Influence of Sheath Radial Crack on Flashover Arc and Leakage Current of Roof Silicon Rubber Insulator for High-Speed Train

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ABSTRACT In this paper, three types of insulators with no crack, short crack, and long crack are taken as the research objects to evaluate the influence of the penetrating cracks on the 1st sheath of the roof silicone rubber composite insulator of high-speed train on the flashover characteristics. The continuous voltage rising method is used to obtain the influence characteristics of the crack on the development process of the flashover arc. The constant voltage withstand method is adopted to compare the leakage current when the contamination degree is 0.1 mg/cm². The test results demonstrate that the crack has no significant effect on the flashover voltage and flashover path, and the flashover arc can burn the edge of the crack. The peak leakage current of the three different tests ranges from 24 mA to 30 mA. Additionally, the development of leakage current can be divided into four stages: rising, continuous violence, falling, and oscillating. Moreover, the sequence of the apparent leakage current of the insulator is long crack insulator, short crack insulator, and the one with no crack. The acceleration of the rising stage of the leakage current increases with the increase in the crack length. Meanwhile, the sum of the time of the rising stage, continuous stage, and falling stage of the insulator with long crack is the smallest. The crack will distort the distribution of current density and the electric field intensity in the vicinity. The results can provide references for evaluating the influence of radial cracks at the edge of the sheath on the flashover characteristics and optimizing the design of the roof insulator sheath structure.

INDEX TERMS High-speed train, roof insulator, radial fissure, electric arc, leakage current.

I. INTRODUCTION

By the end of 2020, the mileage of China’s high-speed railways has reached 37,900 km. Since silicone rubber composite insulators have good hydrophobicity, they are widely used in railway contact lines and electric locomotive roofs [1]–[4]. With the continuous expansion of the coverage of high-speed railways, the composite insulators on the roof of trains that run across multiple areas of different meteorological environments need to withstand more stringent tests. The abnormal flashover of the roof insulators could lead to the interruption of the train’s power supply. Due to multiple factors such as resistance, contact line height, and contact pressure, the structural height of the roof insulator varies in a small range, and the roof insulator with a single structure cannot satisfy the application requirements of different meteorological environments [5]–[8]. Therefore, it is necessary to analyze the causes of the on-site problems and optimize the design of the roof insulator structure on the basis of clarifying the operation problems of the on-site insulators, so as to improve the environmental adaptability of roof insulators and reduce the flashover probability [9].

High-speed train maintenance units in cities such as Shijiazhuang and Wuhan reported that the edges of 1st and 2nd sheath on the high voltage side of the silicon rubber composite insulators with the mileage of more than 2.4 million kilometers appear cracks as illustrated in Figure 1 [10], [11].
The thickness of the silicone rubber at the junction of the sheath and the mandrel of the high-speed train roof insulator is larger than that at the edge of the sheath. The crack may expand towards the root of the sheath when the crack is located on the windward side under a crack on the edge of the sheath. Once the silicone rubber sheath at the interface of the mandrel is damaged, it will facilitate the intrusion of moisture into the mandrel, resulting in the deterioration of the interface adhesion and even the formation of partial discharge channels at the interface. Finally, it can directly increase the probability of flashover of the roof insulator along with the interface [12]. Therefore, the maintenance unit should directly replace the cracked insulators with intact insulators to avoid the expansion of the sheath edge tearing.

The edge cracks of the sheath exhibited in Figure 1 are significantly different from the crescent-shaped cracks at the root of the rod suspension insulator of 750 kV transmission lines in Hami and other places [13]–[15]. The research results of Tsinghua University Zhidong Jia et al. on the crescent-shaped cracks of insulators reveal that the root thickness of transmission line insulator sheath is small, and the soft and high-elastic silicone rubber could decrease the mechanical strength after the reciprocating deflection by the action of airflow. The severity of crescent-shaped cracks at the root is related to factors such as air velocity, air angle, and sheath parameters [16], [17]. Different from the power system, the power supply voltage of high-speed trains is single-phase 27.5kV, and the operating environment of high-speed trains is sometimes more complicated than transmission lines.

