the Technology of Space Electric Field Detection of Deteriorated Insulator Strings Based on Multi Rotor UAV

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Abstract—Porcelain insulator with good insulation performance is the key to the stable operation of power system. In order to characterize its insulation performance safely and accurately, a 1:1 three-dimensional electric field simulation model of 220 kV porcelain tension insulator string is established by using COMSOL finite element software, and a UAV live detection platform for degraded insulator string is built according to the optical electric field sensor. The results show that when the insulator deteriorates, the distribution electric field curve will appear obvious distortion; comparing the simulation results with the live measurement results, it is found that the electric field waveform curve obtained by the live detection platform of degraded insulators based on UAV can be accurate and can effectively judge the insulators with deterioration.

1. INTRODUCTION

Insulator plays the role of electrical insulation and support connection in transmission line. It is a key insulating component of power system to maintain the safe operation of power grid[1-3]. Transmission lines work in complex external environment all year round. With the increase of operation time year by year, the insulator will inevitably deteriorate to varying degrees due to the influence of electromagnetic interference, mechanical stress, temperature and humidity, resulting in flashover phenomenon, which greatly threatens the safety of power grid[4,5]. Therefore, it is very important to carry out regular maintenance on insulators and accurately judge their insulation state.

At present, in the live detection, the detection methods of insulators include: electric quantity detection method (pulse current detection method, electric field measurement method, insulation resistance detection method, etc.) and non-electric quantity detection method (infrared thermal imaging method, ultraviolet imaging method, etc.)[6]. References[7,8] found that the sensitivity of deteriorated insulators based on UV imaging detection technology is low, and misjudgment will occur if the deterioration position occurs in the middle of insulator string. References[9,10] use infrared technology to detect the temperature of insulators in 220 kV substation. It is found that the detection sensitivity of
porcelain insulators is low, because the overall temperature difference of porcelain insulators is small, and they are easy to be disturbed by radiation and surrounding environment in the actual detection process. The non electric quantity detection method is greatly disturbed by the environment, which will affect the accuracy and sensitivity of the detection results. Reference[11] takes the pulse discharge current as the starting point and uses the discharge intensity vector to reflect the distribution of back electric pulse, which is an important basis for judging the deteriorated insulator, but it is vulnerable to the external environment and has insufficient accuracy and sensitivity; The insulation resistance detection method must ensure that the insulator surface is clean, otherwise it is impossible to judge whether the decrease of insulator resistance is caused by the damage of insulator integrity or because there are impurities on the insulator surface[12].

The electric field detection method in the electric quantity detection method has a broader application prospect compared with other methods. It tests the insulation performance of Insulators based on the distortion of electric field distribution curve[13-15]. The electric quantity detection method is less affected by external factors and can directly judge the insulation performance of insulators. If there are defects, the voltage drop between different insulator pieces will change, and the electric field intensity will also change[16].

In reference[17], the live detection tests of composite insulators in good condition and core rod conduction are carried out respectively, which proves that the electric field detection can obtain more reasonable detection results; In reference[18], the finite element electric field model of composite insulator umbrella skirt with different damage positions and damage degrees is established. It is concluded that the spatial axial electric field curve has no effect when the umbrella skirt at the high voltage end of insulator string is damaged. The potential and electric field distribution of composite insulators of 330 kV transmission line are simulated by finite element method in document[19]. It shows that the wire will equalize the potential of the insulator, and the maximum field strength on the high voltage side is 60% lower than that without wire. At present, there are many researches on composite insulators in the research results, and porcelain insulators have become the basic equipment in ultra-high voltage and high voltage transmission lines. Its internal structure contains a variety of materials with large differences in thermal expansion coefficient. The material gap is easy to produce heat and be broken down, which seriously endangers the safe operation of lines.

In order to accurately judge the insulation performance of porcelain insulator and find out the deteriorated insulator accurately and efficiently, according to the electric field distribution characteristics of porcelain insulator, a three-dimensional finite element electric field simulation calculation model of U210BP/170 insulator string is established, and the surface electric field curve when the insulator string has good performance and deterioration and the distribution electric field curve on the outermost side of porcelain piece are obtained; Based on the electric field sensor of photoelectric crystal Pockels effect, a live inspection platform for UAV with deteriorated insulator is built; The live measurement of insulator space electric field in a line in Yinchuan is carried out. The accuracy of the live detection device of UAV degraded insulator is verified by comparing the known degraded insulator electric field detection waveform with the simulation waveform.

