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RESEARCH ARTICLE

Characteristics of Partial Discharge on 10 kV Covered Conductor Around Tower Head

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ABSTRACT The widely use of covered conductor increases the reliability of distribution network. However, a new problem of partial discharge caused by covered conductor at the position of tower head is generated at the same time. This kind of partial discharge will damage the insulation layer or accelerate the deterioration of insulation, which may cause the single-phase grounding fault and affect the power supply reliability. At present, there is few systematic studies on the characteristics of this partial discharge. This paper mainly analyzes the electric field distribution near the covered conductor around tower head, builds the partial discharge experiment platform, and obtains the pulse current characteristics of partial discharge under different working conditions. The results show that the maximum electric field intensity is located at the interface between covered conductor, binding wire and air. The main causes of partial discharge are the wet and dirty of the surface of porcelain insulator and conductor insulation. The minor cause is the breakage of covered conductor insulation. Under different conditions, the initial partial discharge pulse current wave front time is 8ns $\sim$ 45ns, the tail time is 30ns $\sim$ 150ns. The discharge time interval can be as low as 30μs. In addition, it is found that there are two types of partial discharge through spectral analysis. One occurs when the covered conductor insulation is damaged under binding wire; the other is the covered conductor insulation is intact.

INDEX TERMS Covered conductor, distribution network tower head, impulse current characteristic, partial discharge.

I. INTRODUCTION

In 2021, total electricity consumption of China has exceeded 8.3PWh, which is the highest in the world [1]. Over the past few decades, China has invested most resources into its transmission network while only a few attentions were given to distribution network. Chinese Average Interruption Hours of Customer (AIHC) in 2019 is 823 minutes. By contrast, some developed countries are only 20 to 30 minutes, such as German, Japan, and America [2], [3], [4]. In 2019, more than 40 percent of distribution network power outage in China is caused by equipment failure. It suggests that the equipment status significantly affects the reliability of power supply.

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Using covered conductor to replace bare conductor is an effective method to increase reliability. It has reduced the flashover and earthing a lot [17]. However, a new problem of partial discharge has arisen on covered conductor insulation surface around tower head [37]. Recently, with the increasing attentions to the reliability of distribution network, more and more 10kV covered conductor insulation damages caused by partial discharges have been discovered all over the country, such as Zhangzhou of Fujian Province [5], Dalian of Liaoning Province [6], Shenyang of Liaoning Province [7], Hefei city of Anhui province [8], Beijing [9], Nanning of Guangxi province [10]. This problem has a wide distribution and large scope of influence. Figure 1 and 2 below illustrates the partial discharge problem occurs on the 10kV covered conductor around tower head according to our field investigation.

FIGURE 1. Partial discharge problem and burned insulation on covered conductor in Coastal areas.

FIGURE 2. Partial discharge problem and burned insulation on covered conductor in Inland areas.

Figure 1 comes from the maintenance team of power company in Fujian Province. Figure 2 comes from the maintenance team of power company in Beijing City and Anhui Province.

Among them, Zhangzhou and Dalian are coastal cities with high pollution level. The burning of conductor insulation is serious and causes high risk of flashover. In addition, discharge arcs can melt XLPE insulation material. XLPE will drop to the ground and may trigger a fire [5]. The distribution network reliability and safety are affected dramatically. In other inland cities, the degree of covered conductor damages is relatively lower. However, the risk of earth fault and fire still cannot be neglected. According to statistical data of Liaoning power supply recovery, the average recovery time of covered conductor failures exceeds 38 hours [7]. Operation and Maintenance team spent plenty of time on locating the earth point. As showed in figure 2, damaged insulation is usually covered by binding wire [9]. Without proper inspection devices, this damage is hardly to find. During our line patrol actions in Hefei in 2019 [8], we found that some partial discharges on covered conductor can only be detected in some certain weathers, such as high humidity environments. Therefore, lots of partial discharges on covered conductor cannot be discovered due to their high stealthiness and the lack of continuous monitoring device. As the length of 10kV distribution overhead line has exceeded 4,370,800km in China [1], the number of potential partial discharge problems is high.

Although the partial discharge is weak initially, it can develop into spark discharge and damage the covered conductor slowly. This will finally cause flashover, broken line, or single-phase earth fault. The reliability of distribution network is decreased. Although there are troubleshooting methods of ground and short faults, prevent partial discharge from the beginning is still the best solution in economic viewpoint [37].

Covered conductors are fixed on the porcelain insulator top by metal binding wires. In this area, there are three kinds of dielectric mediums, which are XLPE of covered conductor insulation, metal binding wire, and air. Thus, a junction area of these three mediums is formed. The maximum intensity of electric field is always in this area [11]. Kiitam calculated the electric field distribution in this junction area and further proved that the maximum electric field intensity is around the outermost turns of binding wires [20]. When the equipment insulation level is degraded to a certain degree, especially in offshore regions, partial discharges will primarily occur near the junction area [14]. However, how the distribution of electric field changes with working conditions is still unclear.

Only a few current research focuses on the partial discharge on covered conductor around tower head. Some of them are investigations and surveys of covered conductor damages [7], [8], [9], [10]. The cause of partial discharge is not explained. Others only focus on the pollution level in coastal areas while other conditions are not analyzed. Authors claimed that the heavy pollution will not only increase the electric field intensity in the air gap between the conductor and binding wire, but also increase the leakage current and flashover risk [5], [6]. High leakage current is another reason of insulation burning.

Currently, the researches of partial discharge on covered conductor mainly focus on the contacted trees [15], [16]. Unlike cables, if covered conductor is contacted by external objects, partial discharge may happen. The trees are the most common objects. As the origin of these partial discharges is totally different with the one happens in tower head, these researches have little help to our study.

In general, there are few studies on the characteristics of partial discharge and detection methods for the partial discharge happened in the junction area formed by covered conductor, binding wire, and air. The operation and maintenance team can neither eliminate damages in the early stage of partial discharge, nor have targeted solutions. Clear characteristics of partial discharges are the precondition of successful detection and prevention. As the partial discharge on covered conductor around tower head happens all over the country, the environments around the damaged equipment have huge differences. Therefore, the systematic research must be carried out to obtain the complete characteristics for all working conditions. The purpose of this paper is to study the characteristics of partial discharge happened in the junction area. An experiment platform for 10kV overhead covered conductor is built to reproduce the partial discharge, and 240 types of working conditions are tested. Through this systematic research of experiments and electric field simulation, the causes of partial discharge are discussed. The pulse current frequency spectrum, phase distribution, amplitude, front time, and tail time in different working conditions are calculated. These outcomes can not only provide the theoretical basis for partial discharge prevention, status monitoring, and failure risk assessment, but also have high significance of scientific and engineering of covered conduction partial discharge prevention and treatment. Thus, this paper can make contributions to improving distribution network reliability.

II. PARTIAL DISHARGE POSITION IN OVERHEAD LINE

It is proved that high electric field intensity is the root cause of partial discharges in air. Equation (1) below is a commonly used equation to calculate electric field intensity around a long cylinder. The parameters m and n are related to cylinder diameter and the distance between the electrode and the ground. The electric field will increase when electrode is close to the ground.

$$E = \frac{U}{\varepsilon_0 r\left(\frac{\ln m}{\varepsilon_1} + \frac{\ln n}{\varepsilon_0}\right)} \tag{1}$$

Based on the structure of overhead lines, this equation can also be used to qualitatively analyze the electric field around covered conductor. Between towers, the ground is at about 6m away from overhead conductor. However, at tower head, this distance is less than 20cm as the metal crossarm is usually grounded. Thus, disregard to external objects, the area around tower head has the highest electric field intensity and partial discharge risk.

