Study on Fast Contamination Characteristics of Cap and Pin Insulators in Straight Flow Wind Tunnel Simulation

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Abstract

Artificial simulation of rapid insulator contamination can obtain the contamination characteristics of suspension insulators in a short time, providing important reference for the electrical design, operation and maintenance of external insulation. To obtain the contamination characteristics of insulators closer to those under the natural environment, this paper proposed a test method for artificial simulation of rapid natural contamination of insulators using the characteristic parameters of straight-flow wind tunnel, and carried out the artificial rapid natural contamination test of cap and pin insulators under different wind speeds, wind directions, contamination duration and contaminant concentrations. The test results showed that with the wind speed increasing from 2.2 m/s to 7.5 m/s, the contamination degree of insulator surface gradually increased firstly and then decreased, and reached the maximum near 4.5 m/s. With the increase in contaminant concentration, the contamination degree of insulator surface increased, and tended to be saturated when the dust spreading speed was 54 g/min. With the extension of contamination duration, the contaminant accumulation on insulator surface was slow in the initial stage, accelerated in the middle stage, and then slowed down and gradually saturated in the later stage. Under the same contamination conditions, standard, double-shed and triple-shed insulators presented high-to-low equivalent salt deposit density (ESDD) successively on their top and bottom surfaces, and the ratios of ESDD on the top and bottom surfaces were 1:1.20:0.9 and 1:0.63:0.53, respectively.

Index Terms

Wind tunnel test, cap and pin insulator, contamination characteristics, wind speed, contamination duration, contaminant concentration.

I. INTRODUCTION

Insulator contamination may cause pollution flashover accidents on transmission lines, which seriously threatens the safe operation of the power system and causes great economic losses to the power grid [11]–[15]. Therefore, it is of great significance to carry out the research on the contamination characteristics of insulators for the electrical design, operation and maintenance of external insulation in transmission lines [6]–[10].

A lot of researches on the contamination characteristics of insulators has been carried out, summarizing a series of rules of insulator contamination [11]–[14]. For instance, Su Zhiyi et al. of China Electric Power Research Institute have carried out experimental studies on natural contamination of different insulators used for substations and transmission line towers in the northern inland areas of China under alternating current (AC) and direct current (DC) voltages [15]. Zhang Zhijin et al. have conducted natural contamination tests on insulators with different shed shapes in the Xuefeng mountain contamination field [16]. Li Hengzhen et al. performed research on the natural contamination characteristics of glass insulators using the suspension insulator strings of multi-base transmission line towers in Guangzhou, China [17]. Qiao Xinhan, Gu Chunhui et al. have carried out the research on the contamination characteristics test of typical suspension insulators [18], [19]. In the UHV test base, China Electric Power
Research Institute has established an outdoor contamination assessment field in the ultra-high voltage (UHV) test base, with various insulator strings and shed insulators suspended to simulate natural contamination, and obtained the contamination characteristics of different insulators [20]–[22].

The disadvantage of the research on contamination characteristics through natural contamination lies in the long period. What is more, because of the differences in climate conditions and sampling time, the measured data are scattered [23]–[26]. Thus, it is urgent to carry out a multi-factor controllable artificial rapid contamination test of insulators in laboratory wind tunnels. In this paper, based on the investigation of artificial contamination test devices and methods at home and abroad, a straight flow wind tunnel test system that can stimulate the natural contamination of insulator strings was developed. Additionally, the problems such as uneven wind field in wind tunnels and difficulty in accurately controlling contaminant concentration as an independent variable were solved. Moreover, the artificial simulation method for natural contamination test of insulators was explored, in the expectation of obtaining the natural contamination characteristics of insulators in a short time, so as to provide a basis for insulator selection, operation and maintenance.

