Mechanism and Experimental Study on Insulation Defect Discharge of Transmission Line

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Abstract: Common faults on transmission lines, such as insulator pollution flashover, trees flashover, string breakage failure of insulator will undergo a period of discharge before the occurrence of flashover, which is called insulation defect discharge. In this paper, the process of discharge such as floating discharge, insulator pollution discharge and tree discharge is simulated in the laboratory environment and the high frequency current waveform is monitored. The results show that insulation defect discharge will maintain a long period of time and will not immediately form a flashover fault, in addition, a great deal of high frequency discharge current pulses will be generated during this period. The discharge characteristics and the discharge pulses generated by different type of insulation defect discharge are quite different. Frequency of floating discharge current waveform are very high, while the pulse cluster of pollution discharge is dense, and the current waveform generated by tree discharge has notable dispersity. With the degree of discharge increasing, the parameters such as pulse repetition rate and discharge amount are gradually increasing.

1 Introduction

Except for some faults such as lightning stroke and external force damage, the formation of most common faults in transmission lines is a gradual process, which will undergo a period of discharge process [1-3]. This paper calls it insulation defect discharge. Common types of faults with insulation defect discharge on transmission lines include deterioration of composite insulators, broken strands caused by floating discharge of fittings, flashover of trees and pollution flashover of insulators, etc.[4-5]. The proportion of this type of fault is relatively not very high, but once it occurs, it is very easy to cause reclosure failure, or even cause line outage.

There are a series of related studies on the insulation defect discharge of transmission lines, such as paper [6], which analyses the common deterioration characteristics of insulators, and defines the meaning and criterion of crisp fracture. In paper[7], the characteristics of suspension discharge in the insulation defect were tested, and the discharge characteristic map of the suspension discharge under different voltages was obtained. In [8], the characteristics of AC pollution flashover under salt spray state were studied, and the characteristics of insulator flashover and related influencing factors were analyzed. In [9], the mechanism of tree faults in transmission lines was studied. The characteristics of insulation defect discharge process before the failure of trees were discussed, and the characteristic parameters of the discharge were recorded.
In this paper, the simulation experiment of insulation defect discharge of transmission line is carried out, the transient current of discharge process is monitored and counted, and the characteristics and development law of insulation defect discharge are further analyzed, which provides a theoretical basis for the monitoring and warning of insulation defect discharge of transmission line.

2 Test principle

2.1 Test arrangement

The test arrangement is shown in Figure.1 below:

![Figure 1 The test arrangement of insulation defect discharge](image)

In the above Figure 1, the test wire is a steel pipe with an outer diameter of 5.1 cm and a length of 6 m. Both ends of the test wire are suspended under the crane hook by a silk rope with excellent insulation performance, and the space position can be adjusted at will. A 5 m * 5 m aluminum sheet was placed directly below the test wire to simulate the ground. The monitoring terminal is fixed on the wire, and the terminal casing, the grounding end of the collecting circuit and the wire are equipotentially connected.

During the test, the required voltage is applied to the test wire through the test power supply. The voltage on the test wire is connected to the oscilloscope through a standard voltage divider with a voltage division ratio of 1000, and the high-frequency discharge current is measured by the monitoring terminal, which monitoring principle is shown in 2.3 below. The monitoring data is sent wirelessly to the data center and processed and the results displayed.

The test power supply includes a rated voltage of 500kV, a capacity of 500kVA power frequency test transformer, and a rated voltage of 250kV, short-circuit current of 6A, which meet the requirements of this test.

2.2 Discharge gap

The discharge gap layout is shown in Figure.2.

![Figure 2 Schematic diagram of discharge electrode](image)

(a) Tree discharge gap (b) Pollution discharge gap (c) Floating discharge gap

1- Test wire; 2-Tree; 3-Stained insulator; 4-Insulated sheath; 5-Metal fitting; 6-Ground

In Figure.2 (a), the height of the tree is 1.6 m, and the distance \( d \) from the wire is about 20 to 25 cm. In order to ensure good grounding of the trees, multi-layer winding is performed on the bottom of the tree with a good conductive copper wire and connected to the ground electrode. In Figure. 2 (b), the insulator string is ceramic insulator with 7 pieces. The top of the insulator string is connected to the
grounding pole through the grounding wire. In the test, the insulator string was painted according to the method described in paper[6], and the pollution grade was grade III. In Figure. 2 (c), the insulating sheath is wound in the middle of the conductor, and then the fittings are connected to the insulating sheath, so that the fittings do not contact the simulated conductor directly. The thickness of the insulating sheath is 4-5 mm, the length is 40 cm, and the withstanding voltage of single piece of insulating sheath is about 60 kV.

2.3 Principle of high frequency discharge current monitoring

A self-integrating Roche coil sensor with good high frequency response is used to measure high frequency discharge current. The sensor has the advantages of good linearity, wide measurement frequency bandwidth and strong anti-interference ability. The principle of measuring high frequency discharge current with Roche coil is shown in Figure.3.

