ISBN 978-981-11-3671-9
Proceedings of 2017 the 7th International Workshop on Computer Science and Engineering (WCSE 2017)
Beijing, 25-27 June, 2017, pp.95- 99
doi: 10.18178/wcse.2017.06.016

Study on the Force and Motion Characteristics of Contamination Particles around the High Voltage End of 750kV Insulator

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Abstract. In order to investigate the force and motion characteristics of contamination particles under the effect of electric force and air drag force near the 750kV insulator, the simulation model of 750kV composite insulator at high voltage end was established. By the finite element method, the electric field was calculated, the steady turbulent flow field near the insulator high voltage end was simulated. The contamination particles were uniformly charged, the gravity and the computed results of electric field and fluid field were loaded on them. The trajectories of contamination particles were gained. It is found that the influence of AC electric force on the movement of contaminated particles can be neglected when the particle charge is too less. As the charge gradually increases, the magnitude of electric force and drag force is increased both, in addition, the shape of statistical force curves have converged gradually, while the probability of particles contacted insulator surfaces is increased too. After reaching a certain level the quantities of electric charge on particle, the contact probability decreases with the increasing charge. Only the charge on contaminated particles varying in a certain range, it has positive correlation between particle charge Q and contact probability P_{ct}.

Keywords: 750kV insulator, electric force, air drag force, motion of contamination particle, contact probability, multi-physics field

1. Introduction

Outdoor insulation flashover fault had a great impact on the normal operation of the power system [1]. Many scholars have done a lot of work in the study of the characteristics of insulator contamination and pollution flashover, in order to prevent and reduce the outdoor insulation flashover fault [2]. The precondition of flashover is the existing of contamination layer on the surface of the insulator, which is a very complex physical process [3]. Contamination particles will be affected by the local environmental forces, such as air drag force, electric force, collision force and other forces. It is helpful to reveal the physical process and development law of the insulator deposition by analyzing the situation of force on the contaminated particles.

In the analysis of motion process of contamination particles near insulator, the Reference [4] mentioned the characteristics of force on contamination particles near insulator surface under low wind velocity, and established a dynamic model based on the two-phase flow mechanics theory. In the Reference [5], the particle collision coefficient and the relationship of air velocity, contaminant particle size, flow inclination, and particle impact characteristics were analyzed after obtaining the insulator external fluid field by computational fluid dynamics. The above-mentioned studies only analyzed the quantitative relationship

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between air flow field and the contamination state, and did not discuss the influence of the electric field force on the motion of the contamination particles.

According to the insulator operation data [2] and test data [6], there are differences in the characteristics of contaminate deposition when the insulator is charged or not. The deposit process is not only related to the air flow field, but also affected by the electric field. In order to study the forces and motion characteristics of contamination particles under the combined effects of air drag force and electric force, and obtain the relationship between particle charge and contamination state, the simulation model of 750kV transmission line tower and composite insulator was built for the computation of alter current electric field and air flow field. In this paper, the quantitative relationships between the electric force and air drag force in low wind speed condition were studied, the movement process of contamination particle and regularity of contamination degree were analyzed.

2. Forces on contamination particles near AC insulators

The forces on contamination particles near the insulator can be classified into two types: the fluid force and the field force. The air drag force plays the most important role on the movement of contamination particles in all kinds of fluid forces, and other forces can be ignored. The influence of the electric force on the particle movement should be taken into account when the electric field intensity is high near the high-voltage end of insulator [7].

The drag force on single spherical particle in the atmosphere can be expressed as [7]

$$F_D = \frac{1}{2} C_D A_p \rho u_p^2 = \frac{1}{8} C_D \pi d_p^2 \rho u_p^2 \tag{1}$$

where C_D is the drag coefficient, u_p is the relative velocity of the spherical particles and fluid, A_p and d_p are spherical particles projection area and diameter, ρ is the fluid density.

With the complex flow field near the insulators, the air drag force is very different when the spatial position of the particle is changed. Therefore the contamination particles movement is a transient process, the magnitude and direction of drag force can be calculated according to a certain time and position.

