Experimental studies on effects of surface morphologies on corona characteristics of conductors subjected to positive DC voltages

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Abstract: As the surface conditions play a significant role on corona discharge and its related effects of the conductors, the influence of fine particulate matter on positive-polarity, direct-current conductors was studied experimentally in this study. The surface morphologies of the conductor could be discovered from the experiments. The typical morphologies are the parallel chains of particles. To evaluate the surface condition quantitively, the surface roughness of the conductors is measured. It is found that the applied voltage and testing time have a great influence on the surface condition. After that, the corona characteristics of conductors are tested. It reveals that the total ground level electric field and ion flow density increases with the surface roughness growing.

1 Introduction

The surface conditions of a conductor operating at high-voltage might be responsible for the enhancement of electric field that could lead to the inception of electrical discharges in the immediate vicinity of the conductors. These discharges often referred to as corona cause energy loss, audible noise, radio-frequency and photon emission [1–5].

Owing to the fast economic development, industrial expansion and urbanisation during the last few decades in China, and in some other developing countries, the frequent occurrence of regional large-scaled haze or smog episodes characterised by the fine particulate matter (with aerodynamic diameters not larger than 2.5μm or PM2.5) have been discovered and reported [6–8]. In such environment, contamination may adhere to the surface of electrical equipment, which is exposed to the air [9, 10]. The activities of particulate matter in electric fields, especially when subjected to non-uniform fields, are of great interest to scientists in various subjects: physics, chemistry, life science, astronomy and engineering. To physicists and chemists, it is a science of extraordinary and amazing phenomena [11–15]. For materials scientists, it is worth exploring how coatings affect the adhesion and decomposition of particulate matter in electric field [16, 17]. To life scientists, it offers new methods to investigate, better understand and manipulate cells and their sub-particles. It may also contribute to discovering the nature of living systems [18–20]. To engineers, on the other hand, it is a source of useful and effective technique to separate materials or improve their behaviour [21–23]. Especially for human exploration of space, a detailed understanding of lunar and Martian dust dynamics is needed for designing and implementing dust hazard mitigation methods to facilitate successful missions to the Moon and Mars [24–28].

Also, particulate matters under the influence of electric field have become one of the serious challenges in designing, constructing and operating transmission lines used in high-voltage electrical energy systems. Owing to the almost exponential growth in demand for electrical energy, especially in developing countries, the operating voltage levels of transmission lines have already exceeded 1000 kV in order to facilitate economical transmission of large-capacity energy over long distances. Almost all of these transmission lines are overhead lines, which is exposed to atmospheric conditions.

Owing to the geometry of transmission lines, a highly non-uniform electric-field distribution takes place between the overhead conductor and the ground. The intensity of the electric field becomes pronounced especially when the magnitude of the conductor voltage is in the ultra-high-voltage range, such as 1000 kV and above.

In the vicinity of a transmission line when particulate material is charged and polarised in air, some of the particles may move toward the conductors under the effect of the force exerted by the non-uniform electric field produced from the high-voltage conductors [29]. The particulate matter attracted toward the conductors may eventually settle down and accumulate on the surface of the conductors, which may lead to substantial changes on the original conditions of the conductor surface [30].

The contemporary study of fine particles movements in fluid and electric field is well-performed. For an axisymmetrical arrangement of two dielectric spheres under a uniform electric field, solutions were reported by Davis [31] and Stoy [32, 33]. For a three-dimensional (3D) arrangement of two dielectric spheres, Washizu and Jones [34] presented a method utilising multipole re-expansion for calculating the electric field and force on the particles. For avoiding disadvantages of numerical calculation of electric field and force on particles, techaument developed an analytical method based on the method of images that utilised the multipole re-expansion and the fundamental solution for several particle behaviours in an electric field [36]. To explore a global distribution of particles in an electric field generated by different electrodes, Monte Carlo method was also applied by Magna [37].

