Criterion of dripping discharge of falling water droplet on a conductor-to-ground electrode with AC voltage applied

Pengfei Xu[1], Bo Zhang[1*], Shuiming Chen[1], and Jinliang He[1], *Fellow, IEEE*
Dept. of Chemical Engineering
[1] Department of Electrical Engineering, Tsinghua University, Beijing 100084, P. R. China
*e-mail: shizbcn@mail.tsinghua.edu.cn

***Abstract*—The corona discharge types under rain condition for HVAC transmission line are mainly the dripping and crashing discharge, which are also the main sources for annoying noise near HVAC transmission line. However, the mechanism and influencing factors for dripping and crashing discharge are still unclear. In this paper, the initial criterion of water droplet dripping discharge is studied based on the effective ionization integral, which can also be used to crashing discharge. And the effects of the applied voltage as well as the size of water droplet is well studied. Finally, the influence of spaces charges on the dripping discharge is studied, and the results give an insight into the different corona discharge types between HVAC and HVDC transmission lines.**

I. INTRODUCTION

The obvious studies had found that under rainy condition, the audible noise is much larger than that of sunny condition of AC transmission lines[1-4]. And the recent research[5] has found that this phenomenon is mainly caused by the dripping and crashing discharge, which are defined as the corona discharge between the water droplet and the conductor surface. Basically, the dripping and crashing discharges can be regarded as the same kind of corona discharge, as both of them occur when the distance between the droplet and conductor surface is small. The dripping discharge happens when the falling water droplet is reaching the upper conductor surface, and the crashing discharge happens when the separated water droplet is leaving the lower side of conductor surface.

The dripping and crashing discharge are the main corona sources responsible for annoying noise of HVAC transmission line under rainfall condition and therefore, it is essentially meaningful to study the mechanism and influence of these two kinds of discharges. Besides, under the same range of DC applied voltage, there is no dripping or crashing discharge occurring[6], and the audible noise of HVDC transmission line under rainfall condition is much lower than that of HVAC. In this paper, the initial criterion of water droplet dripping discharge is studied based on the effective ionization integral, and also the effects of the applied voltage and the size of water droplet. Finally, the influence of space charges on dripping discharge is well explained based on the proposed criterion.

II. EXPERIMENTAL INFORMATION

The line-to-ground electrode system was used, as the same in ref. [5]. The stranded conductor with a diameter of 8 mm was used. The height between the conductor to the ground was 15 cm. Tap water with a conductivity of 150 μS cm^{-1} at 20 ℃ was supplied. The rainfall was simulated by a series of tiny drips with equal time intervals. The drip volume was 2.5 μL on average, which means the average radius of the water droplet is nearly 0.84 mm. Based on the synchronous measurement of corona current pulse and high-speed photos, the onset AC voltage for dripping discharge is 32 kV (RMS)[5].

III. INITIAL CRITERION OF WATER DROPLET DRIPPING DISCHARGE

Although the appearances for dripping and crashing discharges are different, in theory, the mechanism for both of dripping and crashing discharge is the same, because both of them can be regarded as the gap discharge between the water droplet and the conductor surface. As the dripping water droplet has a more regular shape, the main focus of the paper is to study the initial criterion of water droplet dripping discharge. The theoretical results for the dripping discharge can also be extended to the crashing discharge.

It is found that the magnitude of the effective ionization integral can be used to characterize the strength of corona discharge, and also the initial criterion of corona discharge[7][8]. Therefore, in this paper, the effective ionization integral is used as the corona onset criteria for the discharge generated during water droplet dripping. The effective ionization integral ξ, is defined as[9]

$$\xi = \int_l (\alpha - \eta) dl \tag{1}$$

where α, η, and l are ionization coefficient, attachment coefficient, and path of integration respectively. The value of effective ionization integral is dependent on the air condition as well as the electric field distribution. Under rainfall condition, the relative humidity in air is nearly the saturated humidity, and the value of ionization as well as attachment coefficient can be referred to [8] and [10].

