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Zhenguo Wang

Tiebing Lu

Xiang Cui

Xuebao Li

Huseyin R. Hiziroglu

Influence of AC Voltage on the Positive DC Corona Current Pulses in a Wire-cylinder Gap

Zhenguo Wang, Tiebing Lu, Xiang Cui, *Senior Member, IEEE,* Xuebao Li, and Huseyin Hiziroglu, *Senior Member, IEEE*

***Abstract*—In the development of hybrid HVDC and HVAC transmission lines, the study of radio interference is an important issue. Positive corona current pulses from high voltage transmission lines are the main source of radio interference. In this paper, the design of a wire-cylinder gap electrode system is presented to study the influence of AC voltage on the characteristics of positive corona current pulses. The study shows that the mode of the current pulses is different from that of either DC or AC corona discharge. Waveform parameters of the pulses, such as rise time, half wave time, duration time, repetition rates, average amplitude, and time intervals of secondary pulses are all statistically analyzed in this study. The empirical formulas for the repetition rates with different AC voltages are presented. A theoretical explanation based on an ion cloud model is given to reveal the mechanism behind the influence of AC voltage on positive corona discharge. The experimental results could provide some references for the prediction of radio interference from hybrid AC/DC transmission lines.**

***Index Terms*—AC voltage, corona discharge, current pulses, positive DC corona, radio interference.**

I. Introduction

SINCE negative corona current pulses were first observed by Trichel, corona current has been the focus of study for nearly a century [1]. The complex molecular level reactions in the gas discharge process are of particular interest since the physical mechanism of this discharge phenomenon is still unclear. While corona discharge is found in many important industrial applications, such as electrostatic precipitation and electrophotography printing [2], [3], some of its undesired effects also come in the form of radio interference, induced by corona current pulses on high voltage transmission lines. In China, there will be a demand for high voltage hybrid AC/DC transmission lines due to their high transmission capacity and shortage of land resources [4]. Since positive corona current pulse is the main contributor to the problem of radio interference, the detailed characteristics of the positive current pulses in this new form need to be explored.

Many experiments have been carried out to investigate the mechanism of corona discharge. Since in early investigations the study of corona discharge was restricted by techniques and facilities, the focus was mostly on its current-voltage characteristics and visual appearance. Zeleny measured the positive corona current with pointed conductors of different shapes and sizes, and obtained an empirical formula for current-voltage characteristics [5]. Using the current-voltage measurements at different gap distances, Kip investigated the fundamental processes occurring from the positive point-to-plane corona discharge [6]. Giao and Jordan summarized previous findings and conducted an experiment to classify the modes of corona according to visual appearance and characteristics of current pulses [7].

There are many factors that can influence the process of corona discharge, such as humidity, temperature, wind, and the geometry of electrodes and so on [8]–[11]. Although much work has been done on these characteristics of corona discharge, very little attention has been devoted to the effect of adjacent AC voltage on the characteristic of DC corona current pulse. When a DC conductor is close to an AC conductor, there is an AC electric field component on the surface of the DC conductor. Metwally developed a reduced scale model of hybrid AC and DC transmission lines, and studied the influence of interspacing and arrangement of conductors on the I–V characteristics [12]. Zhou *et al*. measured and calculated the low frequency current from hybrid AC/DC corona in a coaxial cylinder corona cage, and analyzed the evolution of space charge and the ionized electric field [13]. In their experiments, the AC conductor was in the corona, and hence, this was seen as the influence of DC voltage on AC corona discharge. Plank carried out an experiment to investigate the positive corona discharge at combined AC and DC voltage and proposed a statistical model to calculate the probability of formulating a streamer [14]. However, in Plank's study, the AC and DC voltage is simultaneously applied to the electrode, which is quite different from that of hybrid transmission lines. Clairmont *et al*. studied the effect of separation of hybrid transmission lines on the corona and field effects. They concluded that the hybrid lines can interact to produce levels of corona and electric field effects that depart from a simple linear superposition of the effects from the two transmission lines acting separately [15].