In normal conditions, insulator bears most of the voltage drop. However, in some cases, this voltage drop will be mainly applied on the gap between covered conductor and binding wire [5]. Partial discharges are then occurred. According to current researches, there are two possible scenes of developing partial discharges around tower head:

a. Because of pollution, weather and equipment quality, initial partial discharge on covered conductor around tower head will occur [14].

b. As time goes by, the insulation of covered conductor is damaged gradually. The conductor will be exposed to the air at last. In addition, the induced lightning strikes may directly cause the perforation on conductor insulation without initial partial discharge stage [21], [22], [23].

Without the insulation, spark discharge may occur between the conductor and binding wire. The conductor insulation material also may be ignited by discharge arcs. Thus, the risk of earth fault, overhead line broken, and fire is extremely high.

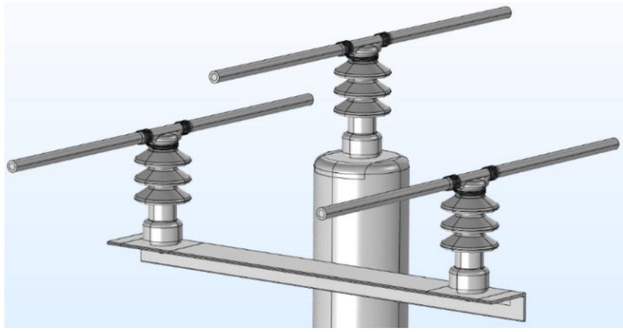


FIGURE 3. Simulation model.

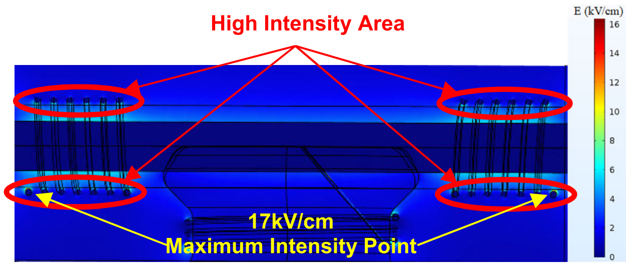


FIGURE 4. Electric field distribution around the junction area.

Calculate electric field distribution is the basis for revealing partial discharge positions in a system. Figure 3 illustrates a simple simulation model for electric field distribution calculation based on typical 10kV distribution network tower. PS-15/300 insulators, 17mm diameter covered conductors with 3.4mm insulation layer, 1mm diameter binding wire, and 6m height tower are built. The metals in model are treated as perfect conductor, so their relative dielectric constant is set to infinite [18].

Figure 4 shows the electric field in normal condition with 11.5kV voltage. It is clearly to see that the high intensity area is in the junction area. In addition, the maximum intensity sections are around the outermost turns of binding wire, which matches the actual damage position and other researches. By creating different defects in simulation model showed in figure 5, the calculated maximum intensity can be 3 times higher at most. Insulation damage and moisture are the most significant factor. Whatever the conditions are, the position of the maximum intensity is always in the junction area. It means that the partial discharge will firstly occur in this area. To detect or prevent partial discharge from the beginning, the partial discharge characteristics in this area must be studied.

III. EXPERIMENT PLATFORM AND METHODS

A. PLATFORM STRUCTURE

Partial discharge experiment platform is the indispensable key to observe the physical process of partial discharge and obtain related data in different working conditions.

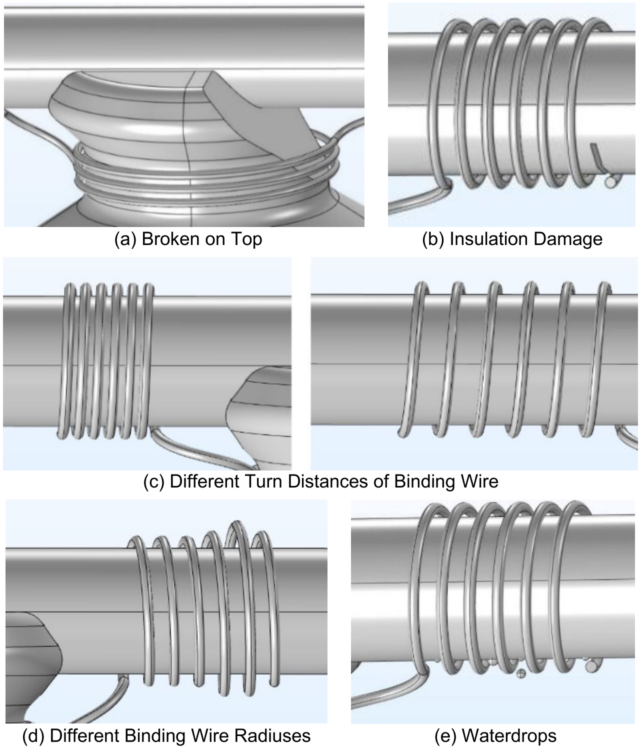
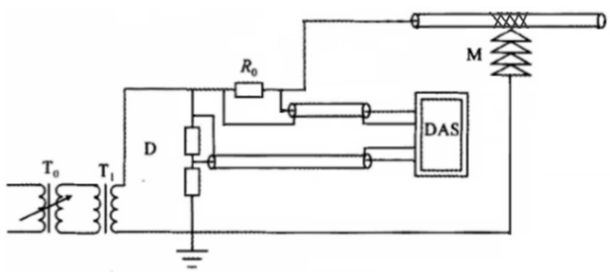


FIGURE 5. Defects in simulation.



T0 – Regulator (220V/220V, 50kVA); T1 – HV Transformer (220V/50kV, 50kVA); D – Inductance-Free Resistive Divider (2000:1, 50kV); R0 – Inductance-Free Shunt (100Ω); M – Insulator, Covered Conductor, Binding Wire and Cross-Arm); DAS – Cable, Digitizer (500MHz) and Computer

FIGURE 6. Experiment platform structure.

A platform demonstrated in figure 6 is built for this purpose. 2m length JKLYJ covered conductor is fixed on PS-10/300 insulator by 1mm diameter metal binding wire. The insulator is installed on a grounded metal crossarm and lifted for 2 meters. PD-free power frequency test system is used to apply maximum 20kV voltage to the covered conductor. The partial discharge pulse current is measured by a 100Ω shunt and the applied voltage is measured by a 200MΩ divider. A 500MHz bandwidth Pico digitizer model 6424D is used to record the outputs of shunt and divider. The digitizer is set to 312.5MHz sample rate, 1MΩ input impedance, and 20ms measurement length.