Only the particles are charged in the vicinity of the insulator, was the movement affected by the electric force. The particle diameter of 90% contamination particles is between 1 μm~100 μm. The most important way of the contaminated particles charging is electrical field charging [7]-[9], the saturation charge by electrical field charging is [9]

$$q_{ps} = \frac{3\varepsilon_r}{\varepsilon_r + 2} \varepsilon_0 \pi {d_p}^2 E_p \tag{2}$$

where E_p is the maximum external electric field intensity with saturation charge in the non-uniform electric field, d_p is the particle diameter, ε_r is the relative permittivity of particle.

When the particles are moving in the non-uniform electric field where the E_p is distributional, the saturated charge of each contaminated particle is different. In order to reduce the complexity of the problem analysis, the E_p can be considered as a uniform value in a small space. When the contamination particles have saturated charge, the electric force F_e is

$$F_e = q_{ps} E_0 \tag{3}$$

where E_0 is the background electric field intensity of the position where charged particle is.

The air drag force, electric force and gravity have a comprehensive effect to the motion of contamination particle near insulator. The motion equation of particle involving the three factors can be expressed as

$$\frac{1}{6} \pi {d_p}^3 \rho_p \frac{d\mathbf{v}}{dt} = \mathbf{F}_D + \mathbf{F}_e + \mathbf{F}_g \tag{4}$$

where ρ_p is particle mass density, g is gravity acceleration, **V** is the moving velocity of particle relative to the ground, $\mathbf{F}_g$ is gravity.

3. Multiphysics simulation

The forces on the contamination particles are related with time and location, it is necessary to obtain the particle motion state in series time based on the 3D model. The finite element method was used to calculate the AC electric field and the fluid field respectively, then the results of the two fields were added to the dispersed phase particles, and the moving trajectory of particle was simulated.

3.1. Simulation Model of AC Electrical Field

The geometry models were established by referring to the actual 750kV cup-tower, composite insulator and bundle conductor. In this paper, the motion of the particles in the vicinity of the high voltage end where the electrical field intensity is higher was considered significantly. For saving computer resource and simplifying model meshing, the insulator model has 5 pieces of sheds on the high voltage end, and ignoring the roles of other sheds in the electric field and flow field. The model of insulator high voltage end has a grading ring. The bundle conductors were replaced by single conductors model built with equivalent radius R_{eq}. The values of voltage applied to the three-phase conductor were 653.2∠0° kV, 653.2∠120° kV and 653.2∠-120° kV.

3.2. Simulation Model of Fluid Field

The fluid field can be limited to the small space near the high end of the insulator, because the air flow near the insulator is less affected by the tower body that is far away from insulator. Meanwhile, for saving computer resource, the 1/2 part of insulator high voltage end was setup into the computation domain of fluid field. The air flow direction was perpendicular to the insulator axis, and the velocity of air flow was 3m/s. Contamination particle was considered as spherical particles, the diameter d_p was 20μm, mass density ρ_p was 2200kg/m^3, is the relative permittivity ε_r was 4.

The fluid particle tracing method was used to simulate the motion of particle regarded as discrete phase. Particles were released from entrance surface with uniform density, and the release velocity was equal to airflow velocity. The wall condition was frozen, that is, once the particles contact with the surface of the insulator, it stays in the contact position. All particles are charged uniformly to saturation charge q_{ps}. The particles were loaded with electric force, drag force and gravity in particle tracing domain.

3.3. Simulation Result

When the entrance air velocity V_0 was 3 m/s, the air velocity distribution near the insulator model was shown in Fig. 1. There was a small area of airflow deceleration zone on the windward side of insulator, the airflow velocity in the vicinity of insulator and grading ring was less than the entrance velocity. There was a wide range of low velocity zone on the leeward side, but the air velocity increased gradually as airflow was moving away from the insulator.