Timely replacement of insulators with cracks can eliminate hidden troubles, while it cannot fundamentally manage the continuous occurrence of sheath tearing [18], [19]. Therefore, it is urgent to conduct a systematic analysis of the tearing problem of high-speed train roof silicone rubber insulator sheath. The influence of the sheath edge cracks on the flashover voltage withstand performance is explored through tests. The deformation and deflection process of the sheath and the formation and expansion process of the sheath edge cracks are analyzed under the high-speed airflow. The design of the sheath structure is optimized; the deformation of the new insulator is experimentally verified under the high-speed airflow. Finally, the frequency of flashover caused by tearing at the sheath edge is reduced.

At present, there is little research on the influence of the edge cracks at the sheath on the flashover characteristics of the roof insulators. For the evaluation of insulation performance of high-voltage insulators, the results of simulation without test are not convincing enough. Therefore, the testing process is indispensable, and simulation work is usually used for the design of the experimental protocol or the interpretation and analysis of the experimental results. In this paper, the soft silicone rubber composite insulator on the roof is taken as the research object to evaluate the influence of the cracks at the edge and the intermediate part of the sheath on the insulation characteristics. Besides, two kinds of radial cracks close to the operation crack parameters are set. Regarding three types of insulators (normal, short crack, and long crack), the withstand method is employed to reveal the influence of cracks on the flashover voltage and collect the leakage current changes on the surface of the sheath under non-arc operation.

II. TEST PRODUCT, TEST DEVICE AND TEST METHOD
A. TEST PRODUCT
The structure of the silicone rubber composite insulator used on the roof of the 200 km/h train is presented in Figure 2, and the structural parameters are listed in Table 1.

Based on the size of radial cracks at the edge of the sheath obtained from on-site research, the radial cracks are
TABLE 1. Structural parameters of high-speed train roof composite insulator.

| Height H (mm) | Mandrel diameter d(mm) | Shed diameter D1/D2 (mm) | Sheath spacing L(mm) | Leakage Distance S(mm) |
|---------------|------------------------|--------------------------|----------------------|------------------------|
| 400           | 27.5                   | 190/170                  | 30                   | 1327                   |

TABLE 2. Prefabricated defect parameters.

| Type         | Crack length L(mm) | Crack width W(mm) | Crack depth       |
|--------------|--------------------|-------------------|-------------------|
| Intact       | /                  | /                 | /                 |
| Short crack  | 11                 | 3                 | Penetrating       |
| Long crack   | 22                 | 3                 | Penetrating       |

FIGURE 3. Schematic diagram of prefabricated defects of sample. (a) Intact. (b) Short crack. (c) Long crack and its profile.

Prefabricated according to the combination method presented in Table 2, and their shape is approximately cuboid. There are 6 insulators used in the test in this paper, involving 2 intact insulators, 2 short crack insulators, and 2 long crack insulators. For the convenience of description, the types of test samples are distinguished by intact, short crack, and long crack. The appearances and crack shapes of the three samples are displayed in Figure 3.

In Figure 3(c), L indicates the radial length of the defect, W denotes the axial width of the defect, and the depth of the defect is the full penetration of the 1st sheath. After prefabricated cracks on the edge of the insulator sheath, the leakage distance is shortened. The red line in Figure 4 represents the shortest leakage distance path of the short crack and long crack. Following the leakage distance path, the decreased values of leakage distance caused by the short and long cracks are the same. The inclined degree of the sheath is less than 5°, the length of the long crack is 22 mm, and the leakage distance of the upper and lower surfaces decreases by about 44 mm. After the thickness of the crack root is deducted, the leakage distance of the 1st sheath of the cracked insulator decreases by about 40 mm compared with the intact insulator.

