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Comparison of Surface Pollution Flashover Characteristics of RTV (Room Temperature Vulcanizing) Coated Insulators Under Different Coating Damage Modes

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ABSTRACT In recent years, room temperature vulcanizing (RTV) coated insulators have been increasingly applied in transmission lines. A large number of RTV coating damages on insulators are currently found. In this paper, three typical damage modes of the RTV coating were simulated, and then, the pollution flashover characteristics were studied. Results indicated that there is a big difference between the ac flashover performances of RTV coated insulators under different damage modes. The flashover voltage, as well as the critical leakage current, is largely influenced by salt deposit density (SDD), damage modes, and damage area. The relationship between SDD and U_{50} still meets negative power function when RTV coating was damaged. Insulators with fan-shaped damage have lowest flashover voltage and greatest critical leakage current. Both 2D and 3D FEM models of the RTV coating damaged insulator pollution layer were developed to calculate leakage current density on the damaged surface; it is discovered that the starting position of the arc usually occurs where the current density is maximum. Different damage modes lead to the change of the surface pollution layer conductivity and the uneven distribution of the current density, which is the main reason that pollution flashover characteristics are directly related to the damage modes.

INDEX TERMS RTV coating damage, pollution flashover, pollution layer conductivity, current density.

I. INTRODUCTION

From more than 100 years ago, porcelain and glass insulators have been used in transmission lines. But when the contamination degree of insulators is serious, these insulators cannot completely prevent pollution flashover.Therefore, RTV coatings have been introduced and used as an improved method to prevent pollution flashover [1]–[3]. However, the influence of external environment will cause some damage to RTV coatings [4]–[10] and obviously affect the insulators' resistance to pollution flashover [11]–[14].

From Literature [10], it can be known that, in the subtropical region, the insulators coated with RTV still have good hydrophobicity and strong anti-pollution flashover ability, which indicates that the insulators in similar environment can operate for a long time, at least for 6 years. Literature [13] presents results from a nine-year study of two different coatings (RTV and SIR). Both coatings showed significant signs of loss of hydrophobicity and surface oxidation. However, both coatings maintained low leakage currents and excellent performance during the outdoor study. Besides, field experience suggests that the RTV coatings life can reach 10 years even under the heavy pollution conditions [5].

The anti-pollution flashover performance of field-aged RTV coatings were studied in heavily contaminated areas [15]. Test results showed that RTV coatings provided long term of protection against the pollution flashover, even in heavily contaminated areas. The conclusion is almost the same as that in the literatures [10], [13].

The aging properties of RTV coatings have been studied in many literatures [4]–[14], however RTV coating damage on insulators were ignored after operating for a long time. RTV coating of insulators could be damaged due to environmental factors such as rain, sun, wind and destruction of

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birds. In recent years, the results of the investigation show that large area of exfoliation of RTV anti-pollution flashover coating were observed in Guangdong province of China [16]. However, the influence of exfoliation of RTV coating on pollution flashover characteristics has not been studied until now. With the increasing use of RTV-coated insulators, the study of influence of RTV coating damage on insulator pollution flashover characteristics is important.

So in this paper, a large number of RTV coating damages on insulators were observed, as is shown in Fig.1. Bottom edge of cap, periphery of insulator disk and windward side were mostly easily damaged position. The damage to RTV coating on the insulator surface is very intricacy, so it is difficult to simulate the practical pattern. For the purpose of investigating the influence of RTV coating damage on the flashover performance of insulators, the pattern of RTV coating damage was simplified to 3 damage modes. They were defined as inner ring damage, outer ring damage and fan-shaped damage respectively, as is shown in Fig. 2. In addition, the maximum damage area is generally less than ten percent of the insulator surface area, and most of the damage area is about five percent of the insulator surface area. Then the typical damage modes of the RTV coating was simulated according to the on-site observation and its pollution flashover characteristics was studied. Test results can provide reference for the external insulation selection of transmission lines. Specifically, whether RTV coating damaged insulators can be used is a concern of the power system, and this study can provide a reference for it.