One of the keys of this experiment is to measure the pulse current of partial discharge correctly. Therefore, the

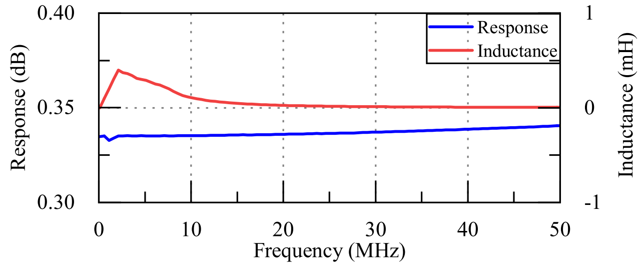


FIGURE 7. Frequency response of 100Ω inductance-free shunt.

performance of shunt is very important. A vector network analyzer (VNA) model E5061B from Keysight is used to measure the response of the shunt. The result is showed in figure 7. It proves that the shunt is inductance-free and has at least 50MHz bandwidth. Meanwhile, the maximum white noise of digitizer is 2mV, so the sensitivity of pulse current measurement can reach 20μA.

B. EXPERIMENT VARIABLES AND METHODS

Based on the practical working conditions and simulation results, the main factors that can affect the electric field are:

a. Covered conductor and insulator. The structure damage can be caused by flaws, mechanical wear, lightning, etc. [19], [24], [25]. The electric field distribution will be changed.

b. Pollution. After the equipment is put into operation, the pollution on its surface will gradually increase, and resulting in a decrease in the insulation performance.

c. Moisture. Waterdrops cannot be prevented on the surface of outdoor equipment. This will change the surface structural parameters and insulation properties of the equipment, resulting in more corona [26].

This paper uses the control variable method to perform experiments. Referring to the above factors, the variables are shown in table 1. It can be calculated that there are totally 240 combinations of all five variables. We tested all of them to measure the partial discharges.

Artificial pollution method is based on standard IEC-60507. According to the classification of environmental pollution range in standard GB/T-16434 and Q/GDW-152, there are four different pollution solutions been prepared as showed in table 2. The liquid is distilled water with 1μS/cm conductivity. Solid pollution is kaolin for NSDD, and pure NaCl for ESDD. Prepared pollution solutions are applied after the insulator is washed and dried.

We made a chamber with fog generation system. The samples are put inside for 3 minutes, and moisture will evenly condense on the sample surfaces with no waterdrops falling. In order to prevent pollution from being wiped by moisture, insulator is washed and re-polluted after each test.

The standard stipulates that the maximum allowable working line voltage of 10kV distribution line is 11.5kV. The highest phase voltage on the line is 11.5kV considering a

TABLE 1. Experiment variables.

Insulator Structure	Covered Conductor Insulation	Binding Wire	Pollution Level	Moisture
1. Intact	1. Intact	1. Regularly	1. Clean	1. Dry
2. Broken on Top	2. Broken point is 4cm from binding wire	2. Pointed end on top	2. I	2. Wet
3. Broken on Sheds	3. Broken point is 2cm from binding wire		3. II	
	4. Broken under binding wire		4. III	
			5. IV	

TABLE 2. Configuration Of pollution solutions.

Type	Level I	Level II	Level III	Level IV
ESDD (mg/cm^2)	0.05	0.1	0.2	0.4
NSDD (mg/cm^2)	0.2	0.4	0.8	1.6

single-phase ground fault as a long-time voltage. Other operating transient overvoltage can reach 22kV [27]. In order to obtain the partial discharge characteristics under power frequency withstand voltage, the maximum rms voltage during experiment in this paper is set to 20kV/1min. The experiment steps are:

a. Prepare the equipment according to the variables. Check environment temperature and humidity.

b. Increase the applied voltage until pulse current occurs. Record this voltage value as initial voltage. Record the waveform of voltage and current at the same time.

c. Increase the voltage step by step until 20kV. Record the waveform of voltage and current under different voltages.

d. Choose a new condition and repeat steps from a to c until all 240 working conditions are tested.

IV. RESULTS AND DISCUSSIONS

There are 240 working conditions been tested. An ultraviolet camera is used to located the partial discharges and typical ultraviolet image is showed in figure 8. It should be noted that the partial discharges observed in this paper are all happens in this junction area.

A. EXPERIMENT RESULT

According to the test results, when the surface of insulator and covered conductor is dry, there is no partial discharge been observed whatever other variables are. Therefore, following summarizes of experiment results in this paper have ruled out the condition of dry surface.

Insulator structure broken or different binding wire shapes also have no significant effect on initial voltages of partial discharge as well. These two factors can only change the electric field distribution around themselves. They cannot change the maximum electric field intensity of the entire covered conductor system, which is around the junction area. Therefore, they cannot be treated as key factors of partial discharge.

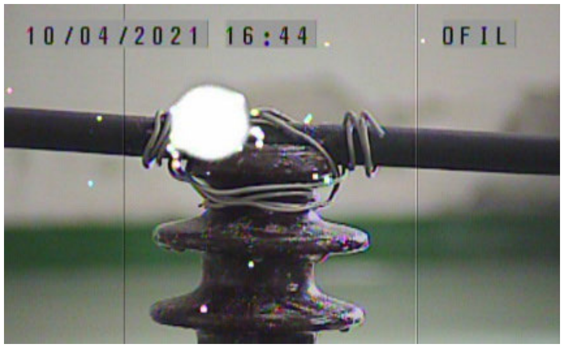


FIGURE 8. Partial discharge position.

TABLE 3. Partial discharge initial voltage in different working conditions.

Moist Pollution	Covered Conductor Insulation			
	Case 1	Case 2	Case 3	Case 4
Level IV	8kV	5kV	3kV	2kV
Level III	14kV	10kV	4kV	3kV
Level II	17kV	13kV	10kV	6.5kV
Level I	No Partial Discharge under 20kV		20kV	15kV
Clean	No Partial Discharge under 20kV			20kV

The partial discharge initial voltages of other working conditions are listed in table 3. It is clearly to see that, with the rising of pollution level and covered conductor insulation damage severity, the initial voltage is dropping.

1) DIFFERENT COVERED CONDUCTOR INSULATION STATES

According to table 3, the covered conductor insulation state has significant effect on partial discharge initial voltages. With the moist pollutions on system surface, the initial voltage drops with the decreasing of the distance between broken point and binding wire. In other words, partial discharge is more likely to happen. For instance, with pollution level II and moisture, the partial discharge initial voltage is around 6kV when covered conductor insulation is broken under binding wire. This is already lower than normal operation phase voltage of 6.6kV.

Figure 9 illustrates the waveform of pulse current and applied voltage with pollution level III and moisture. It suggests that the main effect of covered conductor insulation damage on the pulse current is the partial discharge phase. When covered conductor is intact, pulse currents occur around the peak area of applied voltage. If covered conductor insulation is broken, pulse currents will occur after the zero-crossing point of applied voltage.

2) DIFFERENT POLLUTION LEVELS

According to table 3, the initial voltage drops with the rising of pollution level. Partial discharge is more likely to happen.

