
| 630                        | 30.0          | 123.0             | 28.2            | 151.8           |
| 1200                       | 42.6          | 135.0             | 36.8            | 143.2           |
| 1600                       | 48.0          | 141.0             | 39.8            | 140.2           |
| 2500                       | 61.2          | 157.0             | 45.9            | 134.1           |

4.2 Identification of abnormal images

4.2.1 Locally uniform medium density shadow
X-ray digital imaging was carried out on 110 kV cables in a cable channel, and a single locally existing high-density shadow appeared on a certain image, as shown in Fig.7. Examination of the cable found a small amount of fireproof coating on the corresponding position on the surface of the nodular agglomeration, but the high-density shadow disappeared after removing the nodular coating. Therefore, the cable surface should be cleaned before testing to avoid the impact of high-density substances on the surface of imaging.

4.2.2 Funicular shadow
The cable body radiographic digital imaging detection was carried out on a certain 220 kV cable, and cable position in the perennial hot zone appeared cable shadow on the image, which was evenly distributed along the length direction, as shown in Fig.8. After dissection, it was found that the cable funicular shadow was formed by consolidation of asphalt matrix between cable outer sheath and aluminum sheath after aging. The asphalt matrix consolidated in this position was removed, and then the shadow was restored.

4.2.3 Sandy high density shadow
A section sample of a 220kV faulty cable line was taken and sent to the laboratory for X-ray digital image detection. It was found that the high-density sandy shadow appeared at the lower edge of the cable and the abnormal gritty shadow still existed after a certain rotation angle, as shown in Fig.9. When the cable was poured out vertically along the buffer layer, aluminum powder was found to fall out, and the re-inspection found that the sand shadow almost disappeared. It can be judged that the
sandy high density shadow was the aluminum powder formed by sampling and cutting, which fell into the aluminum sheath along the gap during handling. Therefore, in order to avoid similar situations, factors that may affect sample detection effect during sample submission should be controlled when conducting ex-situ DR test in the laboratory.

**Fig.6 Digital radiographic detection chart of 110kV cable joint construction quality**

**Fig.7 Locally uniform medium density shadow**

**Fig.8 Funicular shadow of cable ray digital image**

**Fig.9 Locally uniform medium density shadow**

### 5. Conclusions

In this paper, the application of ray detection for cables and related components of different voltage levels is studied. DR technology can effectively detect and analyze the internal damage of cable external breaking point, ablative defect of cable buffer layer, construction size and position deviation of cable joint, etc.

When using DR technology to carry out cable detection, the cable surface should be cleaned to avoid the influence of impurities on digital imaging. The causes of abnormal images should be determined by combining detection experience and anatomic test.

The cable body, joint and other accessories produced by different manufacturers have certain structural differences and characteristics, so it is necessary to continue to speed up the DR testing research on cable engineering structural parts of different types and structures, and establish relevant standard comparison atlas.

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