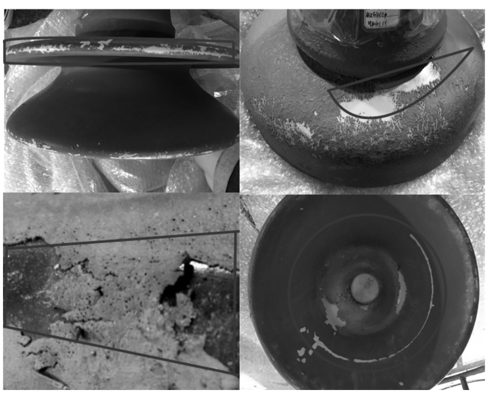


FIGURE 1. Exfoliation of RTV coating.

II. SAMPLES EXPERIMENTAL SETUP AND PROCEDURE

A. SAMPLES

In this paper, the test samples are porcelain insulators XP-160 coated with RTV coating, and then the different coating damage modes were simulated according to the on-site observation. The damage of RTV coatings on the top surface of insulator is much larger than that on the bottom surface, so this paper only studied the damage of RTV coatings on the top surface. The damage ways were divided into six kinds. Their technical parameters, sketch of the XP-160 and simulated damage of the sample are shown in Table 1 and

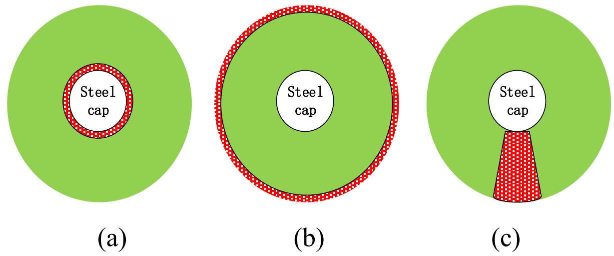
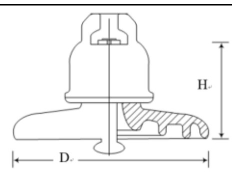


FIGURE 2. RTV coating damage modes. (a) Inner ring damage. (b) Outer ring damage. (a) Fan-shaped damage.

TABLE 1. Parameters of Test Insulators.

Type	D(mm)	H(mm)	L(mm)
XP-160	255	155	305



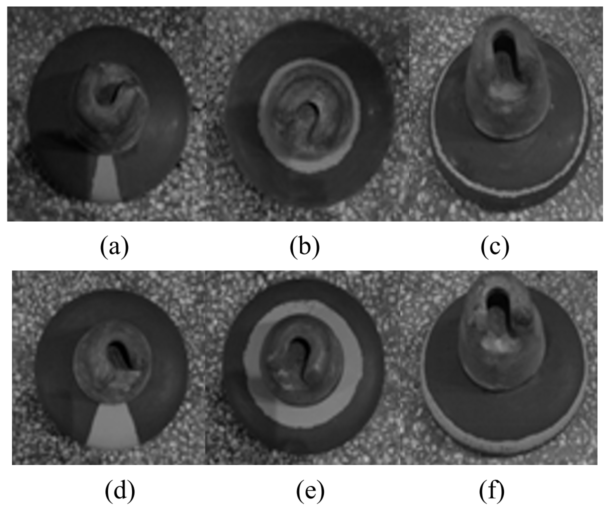


FIGURE 3. Tested insulators with RTV coating damage. (a) Fan-shaped damage (5%). (b) Inner ring damage (5%). (c) Outer ring damage (5%). (d) Fan-shaped damage (10%). (e) Inner ring damage (10%). (f) Outer ring damage (10%).

Fig. 3, in which H is the configuration height, Lis the leakage distance and Dis the diameter of insulators.

B. EXPERIMENTAL SETUP

The equipment used in this test is the same set of experimental equipment in literature [17]. The tests were conducted in an artificial climate chamber. Fig. 4 shows the test circuit, the parameters of T1, T2, R, r, F, C1, C2, H, G and E have been given in detail in [17]. The power transformer [YDTW-500kV/2000kVA] meets the requirement of pollution test [18].

C. TEST PROCEDURE

The experimental process consists of preparation, wetting and flashover [17].

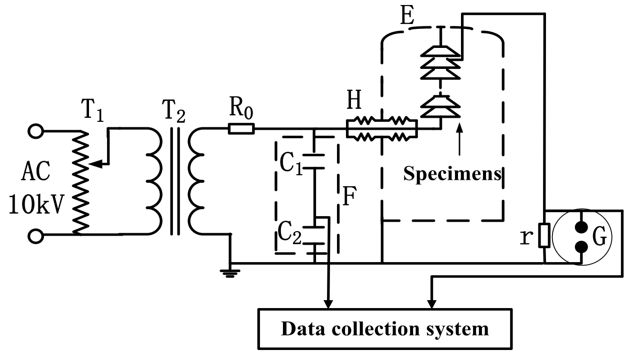


FIGURE 4. Ac test circuit.