Although there were some studies for surface characterisation of conductors due to natural and artificial contamination along with their effects on corona discharges [38–44] and some analysis of particle behaviours in electric field, very little attention was paid to impacts on the accumulation of fine particulate matters on the surface of high-voltage conductors in air and their influence on the corona characteristics. Therefore, the objective of the present study was to investigate the role of fine particulate matters on the surface conditions of conductors and their influence on the corona characteristics when subjected to positive-polarity direct-current (DC) voltage experimentally.

First, an experiment about contamination accumulation was described. Then, the surface morphologies of the conductors operated in the presence of fine particulate matters were observed and measured. On the basis of the tested conductors, their corona
characteristics including total ground level electric field and ion flow density were measured.

2 Experiments

To explore the effects of surface morphologies on corona characteristics, the surface morphologies of the conductors operated in the presence of fine particulate matters were observed and measured as well as the corona characteristics of the conductors.

Contamination accumulation chamber was specially designed and constructed as illustrated in Figs. 1a and b to facilitate the experiments. A cylindrical corona cage with an iron conductor in the centre was utilised to create a non-uniform electric-field distribution in the chamber. The diameter of the conductor was 5 mm, whose corona inception voltage was about 47 kV and corona inception electric field was about 38.6 kV/cm. Before the experiment, each conductor was wiped with alcohol cotton to ensure it was clean. The DC source had a maximum output voltage of 80 kV and a maximum output current of 15 mA. The positive-polarity DC voltage was ∼50 kV in order to assure that the medium inside the chamber would be free of charge, thus the non-uniform electric-field distribution would not be modified due to the free space charge. The main information of the particles is illustrated in Figs. 1c and d. Particles were produced by burning incense, whose main elements were carbon, oxygen and chlorine. At the initial moment, the smaller the particle diameter $d_p$ was, the greater the concentration was. It should be noted that the 0.3 μm particles in Fig. 1d indicated particles’ diameter in the range of 0.3–0.5 μm.
The particle size was mainly concentrated in 0.3–5 μm, and the amount of particles above 5 μm was negligible.

Flowchart of the experiment is illustrated in Fig. 1e. The experiments were performed at different durations and voltages for accumulation of contaminants. The duration for accumulation of contaminants could be reduced to a few hours because the concentration of the incense particles of the experiments was much higher than that of practical situation. The conditions of the conductor surfaces were investigated after the completion of the accelerated tests in the chamber. To better clarify the influence of the particles on the corona characteristics, the morphology of the particles on the conductor surface was observed and quantified by scanning electron microscope (SEM) and white light interference morphology [42, 45]. The surface morphologies were observed by SEM (SEM, Quanta 200FEG) with nanometre accuracy, and the surface roughness and the 3D surface morphologies were measured by white light interferometer (ZYGO NewView), which can accurately measure the roughness of samples below root mean square 0.1 nm.

The corona characteristics of the conductors with different contamination conditions were measured. During the corona tests of the conductor samples, the exact power supply was connected to the centre conductor to let the centre conductor be the discharge electrode. Two transparent spheres with 30 mm diameter were set at both terminals of the conductor to avoid the edge effect. The DC voltages applied to the conductor were raised from 0 to 40 kV in step of 10 kV. To figure out the corona characteristics of contaminated conductors, a Wilson plate and a field mill were used to measure the ion flow density of the conductors and the electric-field strength on the ground electrode, respectively. The field mill was mounted in the hole at the bottom central of the corona cage [2].

3 Analyses and results

After the particle accumulation experiments, the surface condition of the tested conductors was observed and the corona characteristics were measured. On the basis of the above information, the difference in surface state of the wire under different experimental conditions and the effect on corona discharge could be observed.

3.1 Surface morphologies

The morphology of the obtained conductor samples’ surfaces was characterised by SEM. The images of the conductor samples’ surface morphology with a magnification of 1000 are shown in Figs. 2 and 3.

Figs. 2a–e and Figs. 2f and g show the difference in the effect of applying different levels of DC voltage on the surface morphology of the conductor when the time was 1 and 2 h, respectively.