Considering the particles had been charged saturated which still have a certain distance away from sheds and rings, the value of electrical field intensity E_p near the ring of high voltage end was appointed to 300kV/m, the single particle charge was 1 p.u. (Q_{sat}=6.6759×10^{-15} C). The time of releasing contamination particles from entrance is 0s, most of the particles moved to the rear of the insulator after 0.95s, under the comprehensive effect of electric force, drag force and gravity. The particles in contact with insulators were frozen at the contact position. When the charge Q on single contamination were 0.1 p.u., 1 p.u., 3 p.u. and 6 p.u, the distribution of particles frozen on the shed surface is shown in Fig. 2. This is consistent with the characteristics and distribution of insulator deposition experiment [10].

4. Forces on Particles and Motion Characteristics

4.1. Comparison of Drag Force and Electric Field Force

A rectangular projection plane was delimited to extract the force data of all particles in the plane. When entrance airflow velocity V_0 was 3m/s, the single particle charge was 1 p.u., the direction of air drag force and electric force on particles which is in the vicinity of insulator at 0.4s and 0.41s after released is shown in Fig. 3. From the figures, it is be seen that the direction of electric field force is reversed according to the periodic variation characteristic of AC electrical field. But the direction of air drag force has not obvious regularity, it is closely related to the turbulence, electric field distribution and other factors. So it is difficult to quantified the particle motion characteristics from the direction regularity of air drag force.

In order to analyze the relative magnitude relationship between drag force and electric force, the forces data when particle charge were 0.1 p.u., 1 p.u., 3 p.u., 6 p.u. at 0.4s of particles were extracted to plot the curves. The order of magnitude relationship of drag force and electric force is shown in Fig. 4. When the Q is 0.1 p.u., the difference between drag force and electric force on most particles is about 0.4 to 0.5 orders of magnitude. The minimum drag force is much smaller than the minimum electric force, however, the difference between the maximum values of two is not significant. As the Q gradually increasing, the drag force and electric force increases both, and the shapes of two curves become similar. When the Q increases from 0.1 p.u. to 1 p.u., the magnitude difference between drag force and electric force on the particles decreased ,it is can be seen at the right part of the curves. In the process of Q increasing to 6 p.u., the magnitude difference between two kinds of forces increased at first and then decreased.

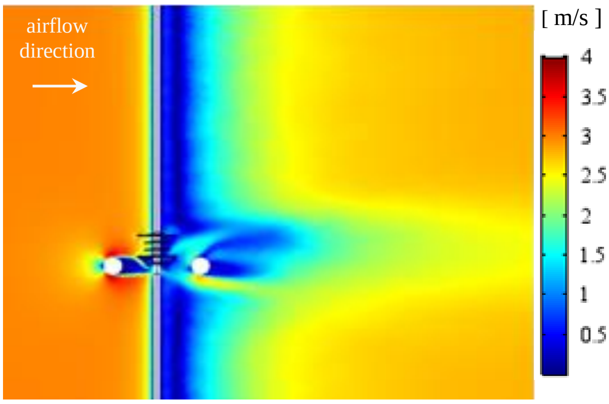


Fig. 1: The contour map of airflow velocity in the insulator axial section,

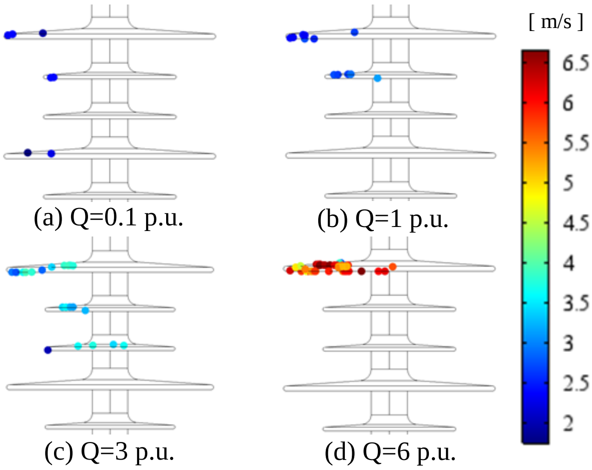


Fig. 2: The distribution map of contamination particles frozen on insulator surface,

4.2. The Relationship between Particle Charge and Contact Probability

An important step of contamination depositing is contamination particles contacted and attached to the surfaces of insulator sheds. The precondition of attachment is contact, the more contamination particles contacted with shed surface is, the higher the probability of contamination depositing is. Therefore, a parameter to indicate the degree of contamination depositing indirectly the probability of contamination particles contacting with shed surfaces P_{ct} was defined, it meant that the ratio of number of particles released from the entrance to number of particles contacted with the insulator:

$$P_{ct} = N_{ct} / N_{total} \tag{5}$$

where N_{ct} is the number of particles contacted with insulator surface, N_{total} is the total number of particles released from the entrance.