Firstly, the insulators were cleaned with Na_2PO_3 solution. Then, naturally dry the insulators. The solid layer method was selected to contaminate the insulators. The non-soluble deposit density (*NSDD*) is 6 times of *SDD*. When the insulators were polluted, the *SDD* were set at 0.05 mg/cm^2, 0.15 mg/cm^2 and 0.25 mg/cm^2 to simulate different pollution levels.

After the samples were contaminated as mentioned above, they were dried naturally for 36 h, the hydrophobicity class is HC3 (After the tests, the hydrophobicity level will change to HC6-HC7) and then the samples were suspended vertically in the climate chamber as is shown in Fig. 4. During the tests, the input rate of the steam fog was 0.05±0.01kg/h·m^3. The temperature was maintained between 30°C to 35°C, and the atmospheric pressure was 98.6kPa.

The up and down method was adopted to conduct the test [18]. The flashover voltage (U_{50}) and relative standard deviation error (σ) were calculated by the equation as follows [19]:

$$U_{50} = \frac{\sum(U_i n_i)}{N} \quad (1)$$

$$\sigma = \sqrt{\left(\sum_{i=1}^{N}(U_i - U_{50})^2\right)/(N-1)}/U_{50} \times 100\% \quad (2)$$

where U_i is an applied voltage, n_i is the number of tests which were carried out at U_i, and N is the number of the whole "valid" tests.

III. AC FLASHOVER TEST RESULTS

Tests on pollution flashover characteristics of insulators with different RTV coating damage were conducted by the process mentioned above, and the results are shown in Fig. 5.

From Fig. 5, it can be concluded as follows:

(1) The relative deviation is less than 6.4%. The flashover voltage dispersion degree is accepted, which means that the method taken in the tests is rational.

(2) For all three types of damages, *SDD* has influence on the flashover voltage of the insulator string. The value of the pollution flashover voltage decreases with the increase of the salt density. For example, when the*SDD* of insulator, with 5% inner ring damage, are 0.05mg/cm^2, 0.15mg/cm^2 and 0.25mg/cm^2, the pollution flashover voltages are 64.5kV, 47.9kV, 41.5kV respectively. Compared with flashover voltage of 0.05 mg/cm^2, the flashover voltage of 0.10 mg/cm^2, 0.15 mg/cm^2 decreases by 25.7% and 35.7% separately.

(3) U_{50} is related to damage modes on insulator surface. To be specific, when the damaged area is 5% and *SDD*is 0.05mg/cm^2, 0.15mg/cm^2 and 0.25mg/cm^2, the U_{50} of fan-shaped damage, inner ring damage, and outer ring damage are 61.8kV,64.5 kV and 65.3kV; 46.3kV, 47.9 kV and 49.7kV; 40.4kV,41.5 kV and 42.4 kV separately. when the damaged area is 10% and*SDD* is 0.05mg/cm^2, 0.15mg/cm^2