The effective ionization integral is dependent on two aspects. On one hand, as the water droplet falling down, the maximum electric field intensity becomes larger and larger. In theory, if the distance between the falling water droplet and the conductor surface is infinitely small, the maximum electric field intensity will be infinitely large. However, this infinitely large electric field will not result to the infinitely large effective ionization integral. Because, on the other hand, the effective ionization integral is also dependent on the distance, l. Due to the fact that the larger the maximum electric field, the smaller the l. Therefore, there should be a limit value of the effective ionization integral during the falling process of the water droplet.

To derive the value of the effective ionization integral, firstly the electric field distribution is calculated. With the applied voltage of 32 kV (RMS value), the electric field distribution during the falling process of the water drop is shown in Figure 1. The maximum electric field intensity becomes greater as the distance between the water droplet and the conductor surface goes smaller. When the distance is 2 mm, the value of maximum electric field intensity exceeds 30 kV/cm. With the further decrease of the distance to 1 mm, the value of maximum electric field intensity exceeds 40 kV/cm.

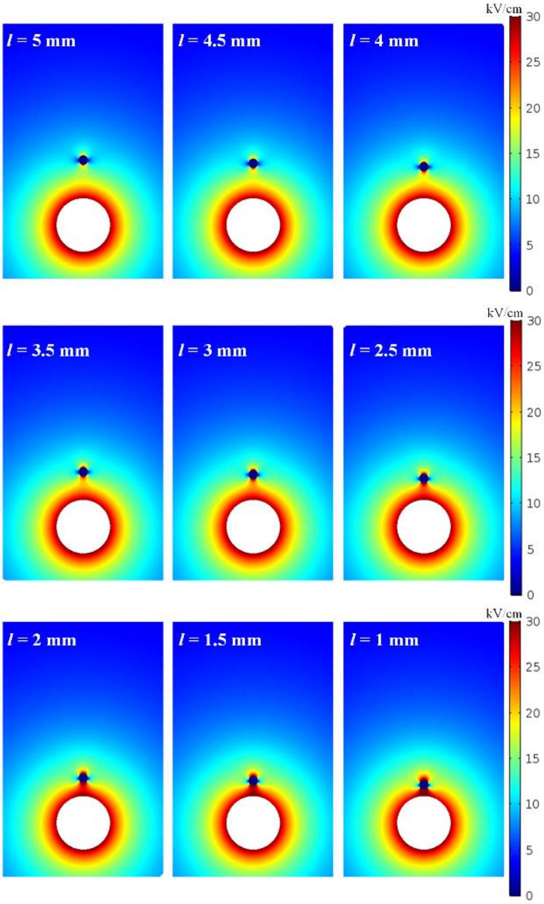

Fig. 1. Electric field distribution as the water drop falling

The more detailed information of the electric field distribution as the water droplet falling process is shown in Figure 2. With the values of the distance *l* being 3 mm, 2 mm, 1.5 mm, 1 mm respectively, the maximum of the electric field increases rapidly. Moreover, the maximum electric field usually appears at the lower side of the water droplet.

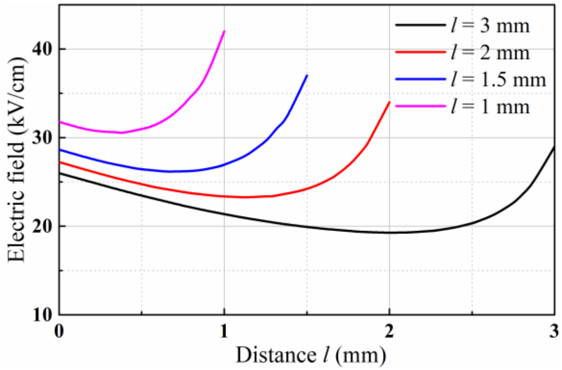

Fig. 2. Electric field distribution under different distance between water droplet and conductor surface

Based on the calculation result of the electric field distribution, the effective ionization integral can be obtained, as shown in Figure 3. It is apparent that effective ionization integral firstly increases with the increase of the distance *l*, and then decreases with the increase of the distance *l*. As a result, there is an upper limit of the effective ionization integral, whose value is nearly 6.3 for the dripping onset voltage (32 kV). And the limit value of the effective ionization integral at the onset voltage, which is defined as ξ_c, can be used as the initial criterion of dripping discharge, which can be expressed as

$$\xi > \xi_c \tag{2}$$

The meaning of equation (2) is that under certain applied voltage, if the maximum value of effective ionization integral during the falling process of the water drop can exceed or at least equal to ξ_c, then the dripping discharge between the falling water droplet and the conductor surface will be excited.

