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Simulation Study of the Pollution Deposition Characteristics of the Insulators on High-Voltage DC Transmission Lines

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Aimed at common insulators in the ±660kV Yin-Dong lines, one-year natural fouling test is implemented to summarize the rules for changes of non-uniformity coefficient at the upper and lower surface of the insulators with different models, and its ash salt ratio and other parameters. AutoCAD software is used to establish the physical 3D models for USSOBP/240H porcelain bell jar insulator and FXBZW-±660/300 composite insulators. Meanwhile, they are also led to Fluent, a fluid mechanics simulation software, to simulate gas solid two-phase flow, analyse distribution of surface static pressure and surrounding air velocity of the insulators, study surface collision characteristics of pollution particles and insulators, and summarize the rules for affecting surface pollution collision rate of insulators by wind speed, diameter of pollution particles, wind declination angle and electric field force and others. Numerical simulation results show that static pressure at windward side of the insulator is greater than the leeward side and airflow velocity can be quickly reduced to be close to zero upon approaching the surface of the insulator. It can be known from this that it’s easy to accumulate pollutions at boundary layer formed at surface of the insulator by ±660kV Yin-Dong lines.

1. Introduction

Insulators are mainly used to support and insulate the overhead lines and electric equipment and play an important role in ensuring safe and stable operation of the power system. With increasing industrial level in China, atmospheric pollution and outer-insulation pollution of power system are becoming more and more serious. Outdoor equipment of substation and transmission line is easy to be polluted by industrial dust, raise dust and guano and others. In the foggy, snowy, fine rainy and cloudy days, i.e. relative air humidity is high, it’s easy to cause pollution flashover accidents, which causes great harm on external insulation of the equipment (Chen et al., 2015). Among common insulator accidents, although flashover accident frequency is lower than lightning accident frequency, its losses are almost 10 times of lightning disaster. Pollution flashover accidents seriously affects the reliability of power supply (Langerudy et al., 2017).

Fouling on the surface of insulators is a complicated and dynamic process involving many factors. There are little studies on mechanism of Fouling in the existing literature. It is lacking in dynamic simulation test (Li et al., 2017). Related simulation test can be implemented to mainly focus on influence of wind speed, wind declination angle, particle size, gravity and electric field force and others on the Fouling, and summarize Fouling regularity of insulators in different weather conditions, so as to avoid pollution flashover accidents to the largest extent and provide basis for determining insulation level of the equipment and have an important engineering significance (Song et al., 2016).

2. Natural fouling test of the insulators in ±660kV Yin-Dong lines

2.1 Test environment and layout of test sites

The natural fouling test site is ±660kV Yin-Dong lines in Dezhou, Shandong Province. Weather in Dezhou is remarkably affected by monsoon, and characterized in four distinctive seasons, hot and rainy in summer, cold and dry in winter, and less snowfall. During field test, two test points were arranged, which is located at #1894 strain tower in light industry with serious pollution, with cotton mill, livestock farm and other light industry and lots of farmlands in the surroundings, and ##1907 tangent tower in the road area. In order to improve measurement accuracy, power-off maintenance should be used to remove insulator strings and clean them on the ground. Specific parameters for sampling insulators are shown in Table 1.

Table 1: Information statistics of sampled insulators

Number	Pole	Type	Material quality	Suspension mode	Sampling sites
A	#1894	U550BP/240H	Porcelain	I strain	Light industrial district
B	#1894	FXBZW-±660/160	Composite	V overhang	Light industrial district
C	#1907	FXBW-±660/300	Composite	V overhang	Highway area
D	#1907	FXBW-±660/300	Composite	V overhang	Highway area

In recent years, with rising industrial level, hazy weather occurs frequently. According to Fog and Haze Ranking Table of 190 Cities in 2014, the polluted degree in Dezhou, Shandong Province ranks the sixth. Fog and haze weather may have remarkable influence on external insulation characteristics of electrical equipment. As the first spring rain generally comes in March in Dezhou, sampling before this can be used to get the maximum fouling in the year. So, the sampling time should be February 2014- March, 2014. Fouling period of sampling insulators should be one year. Then, natural fouling is almost saturated. The test results have certain engineering guidance significance, which can also be used to provide reference for insulation configuration of line insulators in the foggy environment (Sun et al., 2016).