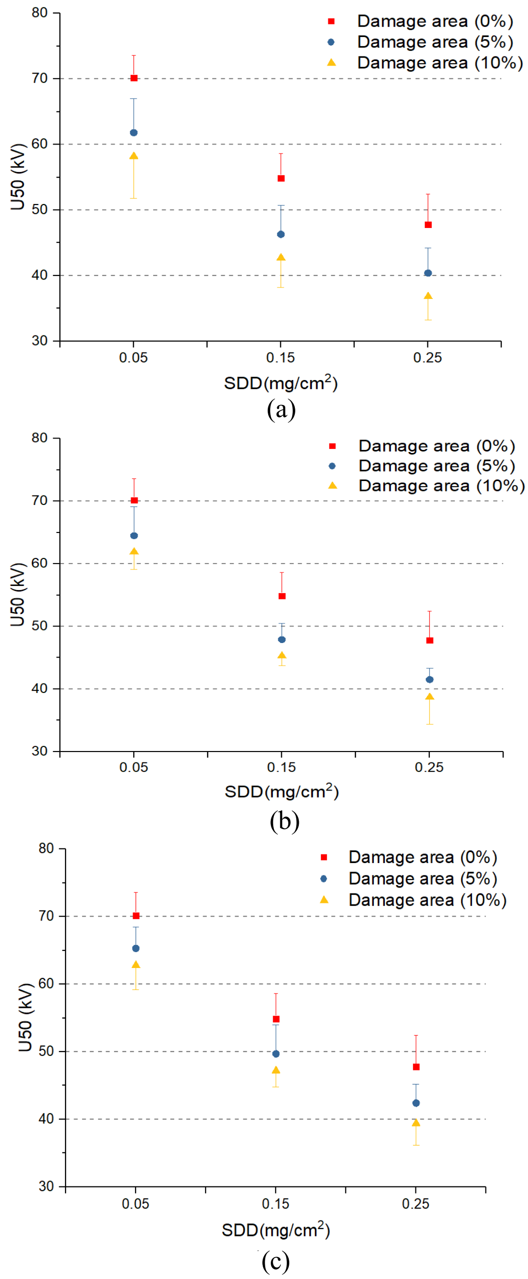


FIGURE 5. Flashover voltage of RTV insulator with different *SDD* and damage modes. (a) Fan-shaped damage. (b) Inner ring damage. (b) Out ring damage.

TABLE 2. Fitting Value of *A a* and R^2 According to the Test Results.

RTV damage modes	Parameters	Damage area (0%)	Damage area (5%)	Damage area (10%)
Fan-shaped damage	A	34.69	28.04	24.85
	a	0.236	0.263	0.284
	R^2	0.9815	0.9881	0.9878
Inner ring damage	A	34.69	28.45	25.96
	a	0.236	0.274	0.291
	R^2	0.9815	0.9866	0.9891
Outer ring damage	A	34.69	29.64	26.92
	a	0.236	0.265	0.285
	R^2	0.9815	0.9882	0.9829

and 0.25mg/cm^2, the U_{50} of fan-shaped damage, inner ring damage, and outer ring damage are 58.2kV,61.9kV and 62.8kV; 42.7kV, 45.3kV and 47.2kV; 36.8kV,38.7kV and 39.4kV separately. It can be seen that under the same *SDD*, no matter what the damage area is, U_{50} with damaged RTV coating is lower than that with non-damaged RTV coating. Thus,U_{50} with inner ring damaged RTV coating is lower than that with outer ring damage, but it is larger than that with fan-shaped damage.

(4) The damage area of RTV coating also has a significant effect on the flashover voltage of insulator strings. Specifically, there is a slight decrease on the flashover voltage when the damage area increases gradually. For example, when SDD is 0.5mg/cm^2, damaged area are 5% and 10%, the U_{50} of fan-shaped damage, inner ring damage, and outer ring damage are 61.8 kV and 58.2kV 64.5kV and 61.9kV 65.3kV and 62.8 kV correspondingly, which indicates that under the same SDD, whether the damage modes of the RTV coating are fan-shaped damage, inner ring damage or outer ring damage, the flashover voltage of the insulator string decreases with the increase of damage area of RTV coating.

Finally, the flashover voltage under drying conditions was also tested. It can be concluded that the flashover voltage under dry conditions is much higher than that under foggy conditions. In addition, it can be found that RTV coating damage has little effect on flashover voltage under drying conditions, while *SDD* has almost no effect on its dry flashover voltage. Specifically, the flashover voltage of 3 RTV-coated insulators under dry conditions is between 182.9 and 184.6kV, and that of damaged insulators is between 177.5 and 182.1 kV.

IV. DISCUSSION

A. EFFECTS OF DIFFERENT DAMAGE MODES ON U_{50}

The relationship between $U_{50}$and *SDD*has been studied in previous researches, which showed that there is

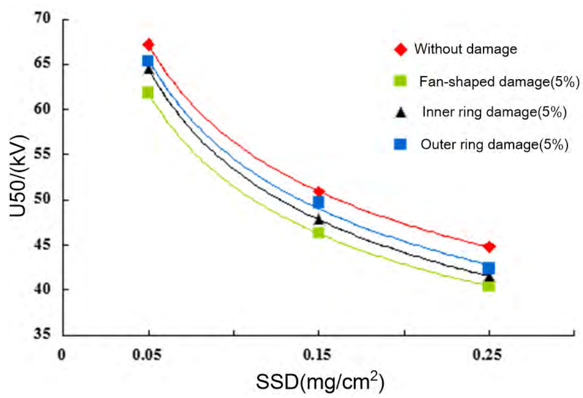


FIGURE 6. Effects of different damage modes (0%, 5%) on U_{50}.

a negative power function between U_{50} and *SDD* as follows [20]:

$$U_{50} = A(SDD)^{-a} \tag{3}$$

where *A*is constant which is up to insulator structure and materials, air pressure and so on. Besides, a is the characteristic index of pollution on the insulator.