B. TEST DEVICE

The test wiring principle is illustrated in Figure 5. The model of test transformer is YDTW-225 kVA/150 kV, whose transformation ratio, maximum output voltage of the high-voltage side, maximum output current, and voltage divider ratio of the capacitor divider is 1:250, 150 kV, 1.5A, and 1000:1, respectively. Additionally, the transformer and the artificial climate chamber are exhibited in Figure 6. The size of the artificial climate chamber (L × W × H) is 4.5m × 3.7m × 2.6m, and the test power supply and the artificial climate chamber meet the requirements of GB/T4585. The leakage current acquisition device is composed of a current sensor and a multi-channel acquisition card with the matching acquisition program. The model of the current sensor is CHB-20L/SP9, the number of turns of the insulated wire drawn from the low-voltage side of the insulator on the side.
steam mist meets the requirements of GB/T4585. The leakage tolerance period through steam mist. The mass flow rate of to obtain the development trend of leakage current during the insulators is determined to be 32 kV. The wetting method is will operate [9]. Thus, the withstand voltage value of the roof insulators of high-speed trains does not exceed 31 kV. If the voltage on the contact line exceeds this value, a discharge will occur, an arc will appear in local areas, and significant leakage current pulse will appear at this time. The discharge is intermittent owing to the continuous fog during the tolerance process. The current change trend during the withstand process is recorded, and the influence of radial cracks on the leakage current change process is analyzed. Accordingly, the previous experience of the constant voltage withstand test, the insulators will not flashover at 32 kV. When the maximum withstand voltage value of insulators at a certain pollution level was obtained, flashover usually occurs during the period of withstand voltage for 18-27 min and 36-43 min, and the leakage current value close to flashover is higher than 100 mA. The test results of the maximum voltage withstand value of insulators many times imply that the possibility of flashover will be significantly reduced once the wetting time is more than 60 min. The preliminary exploratory test results revealed that when the pollution level was 0.1mg/cm², the withstand voltage was 32 kV, the withstand time was over 60 min, the leakage current values of intact, short crack, and long crack were all less than 10 mA. Therefore, the follow-up analysis will only be performed for the leakage current change trend during the first 60 minutes of the constant voltage withstand period.

The constant voltage tolerance method takes a long time. Meanwhile, it is difficult to obtain the development process of the flashover arc and the final flashover channel because the artificial climate room is filled with steam during voltage application. Therefore, the continuous boost method is adopted to observe the development process of the discharge arc to observe the influence of cracks on the development process of the flashover arc and the final flashover channel. The pre-smearing insulator is put into the artificial climate chamber and filled with steam mist. Based on the previous constant voltage withstand method, the wetting time from the beginning of the voltage application to the peak of the leakage current is obtained. After the surface of the insulator is completely wetted, a rapidly increasing voltage excitation is applied until the insulator flashover occurs. During this period, flashover video is recorded and divided into frames. The arc development process is acquired with the divided pictures.

According to the results of constant voltage withstand and continuous voltage rising tests, the influence of cracks on the flashover characteristics of train roof insulators is analyzed in this paper from three perspectives of the arc development process, dry zone location, and leakage current change trend.
FIGURE 7. Insulators flashover process. (a) Intact insulator. (b) Short crack insulator. (c) Long crack insulator.

FIGURE 8. Dry area distribution of insulator after flashover. (a) Intact insulator. (b) Short crack insulator. (c) Long crack insulator.

III. THE EFFECT OF CRACKS ON THE DEVELOPMENT OF CONTINUOUS VOLTAGE RISING FLASHOVER ARC AND THE POSITION OF DRY ZONE

The development process of insulator flashover arc obtained by continuous voltage rising test is exhibited in Figure 7, in which the solid red rectangle is marked as the prefabricated crack location. Figure 7 indicates that the flashover process of insulators can be divided into the following three processes:

(a) Corona discharge stage (1-2). The corona discharge gradually occurs due to severe distortion of the electric field near hanging water droplets at the edge of the insulator sheath. Sporadic arcs also appear at the edge of the sheath and in the transition zone between the column and the surface of the sheath. The discharge of the insulator with a long crack is the most significant.

(b) Partial arc development stage (3-4-5). The insulator leakage current and the intensity of discharge increase. The intact insulator arcs develop circumferential rotation. The insulator with a long crack on the surface of the 1st sheath has a more intense discharge between the high and low voltage electrodes where the crack is located.

(c) Arc intensifies until the flashover stage (6-7). The areas of the dry zone increase ascribed to the high temperature of the arc. Some dramatic arcs appear in the column area near...
the high voltage side. Part of the sheath is bridged by the arc. With the continuous increase in the applied voltage, the brightness of the arc increases. Finally, the arcs connect to the high voltage electrode, and flashover occurs.