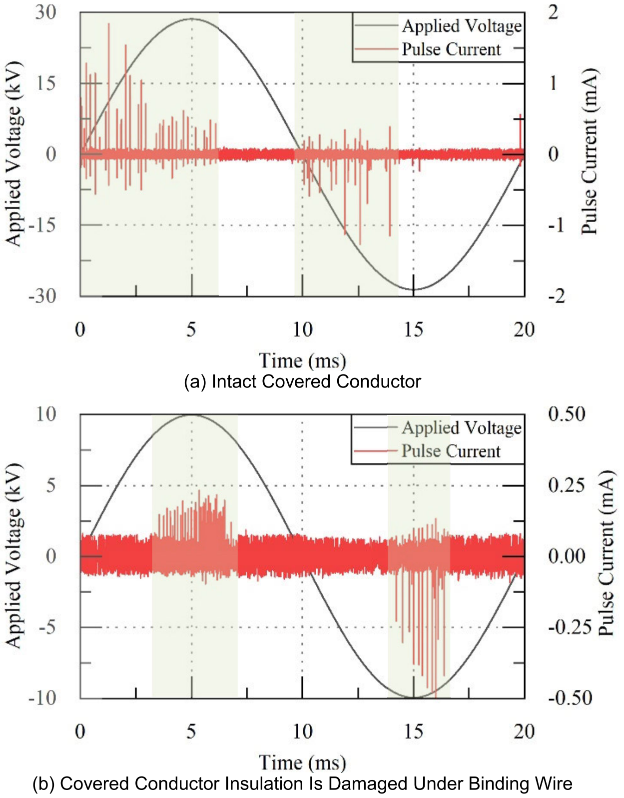


FIGURE 9. PD waveform under pollution Level III and moisture.

During rising applied voltage to 20kV with level I pollution and moisture, partial discharge occurs when covered conductor insulation is broken under binding wire. However, if broken point is 2cm away from the binding wire, partial discharge occurs occasionally. This situation changes if pollution level rises. During rising applied voltage to 20kV with level II pollution and moisture, partial discharge occurs in all cases. After pollution reaches level III, partial discharge will occur below 6.6kV operation phase voltage if there is broken on covered conductor insulation. In other words, in overhead covered conductor in operation, the insulation damage besides binding wire will probably cause the partial discharge.

Figure 10 illustrates the waveform of pulse current and applied voltage when covered conductor insulation is damaged under binding wire. It shows that different pollution levels cannot change the phase of partial discharge.

In addition, with the rising of pollution level, the amplitude of partial discharge pulse current is increasing even if applied voltage is dropping.

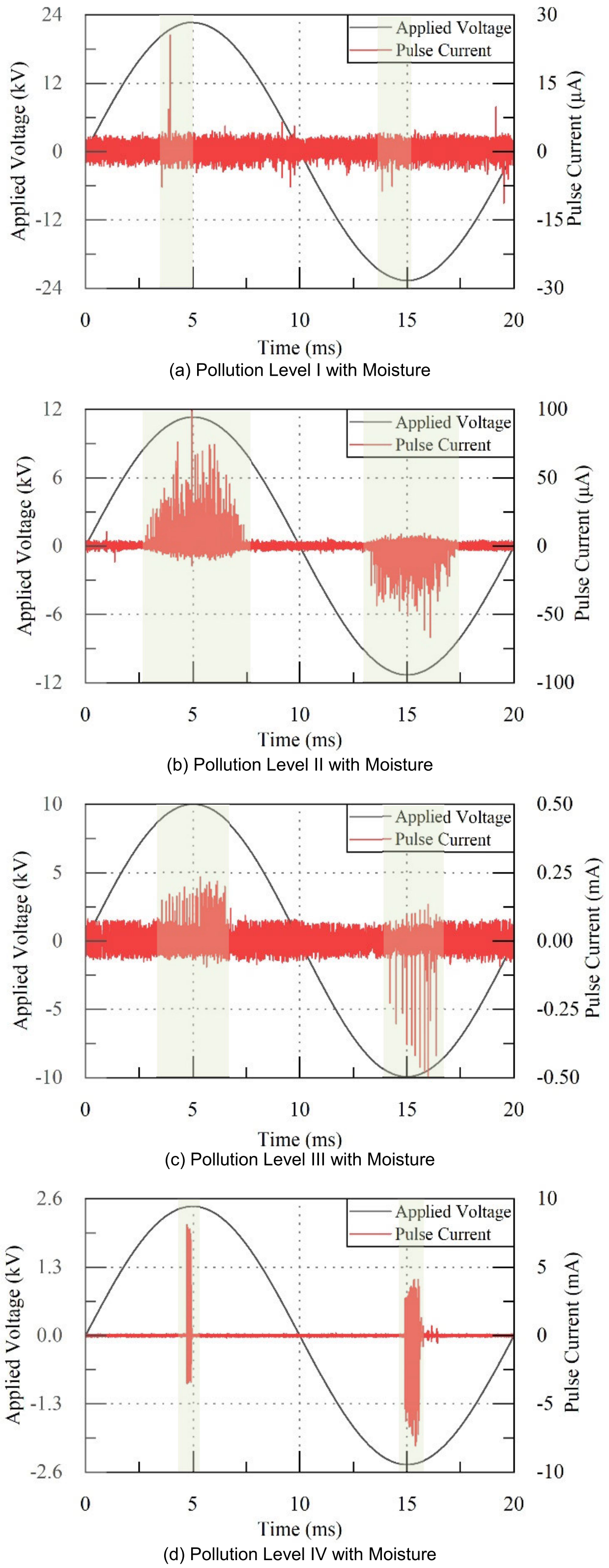
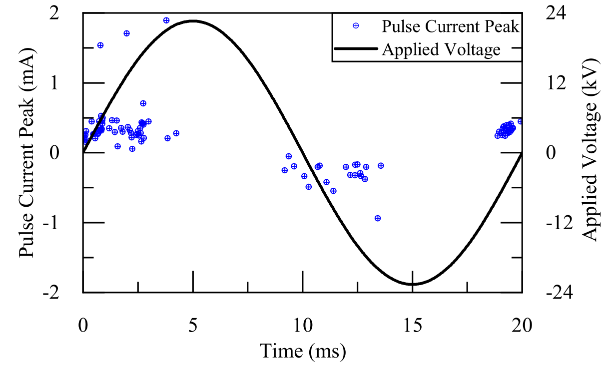


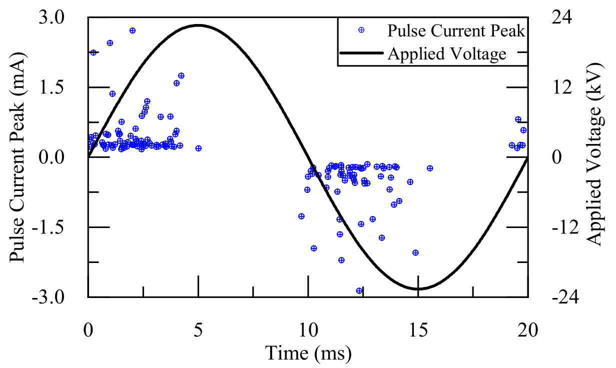
FIGURE 10. PD waveform of damaged covered conductor insulation under binding wire.