The pollution flashover voltage under certain*SDD* can be calculated with given A and $a$in Equation (4). The values of a and n of different insulators have been calculated by researchers. But the relationship between *SDD* and U_{50} of insulator with damaged RTV coating has not been studied, as a result, there is no existing expression for insulator with damaged RTV coating to predict flashover voltage. The fitting curves of *SDD*and U_{50} have been obtained with the tests results. The fitting curves of U_{50} with different RTV coating damage models are shown in Fig. 6 and Fig. 7 when damage area are 0%, 5% and 10%. Besides, A, a and fitting degree R^2 of insulators with different RTV coating damage models were calculated and is shown in Table 2.

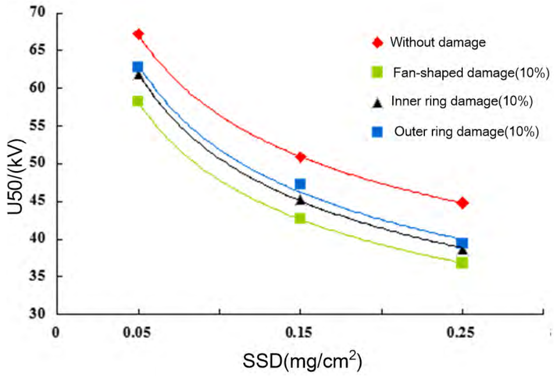


FIGURE 7. Effects of different damage modes (0%, 10%) on U_{50}.

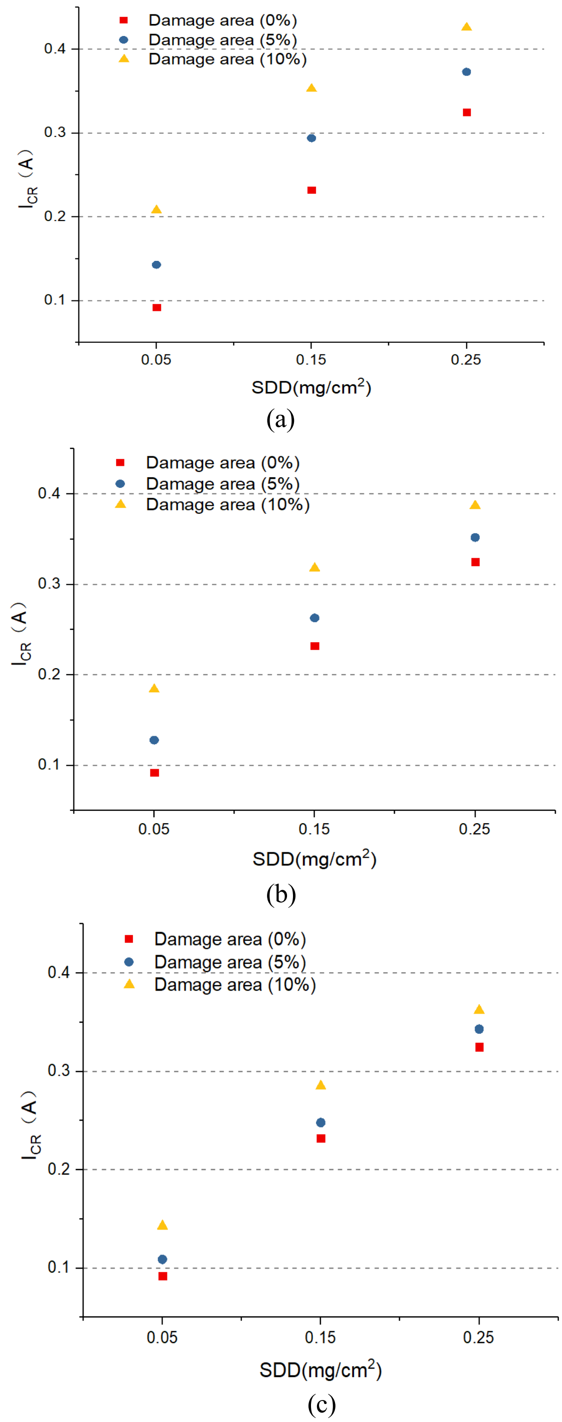


FIGURE 8. I_{CR} of RTV insulator with different SDD and damage modes. (a) Fan-shaped damage. (b) Inner ring damage. (c) Out ring damage.