In short, previous studies on corona discharge, influenced

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Z. G. Wang (corresponding author, e-mail: wangzhenguo1229@163.com), T. B. Lu, X. Cui, and X. B. Li are with State Key Laboratory of Alternate Electrical Power System with Renewable Energy Sources, the North China Electric Power University, Beijing, 102206, China.

Huseyin Hiziroglu is with Department of Electrical and Computer Engineering, Kettering University, Flint, Michigan, 48504, USA.

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by both AC and DC voltages, have been mainly about calculation methods for ion flow field or empirical formulas for the environmental effects, such as radio interference and audio noise [16]–[20]. The detailed corona discharge modes and characteristics of current pulses in these studies have rarely been investigated. For simplicity and convenience, the influence of AC voltage on DC corona discharge was first investigated, which meant that the AC conductor in the experiment was not in corona. On the other hand, since positive corona current pulses are the predominant source of radio interference, this paper focuses on the positive corona current pulses.

This paper describes the design of a coaxial conductor-cylinder electrode system to investigate the characteristic of positive current pulses under the influence of adjacent AC voltage. A new form of current pulse patterns is discovered and the temporal characteristics of current pulses are statistically analyzed and compared with that of only DC voltage exits. The AC voltage has dual effects on the repetition frequency of positive current pulses. A theoretical explanation based on ion cloud model is presented.

II. Experiment Setup

The experimental setup aims to obtain positive current pulses under the influence of AC voltage, as shown in Fig. 1. The electrode system is composed of a cylindrical metal cage and two stainless conductors. The diameter and length of the cage are respectively 60 cm and 150 cm. The system is made up of 30 stainless steel pipes and two stainless steel rings. The diameters of the conductors are respectively 8 mm and 5 mm. To eliminate the influence of space charge from the AC conductor, the AC conductor is kept from corona discharge and an 8 mm diameter conductor is chosen to guarantee the surface electric field intensity of the AC conductor under corona onset field strength. The AC conductor is set on the axis of the cylindrical cage, and the DC conductor is between the inner side of the cage and the AC conductor. The axis is shown in Fig. 1(b). The discharge point is a small stainless steel ball embedded in the middle of the DC conductor with its surface protruding to the AC conductor. The picture of the discharge point is also shown in Fig. 1(b). The surfaces of the AC and DC conductors are smooth and have been wiped using a soft textile before the experiment to make sure that the corona discharge occurs only at the discharge point.

To obtain the corona current pulses conveniently and accurately, the low potential measuring method proposed in [21] is applied and the electrical connection is shown in Fig. 1(c). In this method, the DC conductor is connected to the ground in a series, with two matching resistors on each side. A negative DC voltage is then applied to the corona cage. The AC voltage is applied to the axis conductor, and its frequency is 50 Hz. The negative voltage source is Matsusada AU-80R15, which has the maximum output of -80 kV with a ripple of less than 0.1%. The corona current pulses are detected by an 8585C type current probe produced by Pearson Company. Its frequency response range is 1.5 kHz to 200 MHz. The oscilloscope from Tiepie Company is used to record the current pulses, and the sampling rate is set to be 200 M/s, corresponding to the data in a period of 0.167 s. The corona current pulses and AC voltage are recorded simultaneously. During the experiment, the temperature is between 12°C and 15°C, and the relative humidity is between 30% and 40%.