II. ARTIFICIAL CONTAMINATION TEST SYSTEM AND TEST METHOD FOR INSULATOR

A. ARTIFICIAL CONTAMINATION TEST SYSTEM

It is shown in Fig.1, the wind tunnel used in this paper was a straight flow wind tunnel, with a total length of 26.1 m, which mainly included collector, power section, large-angle diffusion section, stable section, contraction section, test section and diffusion section. An axial flow fan was installed in the power section to generate an air source driven by the variable-frequency motor. The air source entered the stable section after passing through the large-angle diffusion section. Honeycomb and damping net were built in the stable section for uniform wind field, and then the continuous and stable wind field required for the test was generated after passing through the contraction section. The test section was 2.5 m in height, 3 m in width and 9 m in length, which was the core part of the artificial contamination test system. In the test section, the wind speed ranged 1.0 m/s~10 m/s, the wind speed deviation was ±0.2 m/s, the deflection angle of air flow was not higher than 2 degrees, the degree of turbulence was not higher than 3%, and the relevant parameters met the requirements of natural wind field at the horizontal axis. The test power supply was composed of column voltage regulator TYDZ-1200/10.5 and test transformer YDTW-1200/200. The spray volume was 0.5 kg/h, and the droplet diameter was smaller than 100 µm. The rainfall intensity could be set automatically, and the range of rainfall intensity was 0.1~2.0 mm/min. The spraying amount of the dust system could be adjusted, and the dust could fall on the surface of the samples evenly carried by the wind. The maximum dust spreading speed could reach 100 g/min, which can simulate various working conditions of insulators in the natural environment.

B. ARTIFICIAL CONTAMINATION TEST METHOD

1) INSULATORS PARAMETERS AND LAYOUT

The samples for this artificial insulator contamination test included standard, double-shed and triple-shed insulators. The contamination degree was measured on the top and bottom surfaces, respectively. The insulators parameters are shown in TABLE 1, and profile of the insulators are shown in Fig.2.

To simulate the contamination state of insulator strings in transmission lines, the suspension mode of insulator strings on the rotary table in the test section is shown in Fig.3. The insulator strings were suspended in 3 columns side by side and numbered as string 1, string 2 and string 3, respectively. The order numbers of insulators were 1#~5# from the top to the bottom. In addition, the electrical safety distance of the samples was strictly controlled according to the requirements. Insulators contamination test layout is shown in Fig.3.

2) PREPARATION OF CONTAMINANT

In this test, sodium chloride and diatomite were used as contaminant particles to simulate the soluble and insoluble substances in contaminants on the insulator surface. The results of natural contaminant measurement presented that the ratio of conductive and water-soluble substances to non-conductive and water-insoluble substances in the
TABLE 1. Profile parameters of the insulators.

| TYPE  | Height (mm) | Diameter (mm) | Creep distance (mm) | Surface area (cm²) |
|-------|-------------|---------------|---------------------|-------------------|
| XP-300| 195         | 320           | 390                 | 2092              |
| XWP-300| 195       | 330           | 485                 | 3464              |
| XSP-300| 195        | 360           | 550                 | 4313              |

3) SELECTION OF RAINFALL AND RAINFALL DURATION
The rainfall in the natural environment will clean the contaminants on the insulator surface. To obtain the equivalence between the rainfall device of the test system and the natural environment, the loss effect of insulator surface contaminants caused by rainfall was investigated in the laboratory. Under the dust spreading rate of 18 g/min and the wind speed of 2.0 m/s, after the standard insulators were contaminated for 100 min, the top surface was drenched with the artificial drenching conditions referring to IEC 60010-1:2010 [30], and the rainfall intensity at 1.0 mm/min. The relative ratio of ESDD on the rain-facing surface of the insulators under different rainfall were obtained. The result is shown in Fig. 4.

4) SELECTION OF FOG TIME
In this paper, cold fog was used to simulate the natural fog, and the degree of humidity was determined by measuring the changes in resistance on the insulator surface. After standard insulator contamination for 20 min under the dust spreading rate of 18 g/min and the wind speed of 2 m/s, the dust spreading and fan device were stopped, and the resistance of the top surface of the contaminated insulators in the test section was measured after fogging using the type Megger S1-552 high-precision resistance meter, with the measurement interval of 1 min. The relationship between the surface resistance of the insulator and the fog wetting time is shown in Fig. 5.

5) SELECTION OF DRYING TIME
In the artificial simulation of the natural contamination test, the insulators were dried by light, with each light heating lamp at 60 W, and 3 insulator strings under each rotary table corresponding to 48 heating lamps. To determine the time of light heating, the fully-wetted contaminated layer was illuminated and the changes in insulator surface resistance were measured, with the measurement interval of 4 min. When the drying time reached 40 min, the insulation resistance of the samples tended to be stable, which is consistent with the actually observed drying time of the insulator surface. Thus, 40 min was selected as the drying time, and the result is shown in Fig. 6.

6) CONTAMINATION TEST PROCEDURE
Considering the actual natural contamination of insulators, the cycle of contamination in dry season—cleaning in rainy contaminants was about 1:5, and the contaminants with particle diameter smaller than 50 μm on the insulator surface accounted for about 90% of the total contaminants [27]–[29]. Consequently, before the test, sodium chloride and diatomite were ground and sieved to ensure that the particle diameter was smaller than 50 μm, and mixed evenly at the mass ratio of 1:5 to prepare contaminant dust.