It can be concluded from Table II, Fig. 6 and Fig. 7 that:

(1) The correlation coefficients R^2 of all fitting curves are bigger than 0.98, which indicates that the U_{50} and*SDD* fit power function well. The value of *a* is within 0.236-0.291. The pollution characteristic index *a* and the coefficient *A* are all related to the damage modes and the damage area of the RTV coating.

(2) Coefficient*A* of insulators with different damage modes are all smaller than that of insulators with non-damaged RTV coating, and the value of coefficient *A* decreases with the increase of damage area. For example, when the damage area is 5%, the values of *A* of insulators with fan-shaped damage, inner ring damage and outer ring damage are 28.04, 28.45, and 29.64 respectively, which means that the fan-shaped damage, inner ring damage and outer ring damage decrease coefficient*A* of insulator without RTV coating damage by 12.6%, 9.9% and 6.1%. Similarly, when the damage area is 10%, the fan-shaped damage, inner ring damage and outer ring damage decrease coefficient*A* of insulator without RTV coating damage by 21.3%, 17.8% and 14.7% respectively. It can be seen that whether the surface damage area is 5% or 10%, fan-shaped damage has the greatest influence on coefficient *A*, followed by inner ring damage and outer ring damage.

(3) Characteristic index *a* of insulators with different damage position are all bigger than that of insulators with non-damaged RTV coating, and the value increases with the increase of damage area. For example, when the damage area of the RTV coating is 5%, the values of a of insulators with fan-shaped damage, inner ring damage and outer ring damage are 0.263č0.274 and 0.265 respectively, which means that the fan-shaped damage, inner ring damage and outer ring damage increase *a* of insulator without RTV coating damage by 4.4%, 8.7% and 5.2%. Similarly, when the damage area of the RTV coating is 10%, the fan-shaped damage, inner ring damage and outer ring damage increase *a* of insulator without RTV coating damage by 12.7%, 15.5% and 13.1% respectively. It can be seen that inner ring damage has the greatest influence on *a*, followed by outer ring damage and fan-shaped damage.

B. EFFECTS OF DIFFERENT DAMAGE MODES ON CRITICAL LEAKAGE CURRENT

The peak value of leakage current at half a cycle before flashover is recorded as the critical leakage current (I_{CR} which has been defined in literature [21]). I_{CR} of RTV coating damaged insulator was measured during the test, as is shown in Fig.8.

The relationship between leakage current and different damage modes of RTV coating is also not clear yet, in this paper, Fig.8 gives the variation trend. From Fig.8 the following conclusions can be reached:

(1) I_{CR} is directly related to the polluted levels, damage area and damage modes, the values of I_{CR} are between 0.092A to 0.426A.

(2) Under a certain *SDD* and damage types, I_{CR} increases with the growth of damage area. Similarly, under a certain damage type and damage area, I_{CR} also increases with the growth of *SDD*.

(3) Under a certain *SDD* and damage area, I_{CR} under fan-shaped damage mode is largest followed by inner ring damage mode out-ring damage mode and non-damaged mode.

C. ANALYSIS OF POLLUTION FLASHOVER PROCESS OF INSULATOR STRING UNDER DIFFERENT RTV COATING DAMAGE MODES

1) AC POLLUTION FLASHOVER PROCESS OF INSULATORS UNDER RTV COATING DAMAGE

In order to study the AC pollution flashover process of insulators under RTV coating damage modes, this paper shoot the AC discharge process of RTV coating insulators under different damage modes by the SONY HD handheld high-speed camera. Take the flashover process of RTV coating insulator string with five percent fan-shaped damage as an example, the flashover process is shown in Fig. 9.

FIGURE 9. The flashover process of RTV insulator string with five percent fan-shaped damage.

For suspension insulators, local arcing starts from fan-shaped damage area around the cap where the dry bands first appear due to the evaporation of the conductive layer. In appropriate conditions, a unique dominant arc starting from the cap propagates toward the pin resulting to a complete flashover. In this experiment process, it is found that there are some differences in flashover process of RTV coating insulators under different damage modes, mainly in the initial position of arc. More concretely, local arcing, under outer-ring damage and non-damaged modes, only starts around the steel pin. By contrast, local arcing, under inner-ring damage mode, starts around the cap and pin, as is shown in Fig. 10.