B. PHASE DISTRIBUTION OF PARTIAL DISCHARGE PULSE CURRENT

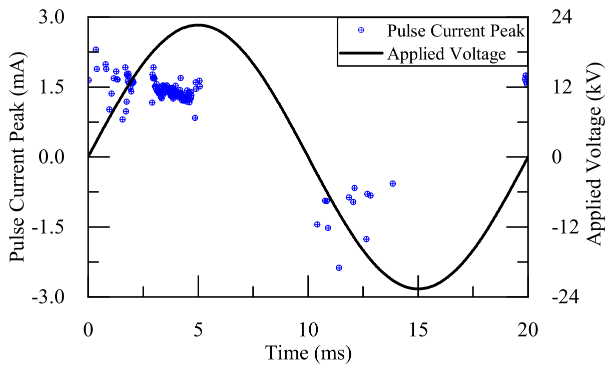
Figure 11 illustrates the Phase Resolved Partial Discharge (PRPD) of level III pollution with moisture. It is clearly to see that the PRPD patterns can be divided into two cases: pulse currents occur around the peak area of applied voltage or after the zero-crossing point of applied voltage. Meanwhile, PRPD patterns of other pollution levels also follows the same rule. These results demonstrate that the phase distribution of partial



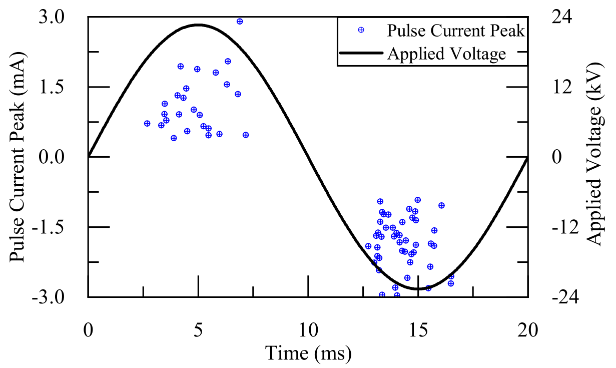
(a) Covered Conductor Intact



(b) Covered Conductor Insulation Damage Is 4cm Besides Binding Wire



(c) Covered Conductor Insulation Damage Is 2cm Besides Binding Wire



(d) Covered Conductor Insulation Is Damaged Under Binding Wire

FIGURE 11. PRPD pattern of pollution Level III and moisture with 16kV applied voltage.

discharge will not change with pollution level. These can help us to classify the partial discharge type happened in covered conductor system.

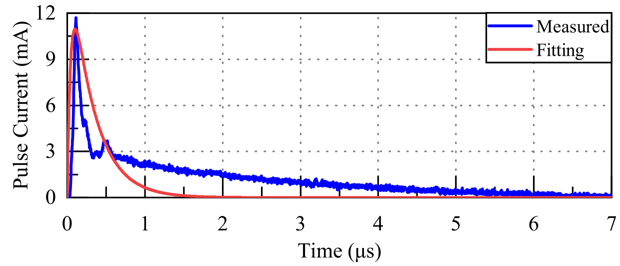


FIGURE 12. Measured waveform of single pulse current.

PRPD pattern represents the partial discharge type [28]. Therefore, the features of PRPD patterns can be used to distinguish different discharge types, such as partial discharge caused by free metal particle, discharge caused by bubble in the dielectric, corona discharge on pointed end, and so on. In this paper, two different types of PRPD patterns are observed as showed in figure 11. The partial discharge in picture a), b) and c) happens when the covered conductor is intact, or the damage of covered conductor insulation is besides the binding wire. The partial discharge in picture d) happens when the covered conductor insulation under binding wire is damaged. According to our ultraviolet camera, all partial discharges happen in the junction area. Space charges generated by discharges are the root cause of different PD types. In case a) to c), space charges cannot dissipate quickly. They collected between covered conductor and binding wire, and changed the electric field. Thus, the partial discharge starts from the zero-cross point of applied voltage. In case d), space charges can dissipate through the conductor core quickly. Electric field is only affected by applied voltage. Thus, the partial discharge happens around the peak of applied voltage.

C. TIME DOMAIN CHARACTERISTICS OF PARTIAL DISCHARGE PULSE CURRENT

1) ANALYSIS METHOD

A single pulse current measured in our experiment platform is showed in figure 12. It is clearly that the waveform is in bi-exponential distribution shape. This kind of waveform can be represented by the bi-exponential formula [29]:

$$i(t) = K\left(e^{-\alpha t} - e^{-\beta t}\right) \tag{2}$$

In equation (2), parameter K is the factor of pulse current peak. $e^{-\alpha t}$ represents ionic current while $e^{-\beta t}$ represents electron current. Since electrons move faster than ions, β is usually higher than α. In other words, α and β is depended on the rising and falling time of pulse current respectively. In the fitting curve in figure 12, K equals to 18.02, α equals to 3.34, and β equals to 22.23. The electron concentration at the initial moment and the difference between α and β together determine the shape of the pulse current.

For example, when the working condition or covered conductor insulation status changes, the electric field distribution is changed. This will lead to the changes in the moving speeds

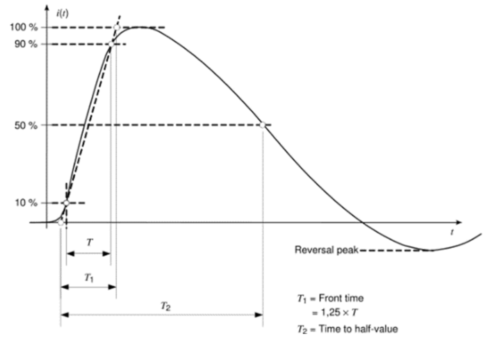


FIGURE 13. Pulse current parameter definitions in IEC standard.

TABLE 4. Pulse current parameters in different working conditions.

Covered Conductor Insulation	Pollution with Moisture	T_1 (ns)	T_2 (ns)	Amplitude under 6kV (mA)
No damage under binding wire	Level I	8 ~ 35	30 ~ 60	N/A
	Level II	15 ~ 45	40 ~ 90	N/A
	Level III	20 ~ 45	30 ~ 100	< 1mA
	Level IV	25 ~ 45	60 ~ 130	< 2mA
Damage under binding wire	Level I	8 ~ 30	35 ~ 60	N/A
	Level II	12 ~ 25	40 ~ 50	< 0.1mA
	Level III	20 ~ 35	20 ~ 100	< 2mA
	Level IV	10 ~ 35	100 ~ 150	> 10mA

and paths of electrons and ions, and finally forms different pulse current patterns under different working conditions.

Standard IEC-62475 has stipulated related evaluation methods of the bi-exponential shape pulse current as showed in figure 13. This paper will use amplitude, front time T_1, and tail time T_2 to describe a single partial discharge pulse current.

2) TIME DOMAIN CHARACTERISTICS

Table 4 shows the ranges of front time, tail time and amplitude in different working conditions. Figure 14 and 15 show the boxplot of changing of front time, tail time and amplitude with different applied voltages. According to test results, following rules can be revealed with the condition of pollution and moisture on equipment surface.

a. The covered conductor insulation status under binding wire can affect the pattern of partial discharge pulse current. When the insulation is damaged under binding wire, the front time is smaller compared with other conditions. However, the tail times are in the same range.

b. When the covered conductor insulation is intact or the damage is besides the binding wire, with the increasing of pollution level, the front time and the tail time both show an increasing trend.

c. When the covered conductor insulation is damaged under binding wire, with the increasing of pollution level, the front time has no obvious changes, but the tail time shows an increasing trend.