It can be seen from Fig.4 that when the rainfall is 5mm, the top surface of the insulator tends to be clean. Considering the cleaning effect of the rainfall on the surface of the insulator, the rainfall intensity and rainfall duration are selected as 1 mm/min and 5 min in this paper.

It can be seen from Fig.5, when the fog wetting time reached 15 min, the surface resistance of the samples tended to be stable. Therefore, 15 min was selected as the spray time and a wetting time of 5 min was added.

According to Fig.6, when the drying time reaches 40 min, the insulation resistance value of the test sample basically tends to be stable, which is basically consistent with the actually observed drying time of the insulator surface, so 40 min is selected as the drying time.

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6) CONTAMINATION TEST PROCEDURE
Considering the actual natural contamination of insulators, the cycle of contamination in dry season—cleaning in rainy
season-re-contamination in dry season-re-cleaning in rainy season was adopted. According to the natural contamination cycle of insulators and the characteristics of the artificially simulated natural contamination test system, the test procedure of artificially simulated natural contamination was determined, including fogging and wetting, contaminant particle deposition, rainfall washing and light drying. The specific process is shown in Fig. 7.

![FIGURE 7. Artificial contamination test procedures.](image)

After the above procedures, the ESDD and non-soluble deposit density (NSDD) of the top and bottom surfaces of the insulators were measured according to IEC/TS 60815-1:2016 [31] and recorded. Considering the end effect of insulator strings, that is, the contact contaminant particles of the top insulator of insulator strings were less compared with other insulators, when sampling, the ESDD and NSDD of the top insulator of the insulator strings were only used as a reference, and not analyzed with the ESDD and NSDD of other insulators for averages.

### III. ARTIFICIAL CONTAMINATION TEST AND RESULTS ANALYSIS

#### A. INFLUENCE OF WIND

The influence of wind power (including wind speed and wind direction) on the surface contamination characteristics of insulators can be divided into two aspects: contaminant amount and contamination distribution. To quantitatively investigate the contamination rules under different wind speeds, XP-300 standard porcelain insulators were selected to simulate the contamination test under different wind speeds and wind directions. Considering the meteorological conditions and actual engineering application, the test wind speed ranged 2 m/s $\sim$ 8 m/s, corresponding to the natural wind force of 2 to 5. Under the contaminant particle concentration of 18 g/min, six wind speeds 2.2 m/s, 3.9 m/s, 4.5 m/s, 5.2 m/s, 6.0 m/s and 7.5 m/s were selected to test the contamination characteristics of XP-300 standard insulators, the test conditions are shown in TABLE 2.

| Type   | Concentration (g/min) | Size (μm) | SDD/NSDD | Wind Speed (m/s) |
|--------|-----------------------|-----------|-----------|-----------------|
| XP-300 | 5                     | 18        | <70       | 1.5             | 2.2 $\sim$ 7.5 |

![FIGURE 8. Pollution status under different wind speeds.](image)

Fig. 8 shows the contamination state of the surface of the insulators under different wind speeds, and Fig. 9 shows the change trend of the salt density on the top and bottom surfaces of the insulator.

As shown in Fig.8, under the wind speed of 4.5 m/s, contaminant amount on the top and bottom surfaces of XP-300 standard porcelain insulators was significantly larger than that under the wind speed of 7.5 m/s. The contaminants on the top surface were concentrated on the back of the gossan, and the contaminants on the bottom surface were concentrated inside and outside the shed edge. As seen in Fig.9, the average ESDD was calculated from 5 insulators under different wind
It could be found from the changing trend of ESDD shown in Fig.10 that the changing trends of the overall contamination degree on the top and bottom surfaces of standard insulators were the same under both fixed and variable wind directions. When the wind speed was 2.2 m/s and 5.2 m/s, the contamination degree of the top surface was higher than that of the bottom surface, and when the wind speed was 6.0 m/s and 7.5 m/s, the contamination degree of the top and bottom surfaces was close. When the wind speed was between 2.2 m/s and 4.5 m/s, the contamination degree of the top and bottom surfaces of insulators increased gradually, and reached the peak near the wind speed of 4.5 m/s. Under fixed and variable wind directions, ESDD reached 0.25 mg/cm² and 0.29 mg/cm², respectively. As the wind speed continuously increased, the contamination degree of the insulator surface showed a downward trend. When the wind speed was higher than 4.5 m/s, the contamination degree of the insulator surface decreased with the increase in wind speed. Among them, when the wind speed was 4.5 m/s~6.0 m/s, the decline was the most obvious. When the wind speed was 6.0 m/s, the surface ESDD of insulators decreased to 0.02-0.04 mg/cm² under fixed and variable wind directions. When the wind speed was higher than 6.0 m/s, the contamination degree of the top and bottom surfaces of the insulators tended to decrease gently.