2. INSULATOR ELECTRIC FIELD MEASUREMENT METHOD

2.1 Measurement Principle of Electric Field Distribution in Live Line
Due to the influence of stray capacitance between wire, tower and insulator, the distributed electric field of insulator presents a U-shaped curve with high at both ends and low in the middle[20]. The equivalent circuit diagram of insulator to tower and wire is shown in Fig.1.
Where $C_i$ is the capacitance of insulator itself, $C_g$ is the equivalent stray capacitance between insulator and tower, and $C_l$ is the stray capacitance between insulator and wire. The stray capacitance $C_g$ of the insulator to the tower increases the voltage drop at the high voltage end of the insulator because its shunting effect is greater than the confluence effect; The shunt effect of the insulator on the stray capacitance $C_l$ of the wire is less than the confluence effect, so that the voltage drop borne by the insulator near the low-voltage end increases accordingly. Therefore, under the combined action of stray capacitance $C_g$ and $C_l$, the distributed electric field intensity curve of insulator approximately presents a U-shaped curve with high at both ends and low in the middle. When the insulator is deteriorated, its own capacitance $C_S$ will become very small or even become a short-circuit state, and the electric field strength will suddenly decrease. Obvious distortion points can be found on the electric field strength curve of the insulator. Therefore, the insulation performance can be judged by deteriorating the electric field characteristics of insulators.

2.2 Maintaining the Integrity of the Specifications
Since the spatial electric field of porcelain insulator is a three-dimensional field without boundary, the calculation model includes porcelain insulator, cross arm, conductor and connecting hardware. The actual line referenced by the simulation is Yinchuan Nafeng double line three-phase line, and the insulator is tension insulator.

The established COMSOL 3D simulation model is shown in the figure below.

![Fig.1 Equivalent circuit diagram of insulator string to tower to conductor](image1)

![Fig.2 Three dimensional simulation model of transmission line insulator](image2)
### Tab.1 Simulation parameter setting

| Parameter | Relative dielectric constant | Conductivity / (S/m) |
|-----------|-----------------------------|----------------------|
| Air domain | 1                           | 0                    |
| Porcelain | 6                           | 10-12                |
| Wire      | 1000                        | 107                  |

2.3 Analysis of Simulation Results

127 kV AC phase voltage is applied to the high voltage side of the insulator string in Figure 2 model to simulate the insulator electric field at 220 kV voltage level, and the potential degree of freedom coupling is carried out between the steel pin and steel cap of the insulator piece to simulate the deteriorated insulator. The surface electric field curve of insulator strings with intact insulation performance and deterioration at different positions is obtained, as shown in Fig. 3.

It can be seen from Figure 3 that for insulator strings with good insulation performance, the surface electric field of insulator pieces near the high-voltage end and low-voltage end is high, and the electric field intensity of insulator pieces near the middle is relatively low. When the deteriorated insulator piece is set at different positions of the insulator, the electric field intensity at the deteriorated position is distorted to varying degrees, and the electric field intensity of the insulator on both sides of the piece of insulator increases abnormally.

The surface electric field curve of insulator accurately reflects the electric field on the insulator surface, but it can not directly judge the deteriorated insulator for engineering practice. Extract the electric field intensity on the outermost side of the insulator tile in Fig. 3 to obtain the distributed electric field curve of the insulator, and the obtained distributed electric field curve of the insulator is shown in Fig. 4.
When the high voltage end of the insulator is deteriorated, the electric field strength decreases to 55.8% of that without deterioration; When there is deterioration in the middle of the insulator string, the electric field intensity decreases to 44.1% without deterioration; When there is deterioration at the low voltage end of the insulator, the electric field intensity is 35% of that without deterioration. It can be seen that when the insulator deteriorates, its spatial electric field strength will decrease significantly, among which the electric field at the high voltage end decreases most, followed by the middle part, and the electric field at the low voltage end decreases least. Using the distributed electric field characteristics of insulator string, the simulated image can be compared with the measured insulator electric field intensity waveform of UAV to infer whether the insulator in the actual line is deteriorated.

3. LIVE DETECTION PLATFORM OF DETERIORATED INSULATOR BASED ON UAV

Using the spatial electric field distribution characteristics of insulators can effectively judge the insulation performance of insulators. Based on this principle, a live detection platform of degraded insulators based on UAV can be built for non-contact rapid detection of insulator electric field.