![Figure 3 Principle of rogoski coil current measurement](image)

In Figure.3 above, \( i(t) \) is the current on the test wire. The sensor output is a voltage signal and is also the amount of acquisition by the monitoring device. For self-integrating Rogowski coil sensors, the value is

\[
e(t) = -M \frac{di(t)}{dt} = L_0 \frac{di(t)}{dt} + (R_0 + r) i(t)
\]

(1)

Where \( M \) is the mutual inductance between the Rogowski coil and the test wire; \( L_0, R_0, C_0 \) and \( r \) are the Rogowski coil self-inductance coefficient, internal resistance, distributed capacitance and terminal sampling resistance, respectively; \( i \) is the current flowing through the sampling resistor. Since the self-integrating Rogowski coil sensor \( R_0 + r \) is small, when the measured current frequency is high, \( wL_0 \) is satisfied, then:

\[
e(t) = i(t) r \approx -\frac{M r}{L_0} i(t)
\]

(2)

It can be seen from the above formula that the output voltage of the sensor is approximately proportional to the current on the test wire. When the voltage is collected, the original discharge current waveform can be obtained.

The main components of the monitoring terminal include high-frequency current sensor, conditioning circuit, acquisition and high-speed processing circuit, battery, GPS clock module and wireless transmitter module.

The monitoring terminal housing is a cylindrical aluminum alloy metal container, and all modules are placed inside. During the test, the terminal housing and the conductor are equipotentially connected to effectively protect the internal functional modules from high voltage and electromagnetic environment interference.

The monitoring terminal collects the high-frequency current on the test wire in real time, and sends the current information to the data center wirelessly. In the test, the monitoring terminal was powered by battery, and the continuous working time was more than 4 hours. The technical parameters of the main components of the monitoring terminal are as follows:

1) Sensor unit: measuring range is 1mA–10A, bandwidth is 10Hz–10MHz;
2) Signal conditioning unit: the acquisition frequency range is 300Hz–10MHz;
3) Acquisition unit: sampling frequency 100MHz.

3 Test results and analysis
3.1 Test circuit corona discharge characteristics

Corona discharge is prone to occur when a high voltage is applied to the test wire. The corona discharge current is generally a high-frequency current, which is easily superimposed on the discharge current generated by the insulation defect discharge, and it is difficult to distinguish and extract the insulation defect discharge, so the influence of the corona discharge should be excluded first.

$U=40 \text{ kV}, 80 \text{ kV}, 120 \text{ kV}$ power frequency voltage is applied to the test wire in turn, and the voltage is applied for about 1 min each time. The test was repeated 3 times. Observe the test phenomenon and check the corona discharge waveform uploaded by the monitoring terminal through the host computer. When the voltage is applied, a relatively obvious sizzling sound can be heard, and the higher the voltage, the more obvious the discharge. When the voltage reaches 120 kV, a small brush arc can be observed on the equalizing ring. During the simulated corona discharge, the maximum voltage applied was 120 kV. The waveform of the corona discharge current with the largest amplitude detected in the test is shown in Figure 4 below:

![Figure 4: Typical corona discharge pulse waveform (U=120 kV)](image)

The corona discharge pulse cluster is dense, and the time interval between the two clusters is about 40–60μs. Statistics on a large number of corona discharge pulses show that as the applied voltage increases, the current amplitude increases, and most of them are within 10 mA. When a maximum voltage of 120 kV is applied, the maximum pulse amplitude is close to 20 mA.

3.2 Test phenomenon of insulation defect discharge

Set the monitoring terminal trigger threshold to 25 mA. When the test circuit applies voltage <120kV, it will not be triggered by corona discharge.

1) Tree discharge

When the applied voltage is about 60 kV, a relatively loud click can be heard. The applied voltage was maintained for 1–3 minutes, and the top of the tree began to burn. In this process, no obvious arc occurred, and the test transformer did not operate, but the monitoring terminal collected and recorded a large number of high-frequency current waveforms. According to the previous test conclusions, the possibility of corona discharge is eliminated, and it is judged that insulation defect discharge has occurred between the tree and the wire.

When the voltage is continuously increased to about 94 kV, the gap breaks down and a bright arc is generated. The test phenomenon is shown in Figure 5:

![Figure 5: The experimental phenomenon of tree discharge](image)

(a) Tree discharge ($U=60\text{kV}$)  
(b) Flashover ($U=95\text{kV}$)

2) Floating discharge

When the applied voltage on the test wire reaches about 40kV, a relatively obvious floating discharge phenomenon begins to occur, and the monitoring terminal triggers and collects a large number of high-frequency current pulses. In the case of bright light, a small discharge spark is
observed at the joint between the wire and the fitting, while in the dark it is a bright white spot. When the voltage is continuously increased to about 286 kV, the gap still cannot be broken down. Tests have shown that floating discharge does not directly cause gap breakdown. The test record discharge phenomenon is shown in Figure 6.

![Position of discharge](image)

**Figure 6** The experimental phenomenon of floating discharge

3) Insulator pollution discharge

The insulator is washed, dried, and smeared according to the method specified in [3], and then the contaminated insulator is placed in the artificial climate chamber, and the voltage is applied after the test is ready.