The flashover process of insulator string is generally recognized as a series circuit formed between partial arc and residual pollution layer [22]. The basic equation to maintain the AC arc along the contaminated insulator string can be expressed as:

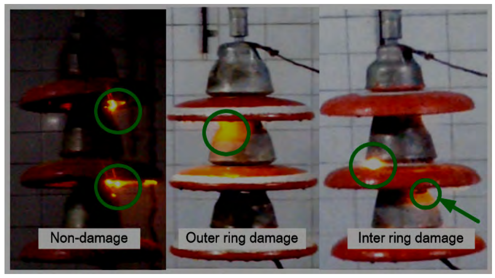


FIGURE 10. Local arcing under different damage modes.

$$U_m = U_{arc\_m} + U_{p\_m} = AxI_m^{-n} + r_a(L-x)I_m \tag{4}$$

where U_m and I_m are the peak value of the applied voltage and the leakage current; U_{arc_m} is arc voltage, U_{p_m} is the voltage on the residual pollution resistance. A and n are the arc constant, L is insulator creepage distance; x is arc length, r_a is the residual pollution resistance per unit length. Besides, the arc propagation criterion could be expressed as [23]:

$$E_p > E_{arc} \tag{5}$$

where E_p is voltage gradient of the residual contaminated parts, E_{arc} is arc gradient. E_p and E_{arc} can be expressed as [24]:

$$E_p = \frac{U_{p\_m}}{L-x} = \frac{r_a(L-x)I_m}{L-x} = r_aI_m \tag{6}$$

$$E_{arc} = \frac{U_{arc\_m}}{x} = \frac{AI_m^{-n}x}{x} = AI_m^{-n} \tag{7}$$

It is well known that the leakage current increases with the increment of the layer conductivity. According to the equations above, for the same arc length (x) on the polluted insulator strings, with the improvement of I_m, E_{arc} decreases and E_p increases. Namely, the probability for the satisfaction of arc propagation criterion increases with the increase of the layer conductivity. Therefore, it is supposed that the effect of different damage modes on flashover voltage is mainly due to the change of its surface conductivity. Because, even if *SDD* is the same, the damage area of the coating is a hydrophilic material, but the RTV coating is a hydrophobic material, which leads to the difference in the wetting process of the pollution layer, so causing the difference in the layer conductivity.

Next, the surface conductivity of damage area and undamaged area under the same *SDD* condition will be further studied, then, the current density distribution of insulators surface with different RTV coating damage modes will be simulated based on the calculated surface conductivity.

2) CALCULATION OF LEAKAGE CURRENT DENSITY ON INSULATOR SURFACE

Often, it is difficulty to calculate insulator resistance due to zero crossing of current. But it is easy to obtain insulator conductivity, which can be converted to surface conductivity (μS) using a 'form factor' F as follows [25]:

$$\sigma inst = F\left(\frac{I_{inst}}{V_{inst}}\right) \tag{8}$$

$$F = \int_0^L \frac{dl}{\pi D(l)} \tag{9}$$

where I_{inst} is the instantaneous leakage current (mA), V_{inst} is the instantaneous voltage (kV), σ_{inst} is the peak value of conductivity (μS), F is the form factor of insulator, l is the distance (mm) along the leakage path, and $D(l)$ is the insulator diameter (mm) at length l.

When the SDD is 0.05mg/cm^2, I_{inst} and V_{inst} can be obtained according to the experimental method above, also, F (0.702) of the insulator can be calculated. Then, the surface conductivity of hydrophobic materials (non-damaged RTV coating) and hydrophilic surface materials (without RTV coating) can be calculated by equation (8).

From the calculation results, it can be known that when the RTV coating is destroyed, the surface layer conductivity will increase, and so will the leakage current. The increased leakage current benefits the production and development of partial arc during the pollution flashover process, which results in decreasing of insulator pollution flashover voltage.

To further explain the differences in the flashover process mentioned above, it is necessary to analyze the distribution of surface current density under different damage modes of RTV coating. It is important to note that the ring damage type can be simulated directly by two-dimensional axisymmetric model, and then the three-dimensional model can be obtained by rotation, but the fan-shaped damage cannot be simulated in the two-dimensional axisymmetric model, so the unfolded plate model should be established to simplify the calculation of surface currents density distribution under fan-shaped damage modes.