As shown in Fig. 2, there were no particles depositing on the conductor surface when no voltage applied. With the applied voltage increasing, the aggregation among particles enhanced, gaps among particle aggregations increased and the number of the particle aggregations decreased. Focused on Figs. 2a–e, with the voltage increasing, the number of particle agglomerates on the conductor gradually decreased from 485 to 200, and the width of the particle agglomerate rose from 2.5 to 9.5 μm. We can find that the electric field is the key to accelerate the deposition of particulate matter on the surface of the conductor. Under the action of the electric field, particles will continue to move and adhere to each other after adhering to the surface of the wire.

Figs. 3a–c and Figs. 3d–f show the change in surface morphology of the conductor over time when the applied voltage was 30 and 40 kV, respectively. With the time increasing, the aggregation among particles enhanced, gaps among particle aggregations increased and the number of the particle aggregations decreased. Focus on Figs. 3a–c, as time increased, the number of sample particle agglomerates gradually decreased from 445 to 240, and the distance between particle agglomerates rose from 5 to 15 μm. During this process, the degree of polymerisation among particles increased, as a result, the particle aggregates aggregated with each other, resulting in an increase in the size of the aggregates and a decrease in the overall number.

To make a more quantitative evaluation of the surface condition, the surface roughness $R_a$ of the samples were obtained, as shown in Fig. 4–7. The difference in unevenness on the surfaces of conductors could be shown more clearly by the chromatic aberration, red for high places and blue for low places. $R_a$ represents the arithmetic mean deviation of the contour and was calculated according to the height value of each point of the sample surface. $R_a$ was calculated according to the height value of each point of the sample surface. The larger $R_a$ was, the more uneven the sample surface was.

The variation of the surface roughness of the samples with the applied voltage is revealed in Fig. 8. It is found that both increasing applied voltage and time can enhance the surface roughness, which indicates that particles will make the surface of conductor rougher after agglomeration.

3.2 Corona characteristics

Corona experiments were performed on all samples. $U_{app}$ was the voltage applied to the conductor by DC source in corona experiments. The synthetic electric-field strength $|E|$, which included the nominal electric field generated by the conductor electrode and the ion current field generated by the corona, was measured by the field mill at the corona cage wall. The variations of the synthetic electric-field strength $|E|$ are shown in Figs. 9 and 10. The turning point of each curve in these figures represented the inception of the corona. It can be found that there was no significant difference in the corona inception voltage of the samples. However, when the applied voltage $U_{app}$ or the time $t_{app}$ of the particle accumulation experiment rose, the electric-field strength of the experimental sample gradually increased after the occurrence of corona.

The variations of the ion flow density $J$ at the wall of the corona cage are shown in Figs. 11 and 12. Similar to $|E|$, the turning point of each curve represented the inception of the corona. $J$ was equal to 0 until corona began, and there was almost no difference in corona inception voltage of different samples. When the applied voltage $U_{app}$ or the time $t_{app}$ of the accumulation experiment rose, the ion current density of the sample gradually increased.

Above all, we can get the conclusion that both $U_{app}$ and $t_{app}$ had a great influence on the corona characteristics due to the change of the surface condition of the conductor. The rise of $U_{app}$ or $t_{app}$ exacerbated the accumulation of fine particles on the surface of the conductor, forming a parallel-lined particle chain on the surface of the conductor, which changed the surface appearance and increasing the roughness $R_a$. The changes of the inception corona voltage and the nominal field were not obvious. This is mainly because in this experiment, the changes of surface morphology caused by particles were in the order of micrometres, but the size of the conductor itself was in the order of millimetres, which indicated that surface morphologies of the conductor did not change so particularly. However, after the corona occurred, the particles on the surface of the conductor were charged, thereby, starting to move under the action of the electric field, increasing the ion flow during the corona. Moreover, the increase of $U_{app}$ and $t_{app}$ could make more particles adhere to the surface of the conductor, which led the ion current to be greater after the corona.

The synthetic electric field also increased due to the increase of the ion flow field. The above was the reason why the particles had little effect on the corona inception voltage and nominal electric field, but had a significant effect on the ion current density and the synthesised electric field after the corona.

4 Conclusions

The effects of surface morphologies on corona characteristics of positive DC conductor were studied experimentally in this paper.