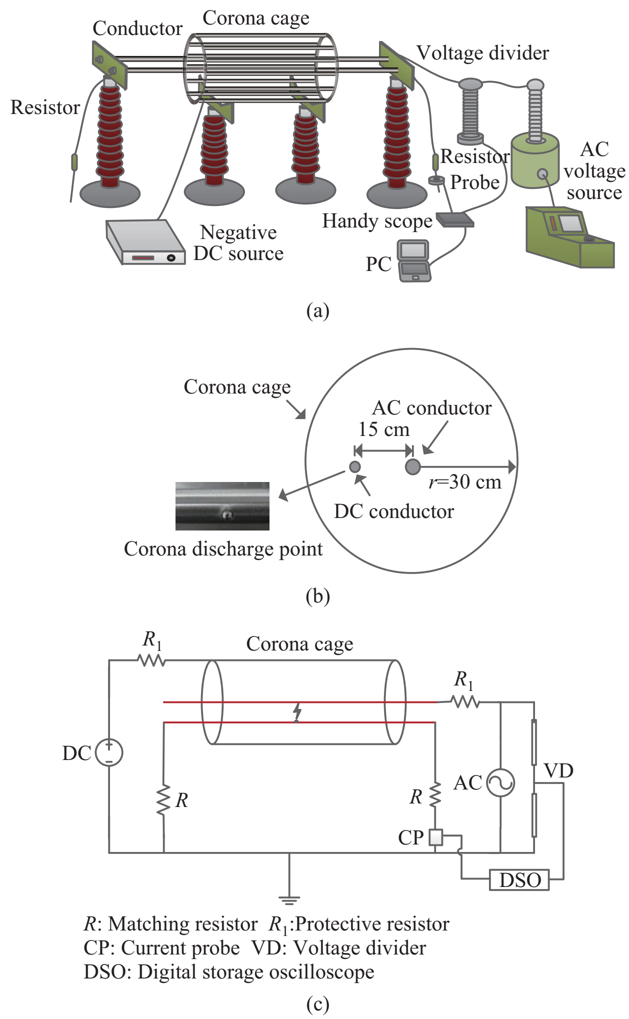

Fig. 1. Experiment Setup. (a) Layout of the platform. (b) Side view of the corona cage. (c) Electrical connection of the platform.

When DC and AC voltage coexist, the resultant electric field on the surface of corona point is time varying and probably transverses different regions of positive corona modes. Since the practical transmission lines are usually at weak corona modes [22], and also tend to avoid the breakdown between electrodes, the applied voltage is controlled below the onset of glow discharge. Since that corona discharge is determined by electric field and the space charge free surface electric field of the corona discharge point is directly proportional to the applied voltage, the relationship between the resultant electric field and the applied voltage can be obtained by calculating the electric field using FEM methods:

$$E_{\text{total}} = 10.33V_{\text{DC}} + 0.33V_{\text{AC}}. \quad (1)$$

For convenience of description, the papers and tables are presented in voltages, and the AC voltage in this paper refers to the effective value. The DC voltage covers from 60 kV to

65 kV, and the AC voltage covers from 0 kV to 12 kV. Here the ratio of AC electric field strength to that of DC component is between 0% and 6.8%.

III. Measurement Results

A. Distribution Patterns of Current Pulses

To vividly present the influence of AC voltage, the responding distribution patterns of current pulses with 0 kV and 12 kV AC voltages are shown in Fig. 2.