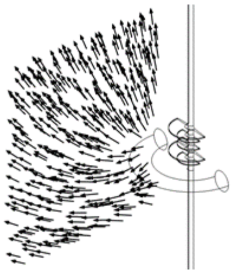
The relationship between single particle charge Q and contact probability P_{ct} as the airflow velocity V_0 was 3m/s from entrance is shown in Fig. 5. In the range of $Q < 0.1$ p.u., the charge variation had no influence to the contact probability P_{ct}. In 0.1 p.u. $\leq Q \leq$ 0.9 p.u., with the charge increasing, P_{ct} slightly increased, and this section of the curve showed some volatility. In 1 p.u. $\leq Q \leq$ 6 p.u., P_{ct} had an approximately exponential increasing. In $Q \geq$ 6 p.u., the probability of contamination particles contacted with insulator decreased rapidly to 0. It indicated that too small AC electric force on particles can be ignored in the movement process of contamination particles, however, too great electric enforces the particles away from the insulator surface. Only particle charge varying in a certain range, there is a positive correlation between particle charge Q and contact probability P_{ct}.

5. Conclusion

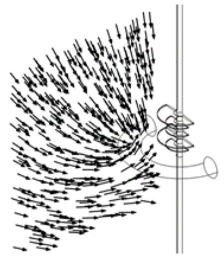
1) The contamination particles contacted with insulator were located both on the lower surface, upper surface and edge of sheds by the influence of AC electric force.
2) In the vicinity of insulator, the direction of electric force on contamination particle has the periodical characteristic, the direction of air drag force has not obvious regularity.

3) The air drag force on particles which uniformly charged on the forward side of sheds is closely related to the electric force on them; as the charge gradually increasing, the drag force and electric force increases both, and the shapes of two curves become similar.

4) Too small or too great AC electric force on particles both has negative influence to contamination particles contacting with insulator; only particle charge varying in a certain range, there is a positive correlation between particle charge Q and contact probability P_{ct}.



(a) electric force direction at 0.4s.



(b) electric force direction at 0.41s

Fig. 3: The direction map of forces on particles at 0.41s after released.

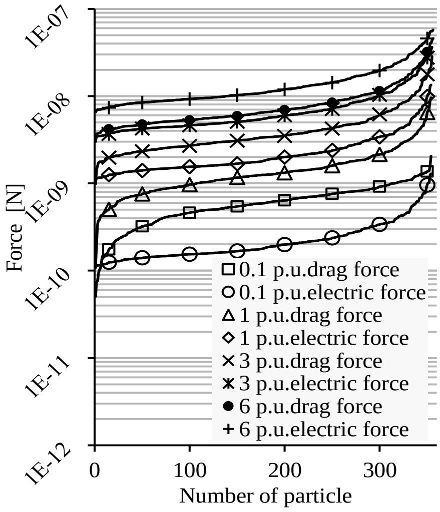


Fig. 4: The curves of drag force and electric field force on the particles with different.

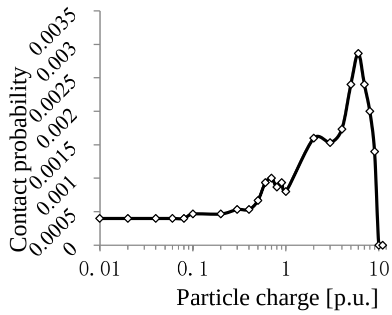


Fig. 5: The relationship of electric charge on particles and contact probability (V_0=3 m/s).

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