Electric field characteristics of X-ray detection and safety protection in live work of transmission lines

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Abstract. Hidden defects in transmission lines can be detected by X-ray. Through the simulation of different voltage/current tests in the laboratory, the live detection test of digital X-ray detection equipment was carried out and the detection tests under the live condition of 110kV transmission line carried by unmanned aerial vehicle, the maximum tolerable voltage of X-ray digital imaging equipment during live operation was determined. By using the electric field finite element simulation, the affected field intensity detected by the equipment is 360kV/m, and the spatial field intensity distribution of ac transmission lines with different voltage levels is given, which provides a reference for selecting reasonable electric field shielding measures for the live operation of X-ray digital imaging equipment.

1. Introduction
During the operation of power transmission lines, hidden defects such as poor tension-resistant clamp connection and corrosion of steel core inside the ground guide wires lead to line breakage [1-3]. Studies have realized the application of X-ray digital imaging technology to the concealed defect detection of transmission line load bearing components in the manually mounted tower operation under power failure conditions [4, 5]. Although the potential operation such as power supply reliability and power failure loss can be improved and reduced by carrying equipment into strong field environment during power failure, the operation difficulty of personnel is high, the safety risk is large, and the inspection volume is small. In contrast, using carrier equipment such as unmanned aerial vehicle (UAV) or insulated arm to carry the X-ray digital imaging equipment to the location of live line for inspection can better solve the above problems.

There is a huge field intensity around the transmission line [6-8], and the spatial distribution of field intensity will change with the difference of voltage level and off-line distance. A large number of studies have been carried out on the spatial electric field distribution of transmission lines with different voltage levels and the operation mode of personnel's equipotential [9-11]. However, when sending X-ray digital imaging equipment containing a large number of electronic components into potential work such as strong field environment, the influence of field strength on weak current of operating equipment should be taken into account, and the size of equipment, material properties and gap structure formed by the equipment are greatly changed compared with conventional human electrification work. The existing
results of personnel live work can not meet the application requirements, so it is necessary to carry out targeted experiments and simulation research.

This article will through the X-ray digital imaging device charged operation test to determine the maximum withstand voltage of the X-ray digital imaging equipment and space field intensity distribution under the maximum withstand voltage equipment is given by the electric field simulation and then the field intensity distribution of transmission lines carried out. It provides a reference for selecting reasonable electric field shielding measures for the live operation of X-ray digital imaging equipment.

2. Live work test

2.1. Simulated electrification test in laboratory

Combined with the structural form and operational requirements of the existing X-ray digital imaging equipment, an X-ray digital imaging equipment bracket that can be lifted and mounted to the transmission line is designed and manufactured, as shown in Figure 1. Before the test, the wire clip is installed to the pressure device, then we open the ray emitter and the imaging board, and mount the assembled electrification detection device to the wire clip to simulate the electrical detection of tension-resistant wire, as shown in Figure 2. After confirming the evacuation to a safe area, start the pressurizing device to step up to the specified voltage. After the voltage stabilizes, the software is operated to control the X-ray machine to emit X-rays and receive and store the detection images.

The detection images received at each voltage level (25/50/75/100kV) are shown in Figure 3. It can be found that the image is not affected at 50kV. When the voltage level reaches 75kV, image noise begins to appear in the detection image, and the image noise intensifies when the pressure is continued. Therefore, it can be considered that DR equipment can withstand the electric field generated by 50kV test high voltage without electric field shielding in that condition.
2.2. Live test of 110kV transmission line

In order to obtain the influence of strong field environment on the operation of X-ray digital imaging equipment under real conditions, the electrification test was carried out on the 110kV dry type transmission line. In the test, the heavy-duty multi-rotor UAV is used to carry the equipment to the position to be inspected of the transmission line through the insulation rope in live operation. According to the existing results, the positioning of the geomagnetic meter is usually affected by the strong electromagnetic environment during the close operation of the UAV, thus affecting its stability.

In order to ensure flight stability, the UAV is equipped with RTK system to avoid the influence of geomagnetic meter, and the flight path into the electric field is planned and an insulating rope is used to connect the UAV to the wire to ensure the distance between it and the wire is more than 2m. Photo of the mounted device of the UAV entering the electric field, as shown in Figure 4.

![Figure 4. UAV mount equipment enters 110kV transmission line](image1)

When the equipment is connected to the electric field about 20cm away from the transmission wire, partial discharge occurs at the flaring hook, and the sound of "fizzing" discharge can be heard, but no obvious arc pulling phenomenon is seen. When entering the electric field operation, the wireless signal transmission of the device is lost for a short time, and then the detection image can be collected, as shown in Figure 5. Some image information in the figure is missing. It can be seen that the 110kV high voltage electric field has a great impact on the unshielded X-ray digital imaging equipment.
Combined with the simulation test in the laboratory and field test results, it can be seen that shielding measures should be taken for the X-ray digital imaging equipment to realize the live operation, and it is advisable to control the maximum field intensity below the equivalent field intensity generated by the simulation of 50kV high voltage in the laboratory.

3. Simulation of laboratory live operation laboratory

Since it is difficult to measure the field intensity of the key positions under the experimental conditions by using the field intensity probe, the space electric field of the high-voltage charged test is simulated by using ANSOFT Maxwell 16.0 software based on the electromagnetic finite element simulation method, and the field intensity distribution on the equipment surface under the laboratory conditions is obtained.