The flashover voltage obtained by the continuous voltage rising test has a certain dispersion. The flashover voltage values of intact, short crack, and long crack insulators are all between 62-67kV when the pollution density is 0.1mg/cm². Thus, the existence of cracks has no significant influence on the flashover voltage.

Figure 8 illustrates the distribution of dry zone on the surface of the sheath after a flashover occurs. Although the flashover path and the position of the partial dry area of the sheath have certain randomness, the prefabricated cracks cannot directly impact the flashover path. In the development process of the discharge arc, when the maximum length of the crack at the edge of the 1st sheath is 22 mm, the discharge in the intermediate stage is more intense, the arc close to flashover is brighter, and the discharge arc sound is louder, compared with the intact. During the continuous voltage rising flashover test, the leakage current amplitude increases with the increase in the applied voltage, and the surface discharge of the sheath is intermittent. Therefore, the leakage current does not present a continuously increasing trend with the rising applied voltage.

IV. CHANGE PROCESS OF LEAKAGE CURRENT DURING CONSTANT VOLTAGE WITHSTAND

A low-pass filter with a cut-off frequency of 300 Hz was employed to filter out the interference signal, the pulse peak value was extracted, and the changing trend of the leakage current peak value during the constant voltage withstand period was drawn. The leakage current amplitude of intact, short crack, and long crack with the action of a constant AC voltage of 32 kV is significantly reduced when the withstand time is longer than 60 minutes. Therefore, this paper only presents the leakage current change trend of the first 60 minutes, as exhibited in Figure 9.

The change process of the leakage current peak value in Figure 9 is divided into four stages (the rising stage a, the continuous violent stage b, the falling stage c, and the oscillating stage d) to facilitate the comparative analysis. The maximum leakage current peak value of stage d is less than that of stage b. Besides, five moments $t_1$, $t_2$, $t_3$, $t_4$, and $t_5$ are defined to compare the differences between the corresponding discharge stages of different insulators. $T_1$ represents the moment when obvious discharge occurs, $t_2$ corresponds to the moment when the leakage current peak reaches the maximum value, and $t_1$-$t_2$ denotes the duration of rising stage a. The short discharge interval and the local leakage current amplitude decline after $t_2$ are ignored, $t_3$ is the starting initial time corresponding to the continuous decline of the leakage current peak, and the period $t_2$-$t_3$ denotes the duration of stage b, which is the duration before the leakage current reaches its peak value for the first time until no continuous downward trend. $T_3$-$t_4$ refers to the duration of stage c, which is the stage of the leakage current with a continuous decline for the first time; $t_4$-$t_5$ is the duration of stage d, which is the oscillating stage of leakage current. The values of stages a, b, c, and d corresponding to the three
different insulators are counted, as illustrated in Figure 10. It can be observed from Figures 9 and 10 that:

1. The maximum leakage current peaks corresponding to intact, short crack, and long crack insulators are 24 mA, 30 mA, and 28 mA, respectively, suggesting that the peak leakage current will increase when there are 11-22 mm cracks on the surface of 1st sheath, and the added value is about 4-6 mA;

2. The $t_1$ values of leakage current waveform corresponding to the significant discharge of intact, short crack and long crack insulators are 15 min, 11 min, and 7 min respectively, indicating that the moment of significant leakage current
during constant voltage withstand will be advanced when there are cracks on the surface of the sheath. Meanwhile, the longer the crack, the less the value of $t_1$, that is, the earlier the occurrence of the significant discharge. This phenomenon is consistent with the conclusion that the discharge degree is more violent when there is a crack on the surface of 1st sheath with a maximum length of 22 mm during the continuous voltage rising:

(3) The duration of the rising stage a in the leakage current trend diagram of intact, short crack, and long crack insulators is 9 min, 8 min, and 6 min, respectively, reflecting that the rising rate of leakage current increases with the increase in crack length. The duration of continuous violent stage b is 7 min, 6 min, and 5 min, respectively, and the maximum difference is 2 min. The duration of falling stage c is 8 min, 10 min, and 7 min respectively, and the maximum difference is 3 min. The sum of stage a, b, and c corresponding to the intact, short crack, and long crack insulators is 24 min, 24 min, and 18 min, respectively. To sum up, the sum is the smallest when the defect is a long crack of 22 mm in 1st sheath;

(4) Compared with the rising stage a, the continuous violent stage b, and the falling stage c, the leakage current amplitude of the oscillating stage d is significantly reduced. The corresponding values of stage d of the three insulators are 21 min, 25 min, and 35 min, implying that the duration oscillating stage of the leakage current of the long crack is the longest.