When the applied voltage reached 35 kV, a significant arc burning phenomenon was observed and the arc penetrated between the high and low voltage electrodes. The applied voltage was maintained for 3 to 5 minutes, and the arc was alternately from bright to dim, or dim to bright, and no flashover occurred throughout the process. Continue to increase the applied voltage to 52kV, flashover does not happen immediately, but occurs when the arc continues to burn for a few seconds. The test record phenomenon is shown in Figure 7 below:

![Pollution discharge](image)
![Pollution discharge](image)
![Pollution discharge](image)
![Flashover](image)

(a) Pollution discharge \((U=35kV)\)
(b) Pollution discharge \((U=35kV)\)
(c) Pollution discharge \((U=52kV)\)
(d) Flashover \((U=52kV)\)

**Figure 7** The experimental phenomenon of insulator pollution discharge

3.3 Discharge parameters in different discharge stages

The experimental results show that the insulation defect discharge is a discharge that is stronger than corona discharge but weaker than flashover discharge. In order to reduce the interference caused by corona on the identification of the discharge pulse, only the discharge pulse whose applied voltage is not more than 80 kV and whose amplitude is >20 mA is counted.

1) Waveform features

The current pulse waveform can reflect the motion characteristics of the charge and help to analyze the discharge mechanism and characteristics. Therefore, the pulse waveform parameters need to be
analyzed. The pulse waveform parameters are defined as shown in Figure 8 below, where $T_r$, $T_d$, and $i_p$ are the rise time, pulse width, and amplitude of the pulse waveform, respectively.

![Figure 8 Definition of waveform parameters for current pulse](image)

The main waves of several insulation defect discharge pulses monitored by the test are shown in Figure 9 respectively:

![Figure 9 Typical insulation defect discharge current waveform](image)

The pulse width of the tree discharge is about 6–25μs, the rise time is 3-10μs, the amplitude is 65–250mA, and the waveform characteristics of each pulse are quite different. The amplitude of the pulse current recorded at the time of flashover can reach 1A~5A.

The floating discharge waveform has a pulse width between 1 and 3 μs, a rise time of <1 μs, and an amplitude of up to 350 mA. Most of the floating discharge waveforms are single pulse waves, and the waveform characteristics are similar between the pulses.

The pollution discharge waveform has a pulse width of 3 to 30 μs, a rise time of 1-6 μs, and an amplitude of 60 to 350 mA. The pollution discharge pulse current waveform has a certain dispersion. Unlike the first two, the pollution discharge is often accompanied by multiple discharges in a short time interval.

2) Pulse repetition rate

The current pulse repetition rate can reflect the frequency of discharge, and the higher the repetition rate, the shorter the time interval between the two pulse discharges. The average time interval of each of the two amplitudes > 20 mA during the 1 min discharge process in each test was calculated and counted, and the reciprocal of this time interval is called the pulse repetition rate $f$. The statistical results are shown in Figure 9 below:
It can be seen from Figure 10 that as the voltage increases, the repetition rate of various insulation defect discharges gradually increases, indicating that the voltage is increased and the discharge is more and more frequent. In addition, it is found by comparison that the floating discharge repetition rate is greater than the other two types of insulation defect discharges, which may be related to the reason that the discharge gap is shorter, the pulse width is narrower, and the time required to form a discharge is shorter.

3) Change in discharge amount

Taking the 1min discharge process as the research object, first calculate the discharge amount of each discharge, and then find the total discharge amount \( p \). The calculation result is shown in Figure 11 below:

![Discharge capacity of different insulation defect discharges under different voltages](image)

**Figure 11** Discharge capacity of different insulation defect discharges under different voltages

With the increase of applied voltage, the discharges of several insulation defect discharges showed a steady increase trend. Compared with the floating discharge, tree discharge and pollution discharge increased faster. This is because the two types of discharges increase with the increase of voltage. Not only the repetition rate increases, but also the average amplitude in the discharge pulse increases greatly, so the amount of discharge increases more significantly.

4 Conclusion

1) Transmission line pollution flashover, tree fault, broken strands caused by floating discharge of fittings will occur for some time before the occurrence of insulation defect discharge process, high frequency and weak current will be generated during the discharge process.

2) Experimental studies show that high-frequency currents generated by 3 types insulation defect discharges are between 60 and 350 mA, and the pulse width is 6 to 25 \( \mu \)s. The pulse current waveform characteristics of different types of insulation defect discharges are different.

3) As the applied voltage increases, the repetition rate and discharge amount tend to increase steadily. In the test, by increasing the applied voltage to simulate the development process of insulation defect discharge, it is inferred that the discharge characteristic parameters will increase with the increase of insulation defect discharge in the actual transmission line.

In the actual transmission line, if the insulation defect discharge current is monitored, combined with the traveling wave positioning technology, the warning function of some typical faults can be realized theoretically. However, in the aspects of the transmission attenuation law of traveling waves,
the extraction of wave heads, and the identification from interference signals, the related research needs further research.

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