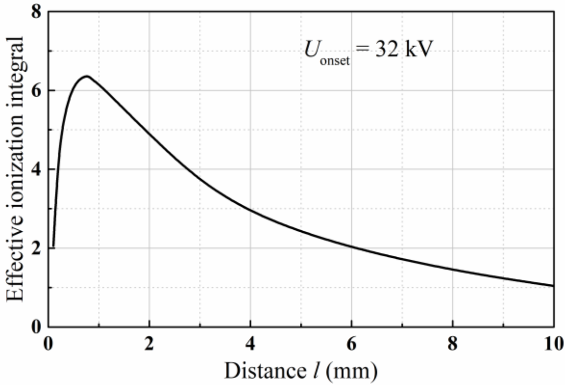

Fig. 3. Relationship between effective ionization integral and the distance between water droplet and conductor surface

IV. INFLUENCE OF APPLIED VOLTAGE AND DROPLET SIZE ON ξ

With other condition unchanged, resetting the applied voltage to 30 kV, 35 kV and 40 kV respectively, and recalculation of the effective ionization integral is demonstrated in Figure 4. With the applied voltage range between 30 kV and 40 kV, there is a maximum ξ during the falling process of the water droplet. In detail, the maximum value of ξ is 5.6 with the applied voltage of 30 kV, a little bit smaller than that of ξ_c, thus there is no dripping discharge occurring under the applied voltage of 30 kV. When the applied voltage increases to 40 kV, the maximum value of ξ is nearly 9.9, much larger than that of ξ_c, as a result, the dripping discharge is excited. In summary, the maximum value of ξ increases monotonously with the increase of applied voltage, and the threshold ξ_c is the maximum value derived under the onset voltage of dripping discharge.

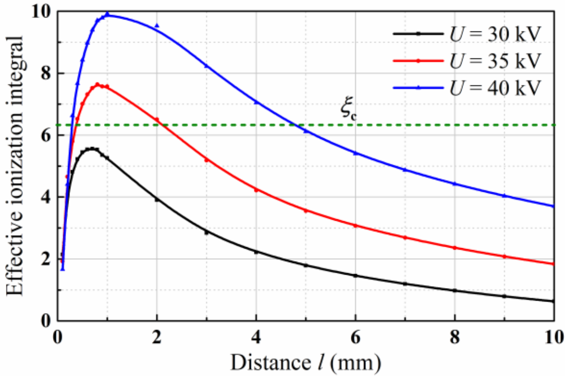

Fig. 4. Influence of applied voltage on the effective ionization integral

When the applied voltage is fixed at the onset voltage, changing the radius of the water droplet to 0.6 mm, 0.8 mm, and 1 mm respectively, the recalculated result of the effective ionization integral is illustrated in Figure 5. The maximum value of ξ increases with the increase of the radius of the water droplet. Besides, it is important to point out that the experimental radius of the water droplet is nearly 0.84 mm, which corresponds to a 2.5 μL in volume. And thus the ξ_c is obtained based on the experimental radius of the water droplet. Therefore, with the applied voltage of 32 kV, the dripping discharge can only happen under the larger water droplet with the radius of 1mm, due to the maximums ξ of smaller droplets with radiuses of 0.6 mm and 0.8 mm are smaller than ξ_c.

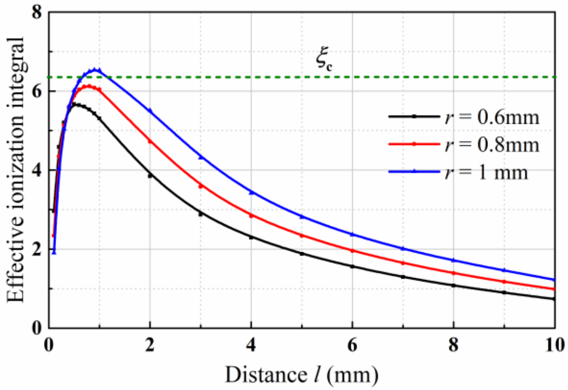

Fig. 5. Influence of the radius of water droplet on the effective ionization integral

V. INFLUENCE OF SPACE CHARGES GENERATED UNDER DC CORONA ON ξ

With the DC voltage applied, there is no apparent dripping discharge occurring during the falling process of the water droplet when the rainfall reaches the steady state, which is quite different from that of the AC voltage [ref my]. The reason for this phenomenon can be attributed to the great influence of space charges generated by DC corona discharge.