**B. INFLUENCE OF CONTAMINANT CONCENTRATION**

It is a necessary condition for insulator pollution flashover that air pollutants accumulate on the insulator surface over time to form a contamination layer. It is generally believed that the more serious the air pollution is, the more serious the insulator pollution is. To explore the influence of the degree of air pollution on insulator contamination, the effect of contaminant concentration on insulator contamination characteristics was tested. In the test, the contaminant concentration in the air was changed by adjusting the dust spreading speed of the artificial contamination test system, the test conditions are shown in TABLE 3. After the test is completed, the ESDD and NSDD of the insulator are measured, and the results are shown in Fig.10.

**TABLE 3. Test conditions.**

| Type  | circles concentration (g/min) | size (µm) | SDD/NSDD | Wind speed (m/s) |
|-------|-------------------------------|-----------|-----------|------------------|
| XP-300 | 5                             | 18-54     | ≈70       | 1:5              | 2.2 |

**FIGURE 10. The pollution degree relationship with dust spreading rate.**

It can be seen from Fig.10, with the increase in dust concentration, the NSDD of the insulator surface increased obviously. When the dust spreading speed was 18 g/min, the increase of NSDD was the most obvious, followed by the dust spreading speed of 36 g/min. When the dust spreading speed reached 54 g/min, the NSDD increased slowly and tended to be saturated. The ESDD on the bottom surface of insulators increased linearly with the increase in dust spreading speed, and reached the maximum when the dust spreading speed was 54 g/min. The reason may lie in that under the same working conditions, the higher the contaminant concentration, the more contaminant particles colliding with the insulator surface in a unit area, and the greater the probability of deposition on the insulator surface. As a result, the higher the contaminant concentration, the more contaminant particles colliding with the insulator surface, and the shorter the time for the insulator surface contamination to reach saturation. After the contaminant particles accumulate on the insulator surface to a certain extent, the contaminant particles no longer collide with the insulator surface directly, but with the contaminant particle layer deposited on the insulator surface. Moreover, the cohesive force between contaminant particles is bottom than that between contaminant particles and the insulator surface. Under the influence of wind power and the gravity of contaminant particles, they are prone to fall off from the contaminant particle layer, so the influence of contaminant particle concentration on the insulator surface presents a saturating trend.
C. INFLUENCE OF CONTAMINATION DURATION

After insulator contamination for certain years, the surface contamination degree will reach a dynamic equilibrium when the ESDD is the saturated ESDD, but the valuing of saturated ESDD always has a large deviation. In this study, with other factors fixed, the contamination saturation trend of insulators was investigated by different times of insulator contamination using the artificial contamination characteristic test system, the test conditions are shown in TABLE 4. After 5 times, 10 times, and 15 times of pollution accumulation cycles, the contamination of the top and bottom surfaces of the insulator was measured to obtain the relationship between ESDD and NSDD of the bottom surface of the insulator and the number of times of contamination, as shown in Fig. 11.

| TABLE 4. Test conditions. |
|---------------------------|
| Type | circles | concentration (g/min) | size (μm) | SDD/NSDD | Wind speed (m/s) |
| XP-300 | 5-15 | 18 | <70 | 1:5 | 2.2 |

It can be seen from Fig.11, the artificial contamination characteristics of insulators mainly experienced three stages. At the initial stage of contamination (from surface cleaning to 5 times of contamination), the contamination rate on the insulator surface was relatively slow, and the contamination rates of ESDD and NSDD were 0.016 mg/cm²/times and 0.10 mg/cm²/times, respectively. At the middle stage of contamination (from 5 times to 10 times of contamination), the contamination rates of ESDD and NSDD were 0.04 mg/cm²/times and 0.16 mg/cm²/times, respectively. At the later stage of contamination (from 10 times to 15 times of contamination), the contamination rates of ESDD and NSDD were 0.01 mg/cm²/times and 0.03 mg/cm²/times, respectively. In the three stages of contamination, the contamination rate of NSDD was higher in the early and middle stages, while it decreased significantly in the later stage, with a trend of saturation. The causes may be as follows: at the initial stage of contamination, the surface of porcelain insulators is smooth and the contaminant particles collide with the insulator surface before contaminated, so the dust is not easy to adhere to the insulator surface. At the middle stage of contamination, with the accumulation of contaminant particles on the insulator surface to form a thin contaminant layer, the surface roughness of the insulators increases. At this time, the contaminant particles are prone to adhere to the rough surface, so the contamination rate is accelerated. At the later stage of contamination, after the contaminant particles accumulate on the insulator surface to a certain extent, some contaminant particles continue to deposit on the insulator surface, and some that are not tightly attached fall off from the dust surface under the external force with the influence of wind power and the gravity of contaminant particles. Thus, the contamination rate slows down. When a dynamic equilibrium is reached, the surface contaminant amount will be saturated.