2.2 Measuring equipment

Surface contamination degree of the insulators should be measured according to DL/T 374-2010 Drawing Method of Pollution Distribution Map for Electric Power System and equivalent salt density and equivalent dust density should be respectively expressed by ESDD and NSDD with unit mg/c. During test of salt density and dust density, it’s mainly necessary to use salt density measuring instrument, electronic scale, drying oven, quantitative filter paper, stirring rod and filter unit and others (Tünnerhoff et al., 2017). Among them, salt density measuring instrument has temperature compensation function, which can show standard conductivity and equivalent salt density at 20℃, and its measuring scope can be up to 0.01 mg/cm2. Measuring range and measuring accuracy of electronic scale should be 120g and 0.0001g respectively.

2.3 Measuring process

In order to improve test accuracy, it’s necessary to minimize contact with surface of the insulators during handling; ensure cleanness of the measuring instrument and reduce fouling loss during measurement; measure by quickly using electronic scale during fouling measurement to prevent filter paper from staying too long in the air to absorb the moisture, which causes the results to be larger (Wang et al., 2017). Specific measurement steps are as follows:

(1) Cleaning: Insulator sampling cloth should be used to wipe clean the insulators with saturated pollutions. Certain amount of deionized water (conductivity<10μS/cm) is used to clean the sampling cloth. During cleaning, it’s necessary to avoid losses of deionized water.

(2) Stirring: Fouling solutions after cleaning the sampling cloth are stirred for 6 minutes by using a stirring rod. It’s necessary to measure the salt density for one time and stir for 4 minutes for another measurement, and observe whether there is great difference in results. Through multiple tests, it’s only necessary to stir for 6-8 minutes to fully dissolve the fouling and the measurement results are stable.

(3) Measuring equivalent salt density: It’s necessary to initialize the equivalent salt density measuring instrument and input consumption of deionized water and surface area and other parameters. Measuring probe is put in to the uniformly stirred fouling solutions for a period. Then, corresponding conductivity and equivalent salt density are shown on the salt density measuring instrument and relevant results should be kept.

(4) Filtering: Test shows that there are more pollutions at the lower surface of porcelain bell jar insulator. In case of filtering immediately after measurement of salt density, the filtering speed is very little, which affects test efficiency. Through accumulative experience for many filter tests, it’s necessary to summarize a set of mature process: uniformly stirred fouling solutions are resting for 1-1.5h and it’s necessary to filter after sedimentation of lots of insoluble substances or in dissolvable substances. During filtering, electric pump should be used to extract the gas in the filter bottle, so as to accelerate. Finally, clean water should be used to clean the bottom and the wall of the beaker, so as to reduce foul losses. Through test, it proves that this method can be used to reduce filter time and improve test efficiency.

(5) Drying: Filtered paper is placed in the drying oven, which is kept at 105℃. The drying time should be determined according to the foul amount. Each filter paper should be dried for about 15 minutes.

(6) Measuring equivalent ash density: In order to prevent moisture absorption of filter paper in the air, it should be always placed in the drying oven. In case of usage, it’s should be weighed by using a high-precision electronic scale. After foul drying, it’s necessary to immediately weigh again by using an electronic scale. The expression of equivalent dust density is same as formula (1):

$$\mathrm{NSDD} = 1000(\mathrm{m}_1 \quad m_0)/s \tag{1}$$

Where, NSDD is equivalent gray density, mg/cm2; m_1 is mass of filter paper and residues after drying, g; m_0 is mass of filter paper, g; S is surface area of sampling insulator, cm^2.

3. Analysis of test results

3.1 Analysis of filth unevenness on the upper and lower surface of the insulators

In order to analyze uneven fouling at upper and lower surface of the insulators, this paper defines ESDD and NSDD at lower and upper surfaces of the insulators. Coefficients of contamination nonuniformity (KESDD and KNSDD) are shown in formula (1) and formula (2) respectively:

$$\mathrm{K}_{ESDD} = \frac{ESDD_{lowersurface}}{ESDD_{uppersurface}} \tag{2}$$

$$\mathrm{K}_{NSDD} = \frac{NSDD_{lowersurface}}{NSDD_{uppersurface}} \tag{3}$$

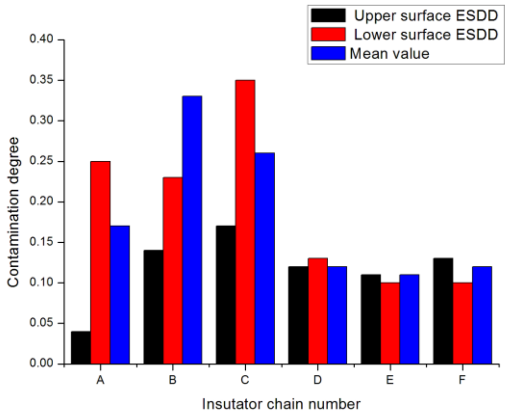
Coefficient of contamination nonuniformity for salt density and dust density of A-F strings of insulators are summarized in Figure 1. It can be known from the figure that there is contamination nonuniformity at upper and lower surface of porcelain bell jar insulator. Mean coefficient of nonuniformity of salt density and dust density is up to 5.12 and 7.1 respectively; coefficients of nonuniformity of ESDD and NSDD of composite insulators at #1894 tower jump are larger than those of #1907. Composite insulators of #1907 tower has a small coefficient of nonuniformity and other values are about 1. In the light industrial area with heavy pollution, there is obvious difference in fouling conditions between upper and lower surfaces of the insulators. The fouling on the lower surface is far larger than the upper surface. The reason is that the upper surface can be flushed by rain and has good self-cleanliness. On the road, there is small comprehensive difference in fouling between upper and lower surfaces. But, salt density at the upper surface is slightly larger than the lower surface.

3.2 Analysis of fouling characteristics at different positions of insulator strings

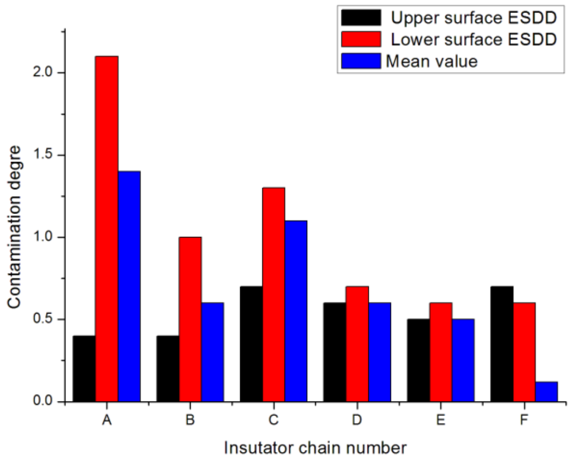
Figure 2 is the diagram for distribution of same-string salt density and dust density at A and B strings in the light industrial area and at E string in the highway and farmland area. The horizontal axis refers to number of insulators. If it is larger, it means being closer to the high-voltage end. It can be known from Figure 2 that there is serious contamination at strings of the insulator at those close to the high-voltage side and at the grounding side, and the maximum values of equivalent salt density and equivalent dust density are at two ends of insulator string. There is little contamination in the middle. The whole has a “U” distribution characteristic of “low in middle and high at two ends”. In the middle, it’s irregular zigzag.

In the AC electric field, surface field strength of insulator string is strong at high-voltage end and grounding end and weak in the middle. It can be seen from natural fouling test that salt density and dust density also have similar distribution characteristics. When DC voltage is imposed on the surface of the insulator, the electric field in the surrounding space is constant, so that charged dust particles can be directionally migrated and deposited at its surface. Therefore, electric field distribution of insulator string may affect contamination accumulation regularity on the surface. They have similar U-shaped characteristics. As there are uncontrollable factors in the nature, contamination accumulation regularity has certain randomness and is in zigzag shape. There is serious contamination in the middle of the insulator string (Xu et al., 2016).

According to the test results, diameter of umbrella group of composite insulators may affect the contamination to a certain degree. Contamination at umbrella group with different diameter is shown in Figure 3. It can be known from the figure that salt density and dust density may be decreased with increasing diameter of the umbrella. This is because that composite insulators is hung in a V-shape. In the rainy season or during manual cleaning, large umbrella may shelter the small umbrella. Small umbrella is less flushed by the water and has poor self-cleanliness. Insulators with large diameter have large area, small drag coefficient, and low comprehensive contamination degree. But, the small umbrella has a high comprehensive contamination degree.