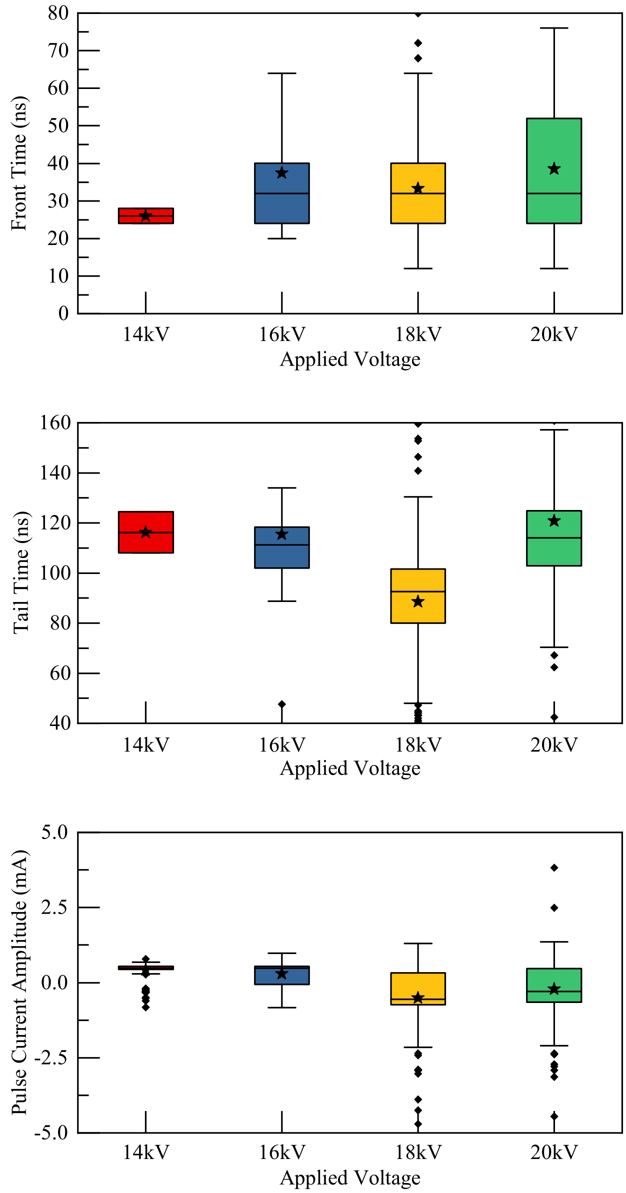


FIGURE 14. Pulse current parameters with intact covered conductor and Level III moist pollution.

d. The pulse amplitude increases with the rising of pollution level and the damage of covered conductor.

e. With the increasing of applied voltage, the minimum, maximum and average values of front time and tail time do not show obvious rules. However, if covered conductor insulation is damaged under binding wire, the averages are increasing with applied voltage.

f. In the same working condition, the amplitude of pulse currents increases together with the applied voltage. In other words, the partial discharge intensity is increasing, which is obviously.

g. In the same pollution level, the amplitude range of pulse currents decrease with the increasing distance between covered conductor damage point and binding wire. It suggests

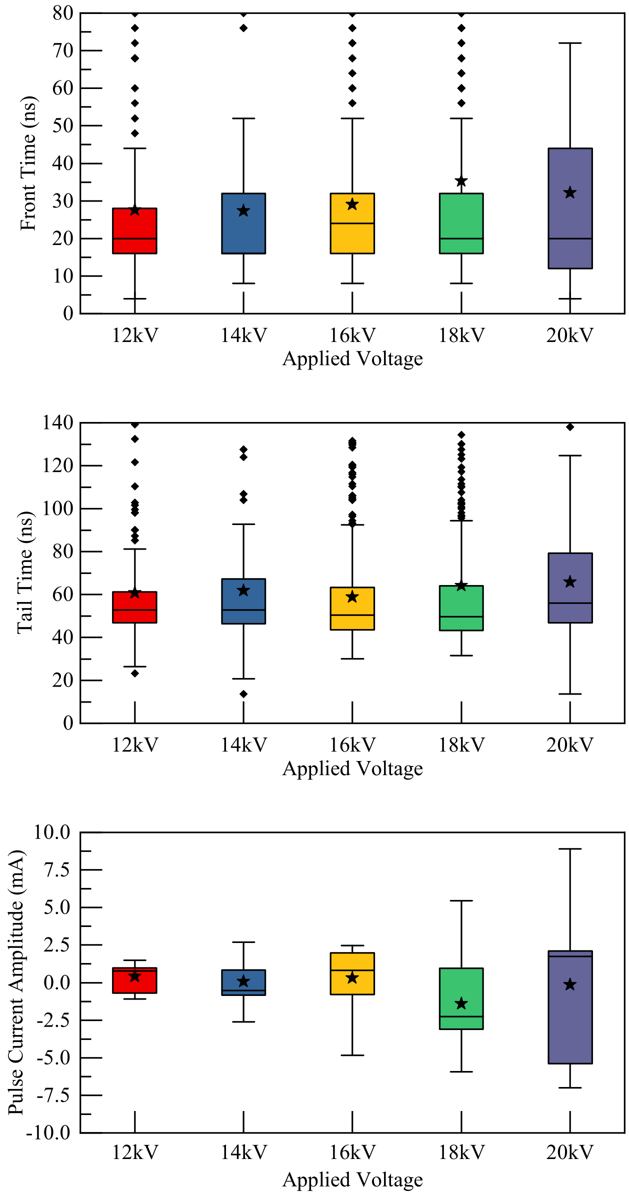


FIGURE 15. Pulse current parameters with covered Fig. 1. Conductor damage under binding wire and Level III moist pollution.

that the electric field intensity in the junction area is decreasing.

h. In the same applied voltage, he amplitude of pulse currents increases together with pollution level. It suggests that the pollution level can cause the electric field distortion in the junction area.

The partial discharge of usually happens between the binding wire and covered conductor [14], [30]. This type of discharge is greatly affected by space charge [31], [32], [33]. If the covered conductor insulation is damaged under binding wire, the space charge generated by the partial discharge can rapidly escape through the uncovered conductor under the action of a strong electric field. Thus, the charge accumulation on the surface of the equipment is reduced, the difference between the ionic current and the electronic current is increased. Finally, the front time is decreased compared with the intact covered conductor insulation.

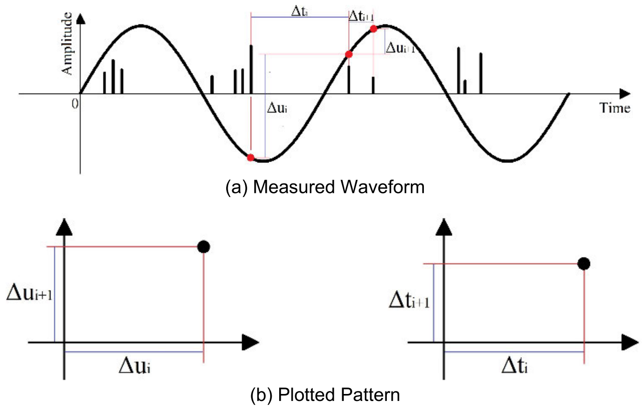


FIGURE 16. Definition of Δu and Δt patterns.