3.1 Optical Electric Field Measurement System

3.1.1 Optical electric field sensor

The transient high-voltage electric field sensor based on photoelectric crystal Pockels effect can convert the electric field signal into optical signal for transmission, and then convert the optical signal into voltage signal through photoelectric converter to complete the transient electric field measurement. In the whole measurement process, the field strength measurement circuit is completely isolated from the high-voltage circuit, which has the characteristics of strong anti-interference and good transient follow-up.

Test and study the power frequency response characteristics of the sensor: place the sensor probe in the center of the 0.5m plate to plate gap, and then apply a power frequency voltage of 12 kV ~ 120 kV to the gap on the premise of ensuring no corona, and the corresponding electric field strength is 24 kV / M ~ 240 kV / m. The power frequency electric field waveforms measured by the sensor under different
electric field intensities are shown in Figure 6. The electric field range measured by the optical electric field sensor is 24 kV / m ~ 240 kV / m, which can be applied to insulator electric field measurement under most field conditions. The power frequency electric field waveform has no distortion and good response. Compared with the actual electric field strength, it can be seen from Figure 7 that the power frequency amplitude characteristic linearity of the electric field sensor is very good[20].

Fig.6 Power frequency response waveform of electric field sensor

Fig.7 Power frequency response characteristics of electric field sensor

3.1.2 Miniaturization design of electric field transmission module

The electric field data transmission module is composed of power adapter, light source driving circuit, polarization maintaining isolator, polarization beam splitter and detector. In order to carry it on M600 UAV for electric field data transmission of degraded insulator detection, it needs to be miniaturized. Since the UAV system is powered by 12V DC power supply, the power adapter of the electric field data transmission module is changed from AC to DC; At the same time, small integrated components are designed according to the fuselage parameters of UAV to replace large-scale polarization maintaining isolator, polarization beam splitter and detector. On the premise of ensuring the accurate transmission of electric field data, three electric field measurement channels are designed to compact all integrated components. The size of the electric field data transmission module after miniaturization design is 100 * 150 * 30MM, as shown in the figure.

Fig.8 Data conversion model after miniaturization design
3.2 Composition of UAV Degraded Insulator Detection Platform

The airborne terminal of the detection platform is in front of the M600 UAV, equipped with an electric field sensor based on the Pockels effect of photoelectric crystal, and the miniaturized electric field measurement data conversion module is integrated under the UAV. In order to accurately locate and detect the insulator, the UAV is also equipped with laser positioning lens and visible light lens to accurately locate the insulator.

When observing the insulator electric field at the ground terminal, the electric field measurement data receiving module is used to receive the electric field data transmitted by the front end of the UAV, and the insulator electric field waveform is displayed through a micro oscilloscope. The airborne end and ground end of the degraded insulator detection platform are mainly interconnected through the wireless signal module composed of data link. The composition of the detection platform is shown in the figure below.

4. INSULATOR FAULT MEASUREMENT

4.1 Live Measurement of Insulators with Good Insulation Performance

In order to verify the accuracy of UAV deterioration insulator detection device, the electric field detection of tension insulator string is carried out on Yinchuan 220kV transmission line. The detected insulator is double umbrella porcelain insulator, and the model is consistent with that in the simulation model. The temperature on the day of testing is 15 °C, and the relative humidity is 50%. In the process of live detection, the staff at the airborne end and the ground end shall ensure standardized operation, and keep the UAV at a safe distance of 3M from the line and insulator during flight under the voltage level of 220 kV. The UAV carries out real-time ranging through the laser rangefinder to ensure that the distance between the probe of the electric field sensor and the outside of the insulator umbrella skirt remains unchanged during the measurement process, and the flight speed of the UAV is about 0.12 m / s. The UAV is used to scan the electric field distribution around a single insulator in the double string insulator at a uniform speed. The test site diagram is shown in the figure below.

![Fig.9 UAV degraded insulator detection platform](image)

![Fig.10 Test site](image)
For insulators with good insulation performance in 220kV line, the measured waveform of electric field is as follows:

![Electric field waveform of insulator without deterioration](image1)

Fig.11 Measured electric field waveform of insulator without deterioration

By comparing with the simulation figure, it can be seen that there is a difference between the measured electric field distribution of insulator string and the simulation calculated value, which is mainly due to the fact that the UAV degraded insulator detection platform has a certain distance from the insulator surface when detecting the degraded insulator string, but in order to realize the non-contact rapid detection of insulator, the insulation performance of insulator string can be judged by observing whether there are distortion points in its own electric field waveform.