The presence of space charges in the vicinity of the conductor surface weakens the electric field intensity between the droplet and the surface of the conductor, which can be attributed to two reasons. On one hand, the electric field near the conductor surface is weakened due to the existing of the space charges directly. On the other hand, during the falling process of the water droplet, a large amount of space charge is adsorbed into the falling droplet, resulting in a further decrease of the electric field intensity between the water droplet and the conductor surface.

As illustrated in Figure 6, with the DC voltage of 45 kV applied, the space ions are absorbed on the lower tip of the water droplet, thus the magnitude of charge density on the lower tip of the water droplet is more than one order larger than that of the surroundings.

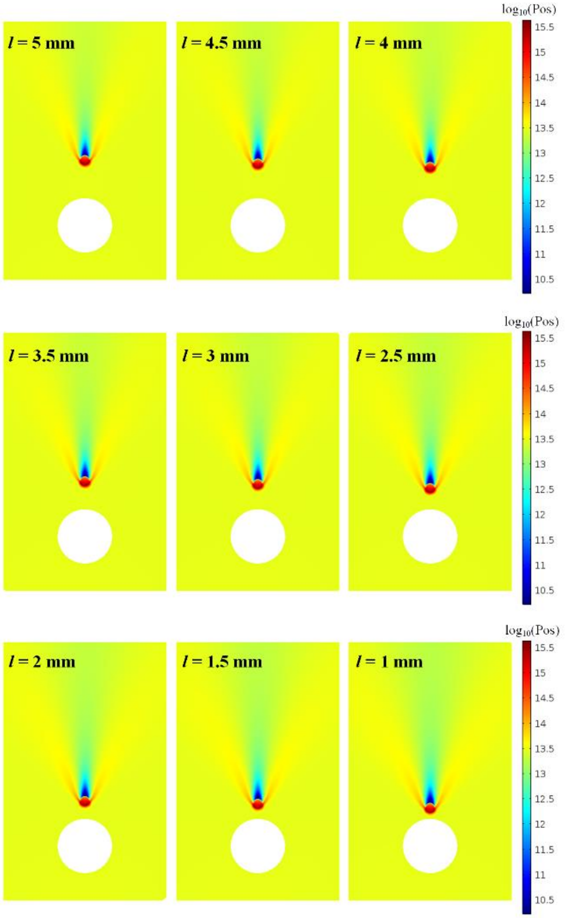

Fig. 6. Positive ion distribution during the falling process of the water droplet under DC applied voltage

The absorption of space charges leads to the reduction of the electric field between the rain drop and conductor, as shown in Figure 7. And the more detailed information of the electric field distribution as the water droplet falling is shown in Figure 8. Compared with Figure 1 and Figure 2, the electric field intensity is weakened greatly. Therefore, at the moment that the water droplet is just about to reach the upper surface of the conductor, it is easier to occur for dripping discharge when the conductor is applied with AC voltage , as there is no space charges suppressing the electric field intensity between the water droplet and the conductor.