D. PARTIAL DISCHARGE PULSE CURRENT PATTERN

1) ANALYSIS METHOD

CIGRE proposes more than 20 types of PD patterns, and $\Delta u/\Delta t$ is one of them. The relationship between space charge and electric field can be describe by Δu pattern, while Δt pattern can be used to the dissipation information of space charge [28]. Figure 16 shows the definition of the patterns. In the plotted pattern, each dot represents a partial discharge while its position represents the relationship between its last and next discharge. In Δu pattern, dots near X-axis mean the applied voltage is almost the same in its next discharges while a dot near Y-axis means the applied voltage is almost the same in the last discharges. In Δt pattern, the rule is the same except applied voltage becomes time interval of discharges. Therefore, if a dot is near original point, the discharges are continuous and dense. This pattern can be used for status evaluation by describing dot distributions with numerical parameters. For example, using neural networks to identify different shapes. However, fulfilling status evaluation is the next step of our research. Therefore, this paper analyzed the shape of dots manually and extracted the average values of Δt and Δu.

For the continuous partial discharge that occurs in a short period of time, the residual space charge of each discharge will affect the development of the next discharge [34]. A single pulse current cannot represent the entire development process of partial discharge. Δu and Δt patterns can eliminate the interference of applied voltage on the partial discharge analysis. The data of different applied voltages can be plotted into a same pattern so the number of samples is expanded. Thus, the discharge can be easily classified for each working condition.

2) PATTERN OF ΔU

Figure 17 shows Δu pattern of different working conditions.

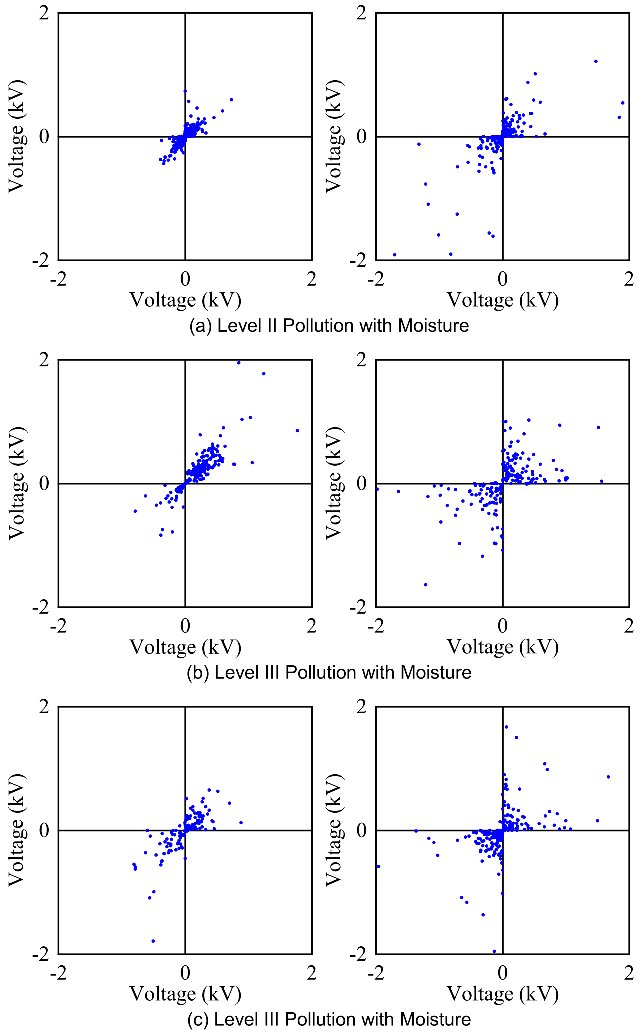


FIGURE 17. **Δu pattern of different working conditions (Left: Covered conductor is damaged under binding wire; Right: Covered conductor is intact under binding wire.)**

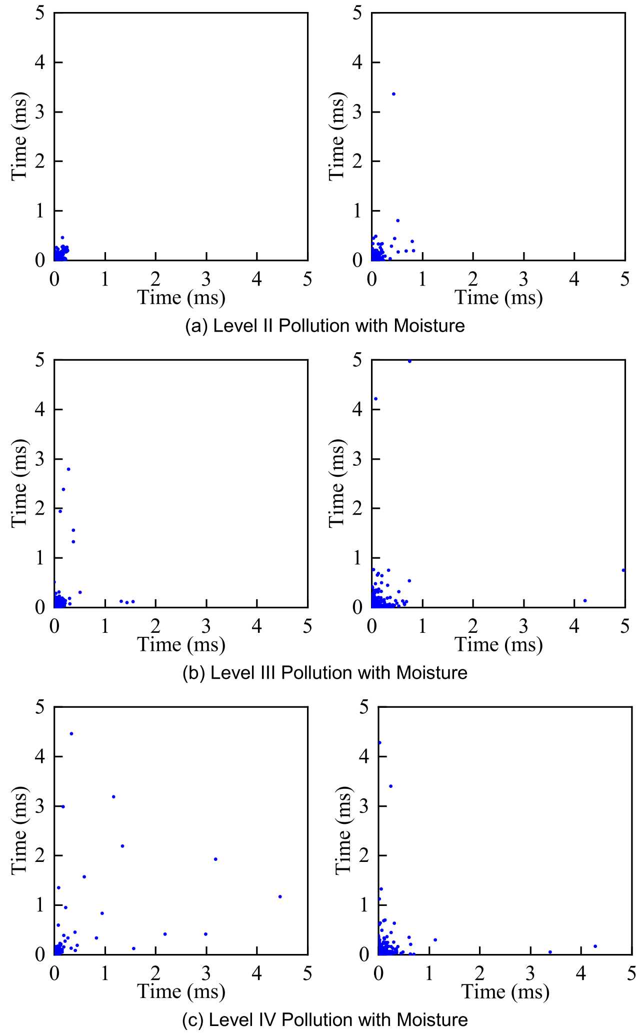


FIGURE 18. **Δt pattern of different working conditions (Left: Covered conductor is damage under binding wire; Right: Covered conductor is intact under binding wire.)**

Left three pictures represent the condition of damaged covered conductor insulation under biding wire. In these patterns, most values of Δu dots are below 1kV. The dots are distributed diagonally in the first and third quadrants, and symmetrical to the origin. With the decreasing of pollution level, the dots in Δu pattern gradually converge towards the origin. In other words, the slope of applied voltage is relatively low when the partial discharge happens. The low slope area is around the peak of voltage waveform. The average values of Δu in level II, III and IV pollutions are 0.11kV, 0.68kV and 1.45kV respectively.

Right three pictures represent the condition of intact covered conductor insulation under biding wire. In these patterns, the value of Δu varies greatly with the range of 0kV to 3kV. But most of them are still below 1kV. The dots are fan-shaped distributed in the x-axis, y-axis, first quadrants, and third quadrants. They are also symmetrical to the origin. However, with the decreasing of pollution level, the dots in Δu pattern do not gradually converge towards the origin. The average values of Δu are between 0.2kV to 0.5kV.

According to the definition of the pattern, it can be known that the first quadrant in the Δu pattern represents the partial discharge occurs in the rising period of the applied voltage, and the third quadrant represents the partial discharge occurs during the falling period of the applied voltage. As all patterns are symmetrical to the origin, it shows that the distribution of partial discharge pulses is similar in positive and negative polarities under different working conditions. In addition, when covered conductor insulation is intact under biding wire, the values of Δu are higher than damaged case. This represents the partial discharge is distributed more widely in a power frequency period.

3) PATTERN OF ΔT

Figure 18 shows Δt pattern of different working conditions.