The typical surface morphologies of the conductor under DC voltage were several parallel chains of particles as a whole and
Fig. 2 Variation of surface morphologies with the applied voltage
(a) $t_{app} = 1 \text{ h}$, $U_{app} = 0 \text{ kV}$, (b) $t_{app} = 1 \text{ h}$, $U_{app} = 10 \text{ kV}$, (c) $t_{app} = 1 \text{ h}$, $U_{app} = 20 \text{ kV}$, (d) $t_{app} = 1 \text{ h}$, $U_{app} = 30 \text{ kV}$, (e) $t_{app} = 1 \text{ h}$, $U_{app} = 40 \text{ kV}$, (f) $t_{app} = 2 \text{ h}$, $U_{app} = 0 \text{ kV}$, (g) $t_{app} = 2 \text{ h}$, $U_{app} = 10 \text{ kV}$, (h) $t_{app} = 2 \text{ h}$, $U_{app} = 20 \text{ kV}$, (i) $t_{app} = 2 \text{ h}$, $U_{app} = 30 \text{ kV}$, (j) $t_{app} = 2 \text{ h}$, $U_{app} = 40 \text{ kV}$
Fig. 3 Variation of surface morphologies with the time
(a) $U_{\text{app}} = 30\, \text{kV}$, $t_{\text{app}} = 0.5\, \text{h}$, (b) $U_{\text{app}} = 30\, \text{kV}$, $t_{\text{app}} = 1\, \text{h}$, (c) $U_{\text{app}} = 30\, \text{kV}$, $t_{\text{app}} = 2\, \text{h}$, (d) $U_{\text{app}} = 40\, \text{kV}$, $t_{\text{app}} = 0.5\, \text{h}$, (e) $U_{\text{app}} = 40\, \text{kV}$, $t_{\text{app}} = 1\, \text{h}$, (f) $U_{\text{app}} = 40\, \text{kV}$, $t_{\text{app}} = 2\, \text{h}$

Fig. 4 Surface roughness when $U_{\text{app}} = 10\, \text{kV}$
(a) $t_{\text{app}} = 0.5\, \text{h}$, (b) $t_{\text{app}} = 1\, \text{h}$, (c) $t_{\text{app}} = 2\, \text{h}$

Fig. 5 Surface roughness when $U_{\text{app}} = 20\, \text{kV}$
(a) $t_{\text{app}} = 0.5\, \text{h}$, (b) $t_{\text{app}} = 1\, \text{h}$, (c) $t_{\text{app}} = 2\, \text{h}$
some small particle aggregations locally. Meanwhile, the applied voltage and testing time had a promoting effect on the formation of the morphologies. Besides, the appearance of the morphologies changed the surface roughness. The increasing applied voltage and testing time enhanced the surface roughness, which could increase the total ground level electric field and ion flow density. It meant that the enhancing surface roughness resulted in a more intensive corona discharge.

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Fig. 6 Surface roughness when $U_{app} = 30\, kV$
(a) $t_{app} = 0.5\, h$, (b) $t_{app} = 1\, h$, (c) $t_{app} = 2\, h$

Fig. 7 Surface roughness when $U_{app} = 40\, kV$
(a) $t_{app} = 0.5\, h$, (b) $t_{app} = 1\, h$, (c) $t_{app} = 2\, h$

Fig. 8 Variation of the surface roughness of the samples with the applied voltage
Fig. 9 Variation of total ground level electric field with the applied voltage
(a) $t_{\text{app}} = 0.5$ h, (b) $t_{\text{app}} = 1$ h, (c) $t_{\text{app}} = 2$ h

Fig. 10 Variation of total ground level electric field with the time
(a) $U_{\text{app}} = 10$ kV, (b) $U_{\text{app}} = 20$ kV, (c) $U_{\text{app}} = 30$ kV, (d) $U_{\text{app}} = 40$ kV

Fig. 11 Variation of ion flow density with the applied voltage
(a) $t_{\text{app}} = 0.5$ h, (b) $t_{\text{app}} = 1$ h, (c) $t_{\text{app}} = 2$ h
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