3.1. The simulation model

The type of the wire is LGJ-300/40, the diameter is 23.94mm, and the height of the wire is 3.5m to the ground during the test. A section of the wire of 4000mm is intercepted as the research object, which is placed in the THREE-DIMENSIONAL coordinate system. The device is hooked into the wire position through the bracket hook. Cuboid was used to truncate the boundary of the calculation domain. The two sides, top surface and ground parallel to the wire were loaded with 0V potential, and the two truncated planes of the solution domain perpendicular to the wire were loaded with natural boundary conditions. The finite element model was shown in Figure 6.
3.2. The simulation results

During the simulation, 50kV voltage is applied to the wires in the model, and the wires attached by the device bracket are coupled to the wire so as to obtain the spatial field intensity distribution in the live operation of DR device, as shown in Figure 7. The presence of the bracket distorts the electric field near the wires, and the maximum field intensity at the outer edge of the imaging plate reaches 378kV/m. X-rays emitted by X-ray machines are not affected by electric fields because they have no electric charge. In the X-ray imaging equipment, the imaging plate is close to the wire, and the electric field will affect the electronic components in the imaging plate to convert the X-ray signals into digital signals. The field intensity distribution of the imaging plate near the wire surface is shown in Figure 8.

The imaging panel has a large field intensity in the frame and the maximum value occurs at 360kV/m near the hook side. Therefore, when the imaging panel is installed in the bracket, it is appropriate to place the concentrated part of electronic components far away from the near hook side.

![Figure 7. The field intensity distribution on the vertical symmetry plane of the model](image_url)

![Figure 8. Field intensity distribution on the side of the plate near the wire](image_url)

4. Electric field simulation of actual transmission line

It is shown above that the tolerated field intensity of the equipment in normal operation under laboratory conditions is 360kV/m. Obviously, the field generated by the actual transmission line conductor will be greater than this value. In this section, the electric field distribution of several common transmission lines is simulated to provide basis for future consideration of the electric field shielding of the equipment.

Select the actual transmission line of a certain 110kV line for simulation, as shown in Figure 9. Horizontal alignment of wires, double lightning conductor, call height 12 m. The type of the conductor is LGJ-240, and the ground wire is GJ-50. Each phase transmission line is simplified as a point, the X-axis represents the horizontal ground, the Y-axis represents the vertical line where the center of the
middle phase conductor is located, and the position of each phase conductor on the tower is represented by the coordinates next to it. The distance $D$ between the middle phase and the side phase is 5m, and the height $H$ between the center of the conductor and the ground is 14.7m, that is, the coordinate of the three-phase transmission line is $A(5, 14.7)$, $B(0,14.7)$ and $C(-5,14.7)$ respectively. Solving area set aside for computing the boundary truncation radius is set to 30 m of semicircle, boundary conditions in the simulation setup, the calculation area bottom boundary (ground) is set to 0 voltage. arc bubble boundary conditions is used to simulate infinity 0 potential, ABC three-phase copper-clad steel 110 kV sine voltage, each phase conductor surface potential value for the corresponding phase, ABC phase respectively consider -120°, 0° and 120° with ABC phase 0°, 120° and 240° respectively.

Figure 9. simple diagram of the actual line

Figure 10. Electric field distribution of 110kV AC line (ABC phase is 0°, 120° and 240° respectively)
Figure 11. Electric field distribution of 110kV AC line (ABC phase is -120°, 0° and 120° respectively)

Figure 12. Electric field distribution of 220kV AC line (ABC phase is 0°, 120° and 240° respectively)

Figure 13. Electric field distribution of 110kV AC line (ABC phase is -120°, 0° and 120° respectively)

5. Electric field protection of operating equipment

No electromagnetic field protection standards for live working equipment have been found at home and abroad. In the research of live work, the principle of electrostatic shielding is usually adopted for protection, and the shielding suits with corresponding shielding effectiveness can meet the requirements of live work for general staff. GB/T 6568-2008 “Shielding Clothing for Live Work” stipulates the protection level of human body for live work: for the whole set of shielding clothing, the local field strength on the exposed part of human body shall not be greater than the "human body electric field perception level" 240kV/m, and the surface field strength in the clothing shall not be greater than 15 kV/m.

In the previous experiment, we have given that the field intensity of X-ray digital imaging equipment is 360 kV/m. Compared with the provisions of national standards on human body protection, the internal field intensity of equipment shielding protection should not be greater than 22.5 kV/m. Therefore, according to the expression of the shielding effectiveness:
\[ SE = 20 \log \frac{E_1}{E_2} \]  

\( E_1 \) is the electric field intensity when the device is not shielded, \( E_2 \) is the electric field intensity when the device is shielded. Table 1 shows the shielding effectiveness requirements for the X-ray digital imaging equipment of 110 kV and 220kV lines. It can be seen that the live operation requirements of 220kV and below lines can be satisfied by shielding measures above 40 dB.

| Voltage (kV) | Maximum field strength (kV/m) | Shielded field strength (kV/m) | Shielding effectiveness SE (dB) |
|-------------|-------------------------------|------------------------------|-------------------------------|
| 110         | 1518                          | 22.5                         | 36.6                          |
| 220         | 2161                          | 22.5                         | 39.6                          |

6. Conclusion
Through conducting electrification test and simulation research on X-ray digital imaging equipment, the following conclusions are drawn:

- Voltage is the main factor affecting the detection operation of X-ray digital imaging equipment. When the surface field intensity of the equipment is greater than 360 kV/m, it starts to affect the image.
- UAV with RTK can successfully fly into the actual 110 kV line, and the short-range operation (2m away from the transmission wire) will not affect its flight, which provides experience for the short-range operation of UAV.
- During equipotential operation, the X-ray digital imaging equipment shall be protected by shielding measures above 40 dB, which can meet the live operation requirements of 220kV and below circuits.

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