Left three pictures represent the condition of damaged covered conductor insulation under biding wire. In these patterns, most values of Δt dots are below 0.3ms. The dots are gathered around the origin. With the decreasing of pollution level, the dots gradually converge towards the origin. This represents the partial discharge occurs around the peak of applied voltage. For the level II, III, and IV pollution level, the average values of Δt are 0.04ms, 0.15ms, and 0.30ms respectively, the maximum values of Δt are 0.4ms, 2.7ms, and 4.5ms respectively.

Right three pictures represent the condition of intact covered conductor insulation under biding wire. In these patterns, most values of Δt dots are below 0.8ms, and the dots are also gathered around the origin. With the decreasing of pollution level, the dots do not gradually converge towards the origin. For the level II, III, and IV pollution level, the average values of Δt are between 0.1ms and 0.15ms, the maximum va- lues of Δt are 4.5ms, 5.1ms, and 4.4ms respectively. There is no obvious rule in the changing of Δt values.

Compare two different insulation status in figure 18, the dots are more gathered around the origin when the covered conductor insulation is intact under binding wire. In other words, the partial discharges happen more intensely. In the view of microscopic analysis, the result shows that the retention charges from partial discharge can be rapidly conducted and released through uncovered conductor if the covered conductor insulation is damaged under binding wire. This results in the weakening of the reverse superposition effect of the electric field generated by charges, so the next partial discharge can occur more quickly. On the contrary, if the covered conductor insulation is intact, the charges formed by partial discharge do not have a fast release path. Therefore, their residence effect is stronger and the dissipation speed is slower. Finally, the reverse superposition effect of the electric field causes the time interval between two partial discharges to increase.

E. DISCUSSIONS

Though this study used existing measurement methods to obtain characteristics, it has some differences. First, this study gives systematic research on the partial discharge on covered conductor around tower head, which has not been done before. So, the causes of partial discharges can be discussed. Moreover, this study analysis the and relationship between pulse current patterns and working conditions. This provides a guidance for equipment status assessment.

1) ANALYSIS OF PARTIAL DISCHARGE CAUSES

According to table 3, under the combined effect of various factors such as covered cable insulation damage, the partial discharge initial voltage is lower. Several conclusions can be obtained:

a. There is no partial discharge under 20kV without moisture. In addition, the initial voltage drops with the increasing of pollution level. It shows that the pollution and moisture are necessary conditions for partial discharge in the junction area.

b. The partial discharge initial voltage is the lowest when covered conductor insulation is broken under binding wire. When the broken point gets away, the initial voltage raises. Therefore, the damage on covered conductor insulation distorts the electric field distribution in the junction area, especially when it is near binding wire.

c. When insulator and binding wire structure changes, the variation range of partial discharge initial voltage is less than 0.2kV. They have no obvious effect on the partial discharge in the junction area.

The main causes of partial discharges in the junction area are pollution level, moisture, and covered conductor insulation status. The moisture greatly enhances the degree of electric field distortion with the combined action of other factors. In moist condition, the conductivity of pollutions on surface can rise to 160μS/cm. This value is around 2μS/cm in dry condition [35], [36]. Thus, the surface resistance of the insulator is reduced, so the voltage it bears is also reduced. Most of the voltage is applied to the gap formed by the covered conduction insulation and binding wire. This results an increase in the electric field strength in the junction area and causes partial discharges. For example, the maximum normal operation line voltage of 10kV distribution overhead line is 6.6kV. In the condition of damaged covered conductor insulation, the initial voltage can be lower than 6.6kV when the moist pollution level is higher than II.

2) FEASIBILITY ANALYSIS OF EQUIPMNENT STATUS ASSESSMENT BASED ON PARTIAL DISCHARGE PULSE CURRENT

Partial discharge characteristics can be used to obtain the mapping relation between equipment states and pulse current patterns. Equipment status assessment is then carried out base on it. The patterns used for assessment is usually called ''data fingerprint''. According to the experiment results in this paper, following fingerprints can be obtained.

a. The fingerprint of front and tail time. The range of times are changing with different pollution levels according to table 4. Therefore, this fingerprint can be used to assess current pollution level.

b. The fingerprint of pulse current peak value. The peak of the pulse current represents the intensity of partial discharge. This fingerprint can be formed based on a series of peak values of continuous partial discharge. However, according to figure 14, figure 15 and table 4, the differences of peak values are small in different working conditions. Therefore, the assessment result based on peak values has a relatively low confidence.

c. The fingerprint of PRPD. According to figure 9 and figure 10, there are two different types of phase distribution. This fingerprint can be used to judge whether the covered conductor insulation under binding wire is intact.

d. The fingerprint of Δu and Δt patterns. Figure 17 and figure 18 also illustrate two different distribution types: one is the dots are gathered around the origin while the other one is the dots are diffused. This fingerprint can also be used to judge whether the covered conductor insulation under binding wire is damaged.

In summary, the covered conductor insulation state can be determined based on the fingerprints of Δu, Δt, and phase distribution. If applied voltage cannot be measured, this purpose can be fulfilled by Δt fingerprint alone. In addition, the probability of the equipment pollution levels can be obtained by analyzing the fingerprints of pulse current front time, tail time and peak value. Therefore, it is feasible to achieve the equipment status assessment for covered conductor around tower head by using multiple partial discharge fingerprints.

V. CONCLUSION

This paper carried out systematic study in the characteristics of partial discharge on 10kV covered conductor around tower head. An experiment platform for covered conductor is built and partial discharge is reproduced. By pulse current measurement and electric field simulation, partial discharge causes in different working conditions are analyzed and characteristics is obtained. The main conclusions are as follows:

a. Electric field simulation of the area in 10kV distribution network tower head is carried out. The results show that the highest electric field always locates in the junction area formed by covered conductor, binding wire, and air.

b. The causes of partial discharge in the junction area is analyzed. It is proved that moisture and pollution are the main reasons of partial discharge. The secondary cause is the damages on covered conductor insulation. The structural integrity of the insulator and binding wire shapes have little effect on the partial discharge. They will cause voltage drop be mainly withstood by the small gap between covered conductor and binding wire. This finally results in high electric field and partial discharge. When covered conductor is damaged and pollution level is greater than class II, partial discharge may occur under the normal operation voltage.

c. Through the experiment platform, partial discharge pulse current characteristics is obtained. Results show that continuous pulse currents are generated in both positive and negative cycles of applied voltage. The time interval of pulse currents can be as short as 30μs. Under the normal operation phase voltage of 6.6kV, the amplitude of pulse current in class III and IV moist pollution can exceed 2mA, while the peak is lower than 0.5mA in class I or II moist pollution. Two different types of partial discharges are discovered by PRPD pattern and Δu/Δt pattern. One kind of partial discharge occurs around the peak section of the applied voltage, which is happened when covered cable insulation under binding wire is damaged. The other one occurs from the zero-crossing point of applied voltage. It is observed when covered conduction insulation under binding wire is intact.

d. Equipment status assessment can be achieved with a suitable classification algorithm. Pollution level, covered cable insulation states can be analyzed based on the pulse current characteristics.

This paper preliminarily analyzed the causes of partial discharge in 10kV distribution network tower head. The results provide a theoretical basis for the fulfillment of equipment status assessment. Our future work will focus on the following aspects.

a. Measure pulse currents of other working conditions in actual 10kV overhead covered conductor.

b. Build a feature library of partial discharges in 10kV distribution network covered conductor. In addition, related classification algorithm will be studied to fulfil the equipment status assessment.

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