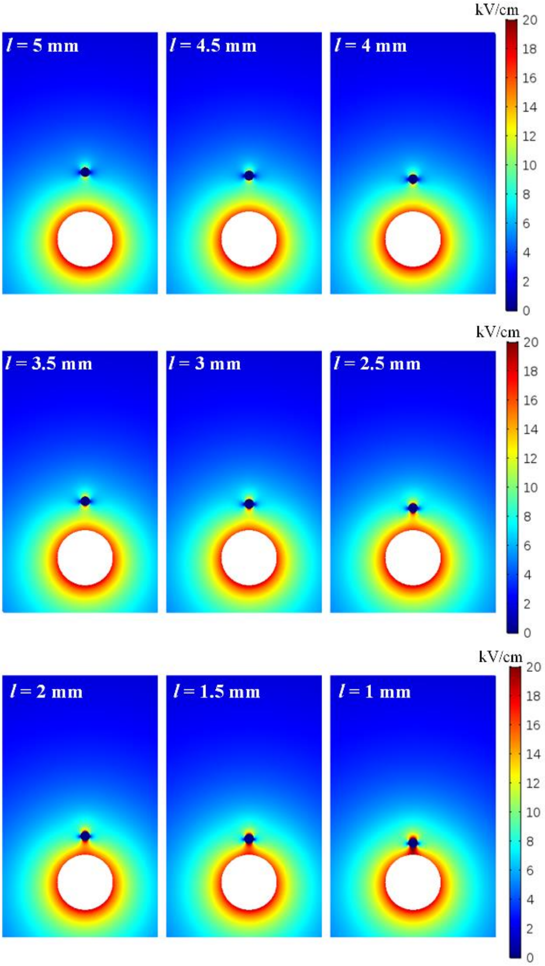

Fig. 7. Electric field distribution during the falling process of the water droplet under DC applied voltage

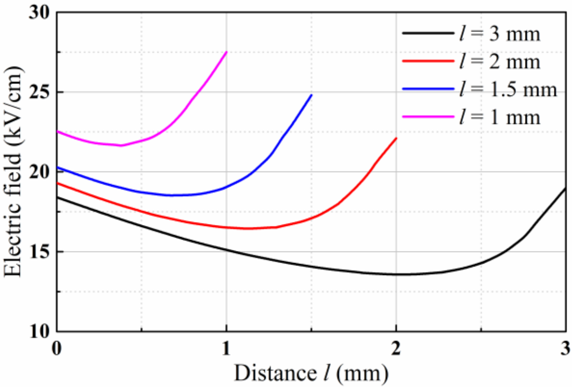

Fig. 8. Electric field distribution under different distance between water droplet and conductor surface with DC voltage applied

Based on the electric field distribution, the relationship between the effective ionization integral and the distance *l* under DC voltage is obtained, as shown in Figure 9. Besides, the pattern of effective ionization integral vs. the distance *l* under AC applied voltage is also illustrated in this figure. It is obvious that the patterns of effective ionization integral vs. the distance *l* under both DC and AC voltage are basically the same. The effective ionization integral firstly increases with the increase the distance *l*, and then decreases with the increase the distance *l*, which means for both of them, there are upper limits of the effective ionization integral. However, due to the great reduction of electric field caused by the space charges, the maximum value of ξ for DC is just 1.4, which is much lower than that of AC. As a result, the dripping discharge under DC applied voltage is unable to occur.

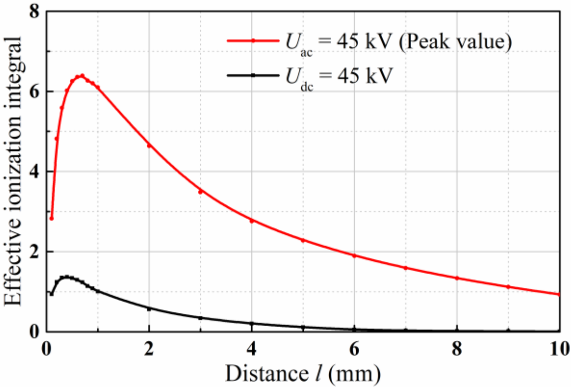

Fig. 9. Relationship between effective ionization integral and the distance between water droplet and conductor surface

VI. CONCLUSION

In this paper, the criterion of dripping discharge is proposed. It is found that there is an upper limit of the effective ionization integral during the falling process of the water droplet, which can be used as the criterion of dripping discharge. The effective ionization integral is found to be closely related to the applied AC voltage and the size of water droplet. In detail, the effective ionization integral increases with both the increases of applied AC voltage and the droplet size, which means that for higher AC voltage and larger droplet size, the dripping discharge is easier to occur. Finally, based on the proposed criterion, the mechanism of non-existing dripping discharge under DC applied voltage is revealed. The reduction of electric field caused by the space charges is the main reason responsible for the non-existing dripping discharge phenomenon under DC voltage. In conclusion, the reason for the different characteristics of AC and DC corona produced under rainfall conditions can be mainly attributed to the reduction of electric field in the vicinity of the conductor surface caused by the space ions.

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