The UAV flies at a uniform speed relative to the insulator string, and the time node corresponding to the electric field intensity amplitude of each insulator is calculated according to the measured time. The corresponding position of each time node is taken as the center position of each insulator skirt. Each measured strain insulator string has 15 insulators. During data processing, 15 typical observation points can be selected according to the center position of each insulator umbrella skirt for key analysis, and the curves are as follows:

![Electric field intensity vs Insulator number](image2)

Fig.12 No deterioration of insulator electric field after data processing

It can be seen from the figure that although the measured electric field intensity is lower than that of the simulation model due to the long distance from the insulator, the lowest measured electric field of the insulator is 5.93kV/m, and the electric field amplitudes at both ends of the insulator string are 5.39kV/m and 8.88kV/m respectively. The distributed electric field of insulators is a U-shaped curve with high at both ends and low in the middle. The measured electric field waveform of Yinchuan line is similar to the COMSOL simulation results. The UAV degraded insulator detection device is reasonable.

4.2 Comparison of Measured Electric Field of Deteriorated Insulator

Based on the judgment results of manual detection: there are degraded insulators in the tower of a line and they are running on line. The live measurement results by using UAV degradation detection system are as follows:
During the field test, there will be an obvious "drop" phenomenon along the scanning electric field amplitude of the insulator, resulting in the depression of the overall measurement waveform in a certain period of time. Considering that the insulation effect of some insulator pieces of deteriorated insulators is weakened and the bearing voltage at both ends is low, resulting in the weakening of radiated electric field, it is reasonable to think that when the amplitude of scanning electric field drops significantly, the insulator pieces will deteriorate at the corresponding measurement time. Therefore, in the measured line, if there is an obvious abnormal decrease in the amplitude of insulator electric field, it can be judged as a deteriorated insulator.

According to the measured insulator electric field intensity waveform of UAV and COMSOL simulation results, it can be found that there is obvious distortion in the insulator string electric field waveform, which can basically judge the deterioration problem of the seventh insulator. The electric field intensity amplitude of the seventh insulator is: in order to ensure the accuracy and repeatability of the spatial electric field detection results of insulators, the insulators with significant electric field drop during the detection process are repeatedly detected. It can be seen that at the seventh insulator, the average value of the three electric field measurements is 5.56kV/m, and the effective value of the electric field is significantly reduced, It can be considered that it is in a degraded state near the seventh insulator. The test shows that the electric field distortion near the deteriorated insulator measured by the electric field measuring device carried by UAV has high repeatability, and can effectively identify the existence and location of the deteriorated insulator.

5. CONCLUSIONS
(1) Under the influence of stray capacitance of lines and towers, the electric field curve of insulators with good insulation performance presents a U-shape of high at both ends and low in the middle. The electric field at the deteriorated insulator has a steep drop, while the electric field on both sides increases abnormally. The deteriorated insulator has the greatest impact on the electric field at the high-voltage end, followed by the middle part, and the electric field at the low-voltage end has the least obvious decline.
(2) The transient high voltage electric field sensor based on photoelectric crystal Pockels effect has good response to the power frequency electric field waveform less than 60 kV/m, good linearity of power frequency amplitude, and no distortion and distortion. After the miniaturization design of the electric field data transmission module, the size is 100 * 150 * 30MM, which can be integrated into the UAV fuselage. The space electric field measurement system can carry out insulator detection based on UAV platform to meet the needs of engineering.

(3) Based on the live detection of the spatial electric field of insulators by the photoelectric sensor detection device of UAV, it can be found that the device can efficiently and accurately collect the distributed electric field of insulators, extract the electric field amplitude at the center of each insulator umbrella skirt after data processing of the measured electric field waveform, and determine whether there are distortion points in the obtained insulator electric field curve. It can accurately judge whether there are deteriorated insulators in the insulator string. The UAV degraded insulator detection platform based on optical electric field sensor can be used for non-contact accurate judgment of insulator insulation performance.

ACKNOWLEDGMENT
National Natural Science Foundation of China (Youth Science Foundation Project) (52007064)

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