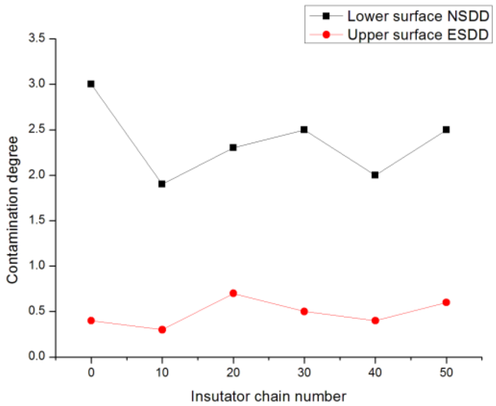


(a) Collation graph of salt density

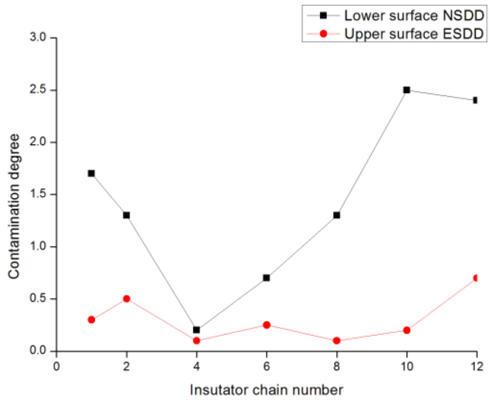


(b) Collation graph of dust density

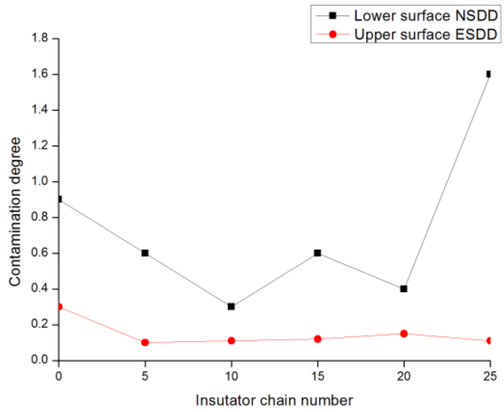
Figure 1: Contamination distribution of insulator chain



(a) Nature insulator law of A chain porcelain bell jar



(b) Nature insulator law of B chain porcelain bell jar



(c) Nature insulator law of E chain porcelain bell jar

Figure 2: Measurement result of salt density and dust density of insulator chain

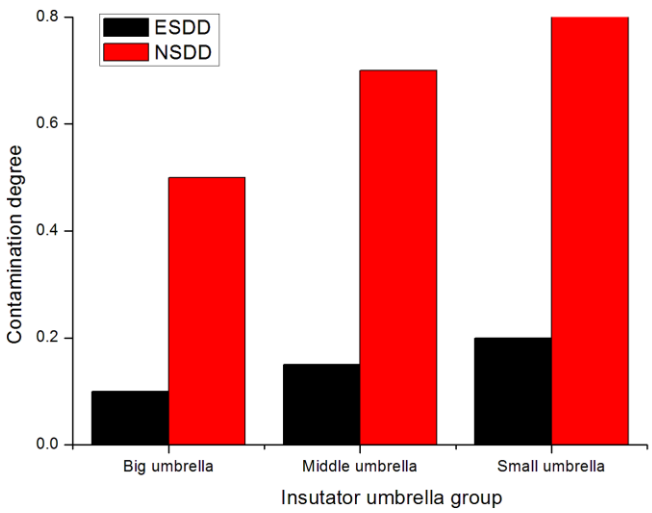


Figure 3: Distribution of fouling in different umbrella groups of composite insulators

4. Conclusions

This paper introduces the arrangement of natural fouling test sites of the insulators in the ±660kV Yin-Dong lines and distribution of its surrounding pollution sources; details the process for testing salt density and dust density; analyzes distribution characteristics of surface contamination degree and other parameters and summarizes the natural pollution deposition characteristics of the insulators. The results are as follows: firstly, pollution at upper and lower surface of porcelain insulators is very uneven and mean value of KESDD and KNSDD is up to 5.12 and 7.1; Coefficient of contamination nonuniformity of composite insulators is small with mean value about 1; surface equivalent salt density and equipment dust density on the upper surface of composite insulators in the light industry area are generally larger than those of porcelain insulators, while equivalent dust density on the lower surface is less than porcelain insulators; insulator string of strain tower has serious contamination and mean salt density of composite insulator string is up to 0.26 mg/cm2, and it's necessary to increase quantity of insulators or strengthen special patrol to avoid pollution flashover accidents. Secondly, the regularity for contamination distribution on the same string of insulators is that the contamination amount is the largest at two ends of insulator string and small in the middle, and it is distributed in a saw-toothed shape; deposition of pollution particles is easy to be affected by electric field force; for composite insulators, if diameter of the umbrella group is larger, the deposition is less. Finally, ash salt ratio of porcelain and composite insulators is distributed according to following regularity: it's not relatively distributed on the upper and lower surfaces of the porcelain insulators and those on the lower surface is higher than the upper surface; composite insulators are distributed evenly, which is slightly higher on the lower surface. Ash salt ratio of two kinds of insulators obeys normal distribution and overall expected value for ash salt ratio of porcelain and composite insulators should be 12.44 and 5.86, respectively.

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