D. INFLUENCE OF SHED SHAPE

By mastering the contamination characteristics of insulators with different shed structures, the contamination shape coefficient of different shed insulators under the same environmental conditions can be determined, which can provide a basis for the reasonable selection and optimal configuration of insulators. The standard, double-shed and triple-shed porcelain insulators were used as the subjects. The test conditions are shown in TABLE 5.

| TABLE 5. Test conditions. |
|---------------------------|
| Type | circles | concentration (g/min) | size (μm) | SDD/NSDD | Wind speed (m/s) |
| XP-300 | 5 | 18 | <70 | 1:5 | 2.2 |
| WXP-300 | 5 | 18 | <70 | 1:5 | 2.2 |
| XSP-300 | 5 | 18 | <70 | 1:5 | 2.2 |

After the test, pollution measurements were carried out on the top and bottom surfaces of the double-shed and the triple-shed insulators. The ESDD values of the top and bottom surfaces of XP-300 insulator were used as the reference. The results are shown in TABLE 6.

| TABLE 6. ESDD ratio of different insulators. |
|---------------------------|
| Type | Top surface | Bottom surface |
| XP-300 | 1 | 1 |
| WXP-300 | 1.20 | 0.63 |
| XSP-300 | 0.90 | 0.53 |

It can be seen from TABLE 6, under the same operating environment, the ESDD on the top surface of different shed insulators was close, while that on the bottom surface was quite different. There is little difference in the top surface structure of standard, double-shed and triple-shed insulators. Being washed by rain after contamination, the ratio of ESDD was 1:1.20:0.9, and the ESDD on the top surface of the insulators with triple-shed structures was low and less different. The ESDD on the bottom surface of the three types insulators showed great differences, with the ESDD ratio of 1:0.63:0.53. For the insulators with an edge under the shed, the air velocity dropped sharply due to the block by the vertical edge, which is likely to form a low-speed rotating eddy-current, and deposit the contaminant particles under centrifugal force. Additionally, air formed a rotating eddy-current region at a...
specific part around the insulators because of the block of the shed and rod diameter when flowing around the insulators. Subsequently, the velocity of the contaminant particles in the eddy-current region decreased, so that the particles have the chance to deposit on the insulator surface under electric field force, rotating centrifugal force or turbulent diffusion. Therefore, eddy current is easy to form on the bottom surface of standard insulators, leading to serious contamination. However, the bottom surfaces of triple-shed and double-shed insulators have good aerodynamic characteristics and are not prone to form eddy current, so they are not easy to be affected by contamination.

**IV. CONCLUSION**

In this study, through the development of an artificial contamination test system in straight flow wind tunnels, as well as the combination of the natural contamination rule of insulators with the characteristics of the artificially simulated natural contamination test system, the key parameters for artificially simulated natural contamination test, such as rainfall 5 mm, artificial fogging time of 15 min and drying time of 40 min, were proposed, and the test process and method were determined.

The wind had obvious influences on contaminant amount and contamination distribution on insulators. With the wind speed increasing from 2.2 m/s to 7.5 m/s, the pollution level on the insulator surface gradually increased firstly and then decreased slowly, and the NSDD reached the maximum when the wind speed was around 4.5 m/s.

The contaminant amount on the insulator surface increased with the increase in contaminant concentration, and tended to be saturated when the dust spreading speed was 54 g/min. With the extension of contamination duration, the insulator surface contamination tended to be slow in the initial stage, accelerated in the middle stage, and slowed down and gradually saturated in the later stage.

For standard, double-shed and triple-shed insulators, the ratios of ESDD on the top and bottom surfaces were 1:1.20:0.9 and 1:0.63:0.53, respectively, under the same test environment, and the difference in shed type had an obvious effect on the contaminant amount.

The process of insulator contamination in the natural environment is very complex. The rapid contamination test carried out using this contamination characteristics test system cannot be simply equivalent to natural contamination. In addition to wind speed, atmospheric particle concentration, rainfall and other environmental parameters, the shed type of insulators, the adhesion of different insulation materials to particles, voltage type and the role of rainfall all have an important impact on insulator contamination, which should be considered in the subsequent study. Moreover, a more reasonable test method should be explored to further reveal the mechanism of insulator contamination.

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