With a short crack as an example, the current waveforms at each stage of a, b, c, and d are illustrated in Figure 11, in which the horizontal axis of the figure denotes the duration of wetting through the fog. It can be observed that the current pulse in stage a is a distorted sine wave, the positive and negative axes are not symmetrical, and the amplitude of adjacent pulses is dramatically different. In stage b, the discharge is more intense, the dirty layer on the insulator surface is fully wetted, and the conductivity is the highest. The difference between positive and negative axes is not significant, and the amplitude between adjacent pulses presents a minor difference. Compared with stage b, the discharge pulse amplitude of stage c is significantly reduced, and the number of discharge pulses with a peak value of less than 5 mA accounts for a larger amount. Stage d can be regarded as a repetition of stages a, b, and c, and its discharge pulse amplitudes are all smaller compared to stage b. To sum up, a 22 mm crack at the edge of the 1st sheath can affect the initial time of stage a and the duration of stages a, b, and c, though it cannot affect the peak leakage current during the voltage withstand.

V. DISCUSSION AND ANALYSIS
As revealed by combining the flashover process of the continuous voltage rising test and the change process of the leakage current during the constant voltage withstand, the crack affects the intensity of the discharge arc in the intermediate stage of the continuous voltage rising and the duration of each stage of the leakage current. When there is penetrating crack on the surface of the insulator sheath, the arc burn marks shown in Figure 12 will be formed after repeated continuous rising flashover and constant voltage withstand tests.

When there is a crack at the edge or intermediate of the insulator, the shortest leakage distance diagram is exhibited in Figure 13, and the average voltage of unit leakage distance during the constant voltage withstand is presented in Table 3. Table 3 indicates that compared with the intact insulator, the maximum leakage distance of the cracked insulator is the same, the minimum leakage distance is 40.31 mm different, and the average voltage of the leakage distance per millimetre differs by 0.76 V.

When using the solid coating method to simulate the filth on the sheath surface, it is difficult to make the filth mucus...
adhere to the surface of the cracks because of the small cracks. The decrease is not obvious in terms of the voltage per unit leakage distance. When the filth layer on the sheath surface is wetted by steam mist, it is assumed that the filth layer on the sheath surface is evenly distributed and the difference of wetting degree is small, and the resistance value of the crack without filth attachment is large, so according to the series resistance model, the two ends of the crack bear a high voltage, which is prone to discharge. When the completely wetted filth layer is regarded as water film, the crack defect edge is at the gas-liquid-solid three-phase intersection, and the electric field near it is distorted, which is more likely to trigger local arc. The silicon rubber is burned by high temperature during local arc combustion many times, leaving black traces at last.

To analyze the distortion degree of electric field distribution caused by cracks, the quasi-static field model was used to calculate the distribution of electric potential, electric field and current density under different working conditions by combining 3D cartographic software with finite element simulation software. In the simulation model of the filth layer on the sheath surface, the crack surface had no filth. The schematic diagram of the 3D model is shown in Figure 14, and the simulation calculation formulas are shown in Equations (1) - (3) [24]-[27].

\[(\sigma + j\varepsilon_0\varepsilon_r) \nabla^2 \varphi = 0 \]

where \(\sigma\) and \(\varepsilon\) represent the conductivity and relative permittivity, respectively, \(\nabla^2\) is the Laplace operator, and \(\varphi\) is the vector of the potential.
The boundary conditions of the interface of the two media are as follows:

\[
\varphi_1 = \varphi_2 \quad (2)
\]

\[
(\sigma_1 + j\varepsilon_0\varepsilon_1) \frac{\partial \varphi_1}{\partial n} = (\sigma_2 + j\varepsilon_0\varepsilon_2) \frac{\partial \varphi_2}{\partial n} \quad (3)
\]

where \(n\) represents the normal direction of the junction.