The geometric parameters of XP-160 insulator unfolded plate model can be obtained by the following equation:

$$D(l) = \pi \cdot d(x_i, y_i) \tag{10}$$

where (x_i, y_i) is the point coordinates of the insulator surface, $d(x_i, y_i)$ is the insulator diameter (mm) at (x_i, y_i), $D(l)$ is the vertical distance in the model. XP-160 insulator unfolded plate model is as follows.

According to the current continuity equation and the relationship between current density and electric potential, we have:

$$\begin{cases} \nabla \cdot \mathbf{J} & = -\frac{\partial \rho}{\partial t} \\ \mathbf{J} & = \sigma \mathbf{E} \\ \mathbf{E} & = -\nabla V \end{cases} \tag{11}$$

where, J is the current density, A/m^2; ρ is the charge density, C/m^3; $\boldsymbol{E}$ is the electric field strength, V/m; σ is the conductivity of the wetted pollution layer, S/m; V is the

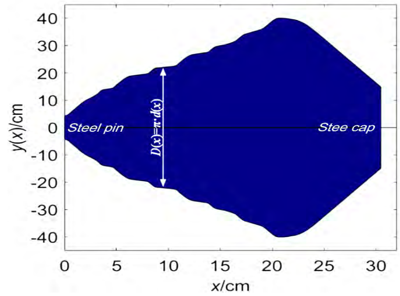


FIGURE 11. XP -160 insulator unfolded plate model.

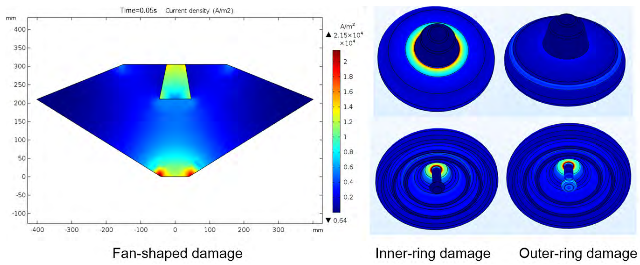


FIGURE 12. Current density distribution of insulators with different forms of damage.

electric potential, ∇ is the differential operator. The pollution layer volume conductivity of the RTV coating and the damage position is 0.1573 and 1.4030 S/m respectively. For the three-dimensional model, the thickness of the wetting layer on damaged surface is set to 0.007cm [25], while the thickness of the wetting layer on RTV coated surface is set to 0.032cm. The voltage of each insulator is 10kV. Then the finite element analysis is carried out to get the following results.

From the simulation results, it can be known that the current density distribution of insulators with different forms of damage has two things in common, one is, the current density at the steel pin is very large, about 21.5mA/mm^2. Another is, the current density in the undamaged area is small, only about 0.5mA /mm^2. Besides, for fan-shaped damage and inner-ring damage types, the current density at the damage site is obviously larger than that in the undamaged area, about 13 and 12 mA/mm^{2}respectively. However, for outer-ring damage type, the current density of the damage site is not significantly larger than that of the undamaged site, about 5.2 mA /mm^2. So a new discovery was that the starting position of the arc usually occurs in the position where the current density is greatest. It is because the dry bands are easier to appear where the current density is greatest due to the excessive evaporation of the conductive layer, which provide the prerequisites for the flashover process. Based on the above discussion the conclusions can be drawn that different damage modes lead to the change of the surface pollution layer conductivity and the uneven distribution of the current density, which is the main reason that pollution flashover characteristics are directly related to the damage modes.

V. CONCLUSION

Influences of RTV coating damage on the pollution flashover characteristics of insulator were studied in this paper. The conclusions can be drawn as follows:

The flashover voltage, as well as the critical leakage current, is largely influenced by *SDD*, the damage modes and the damage area. The relationship between *SDD* and U_{50} still meets negative power function when RTV coating was damaged. Insulators with fan-shaped damage had a lowest flashover voltage and largest critical leakage current. Besides, with the increase of the damage area, the critical leakage current increases while the flashover voltage decreases.

Both 2D and 3D FEM models of RTV coating damaged insulator pollution layer were developed to calculate leakage current density on damaged surface. A new discovery was that the starting position of the arc usually occurs in the position where the current density is greatest. The different damage modes lead to the change of the surface pollution layer conductivity and the uneven distribution of the current density, which is the main reason that pollution flashover characteristics are directly related to the damage modes.

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