The calculation formula of the conductivity of the dirty layer is shown in Equations (4) and (5) [28].

\[
\rho_s = 822.8 \times 10^{-6} \times ESDD \quad (4)
\]

\[
\rho_y = \frac{\rho_s}{h} \quad (5)
\]

where, \(\rho_s\) represents the surface conductivity of the filth layer (S); \(ESDD\) represents the equivalent salt density of the filth layer (mg/cm\(^2\)); \(\rho_y\) represents the volume conductivity of the dirty layer (S/m); \(h\) represents the thickness of the filth layer (m). In the model, the thickness of the filth layer is 1 mm, and ESDD is set as 0.1 mg/cm\(^2\), then the volume conductivity of the filth layer is 0.08228 S/m. The specific simulation parameter settings are shown in Table 4. The voltage applied to the high voltage terminal of the insulator is 45254.8 V.

The three-dimensional section of space is made, as shown in Figure 15, in which yz section is vertically distributed...
across the crack center, and xz section is horizontally distributed across the crack center. The simulation results are shown in Figures 16-18. Figure 16 is the potential line distribution of the xz section of the calculated model, Figure 17 is the electric field line distribution of the yz section of the model, and Figure 18 is the cloud diagram of the current density distribution of the fifth layer in the crack area on the sheath surface of model 1#.

Figures 16 - 18 show that, compared with intact insulators whose sheath surface has no cracks, when there are cracks on the sheath surface, the electric field lines near the cracks are dense, and the existence of cracks makes the electric field of the air domain near the cracks have a distortion. Meanwhile, the distribution of the current density contour of the filth layer in the crack area is dense and the current density on the crack end increases significantly. Under the same conditions, this area is more likely to form a dry zone and a local arc.

To analyze the electric field distribution characteristics near the edge of the crack, the three-dimensional transversal as shown in Figure 19 is selected. The transversal is parallel to the edge of the crack and located directly above the crack. The vertical distance between the transversal and the upper surface of the filth layer is 0.1mm, the starting point is near the root of the sheath, and the ending point is at the edge of the sheath. The distribution of the electric field intensity of intact, short crack and long crack insulators along the three-dimensional transversal in space is shown in Figure 20. It can be seen from Figure 20 that the electric field at the crack edge of the insulator with short and long cracks is distorted. The expression formula of the distortion rate is shown in Equation (6). The absolute difference electric field strength value and aberration rate of the most seriously distorted point at the 3-D line is shown in Table 5. In the table, the distance from origin indicates the position along the three-dimensional section line where the electric field distortion is the most serious from the starting point of the section line.

$$\eta = \frac{\Delta E}{E_0} \times 100\% = \frac{E - E_0}{E_0} \times 100\% \quad (6)$$

where $E_0$ is the electric field intensity of intact insulator along the transversal line, and $E$ represents the electric field intensity of short crack or long crack along the transversal line.

**VI. CONCLUSION**

Following the maximum crack length obtained by in-site investigation, prefabricated insulators with short crack and long crack lengths of 11 mm and 22 mm possess pre-coated pollution salt density of 0.1 mg/cm² and the ash-salt ratio of 6:1. The conclusions of continuous voltage rising flashover and constant voltage withstand leakage current tests are drawn as follows.

1. The results of the continuous voltage rising flashover test demonstrate that the existence of cracks has no significant effect on the flashover voltage and the location of the dry zone, and the flashover voltage is higher than 60 kV. Before the formation of the long discharge channel from the high voltage end to the ground, the arc development on the surface of long crack insulator sheath is more intense;

2. The peak leakage current of the intact, short crack, and long crack insulators during wetting is less than 30 mA when the withstand voltage is 32 kV, resulting in no occurrence of flashover;

3. When there is a crack on the sheath surface, it does not significantly change the distribution of the electric field near the air domain of other sheathes with no cracks, and the crack of the 1st sheath will distort the electric field distribution of interface among the crack edge, wet filth layer, and the air. Meanwhile, the crack edge will also have a local high current density area, and the distorted electric field distribution and current density area intensify the degree of discharge at the crack edge. When repeated continuous rising flashover tests or constant voltage withstand tests are carried out for the insulator with crack on its 1st sheath, arc burning marks will be found on the edge of the crack.

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