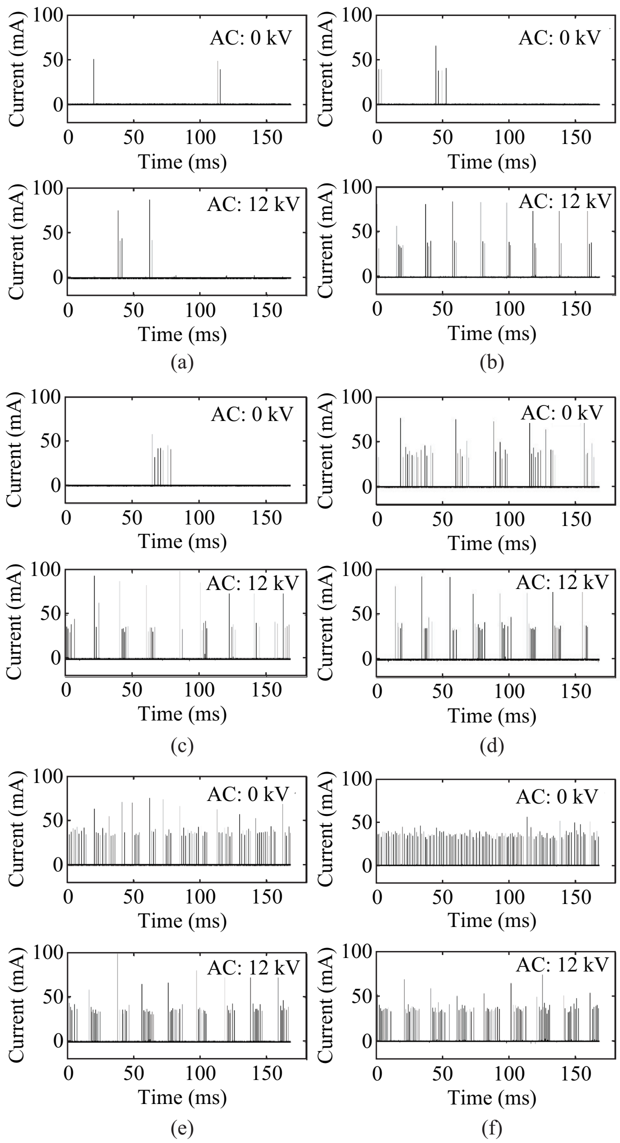

Fig. 2. Distribution patterns of positive current pulses with different DC and AC voltages. (a) DC: 60 kV. (b) DC: 61 kV. (c) DC: 62 kV. (d) DC: 63 kV. (e) DC: 64 kV. (f) DC: 65 kV.

When AC voltage is 0 kV, we see that with increase of DC voltage, the positive corona pulses first appear as isolated pulses with large time intervals. Then come burst pulse trains, which consist of one big amplitude pulse and several others of much lower amplitude, as shown in Fig. 2(b). The number of burst pulse trains and number of pulses in a burst train both increase with DC voltage. When DC voltage further increases, the big amplitude pulses disappear and the current pulses tend to be evenly distributed as shown in Fig. 2(f).

When AC voltage is 12 kV, the positive corona discharge is always in burst pulse mode due to increased DC voltage, wherein positive current pulses appear in the form of pulse trains [22]. The burst pulse trains all emerge in the negative cycles of AC voltage. This means that the repetition frequency of burst pulse trains is equal to 50 Hz, which is of the power frequency in China. The length of burst pulse train (time span of one burst pulse train) increases with the AC voltage.

One burst pulse train contains a big amplitude primary pulse and several small secondary pulses [22]. This is shown in Fig. 3 with the enlarged primary pulse. The respective DC and AC voltage is 62 kV and 12 kV. The mechanism of the occurrence of burst pulse trains is explained in [22]. The time interval between primary pulse and the following secondary pulse is relatively larger than that of between secondary pulses. The parameters of positive current pulse shape such as amplitude A, rise time t_{r}, half-wave time t_{f}, and duration time t_{d} are also defined in Fig. 3. T_i is the time interval between secondary pulses.

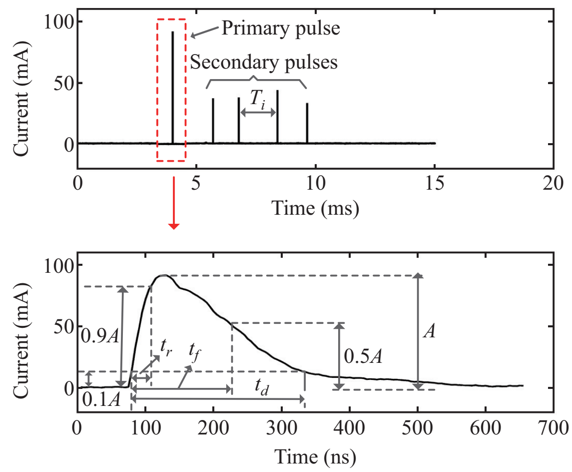

Fig. 3. One burst pulse train and the enlarged primary current pulse.

B. Temporal Characteristics of Current Pulses

To investigate the influence of AC voltage on the shape of positive current pulse, the temporal characteristics such as rise time, half wave time, duration time, and amplitude are statistically analyzed, as shown in Fig. 4. The error bars stand for deviations for respective parameters.

Under different AC voltages, the rise time, duration time, and half wave time almost remain unchanged, as shown in Fig. 4(a), Fig. 4(b), and Fig. 4(c). They are respectively about 27 ns, 290 ns, and 160 ns. When the DC voltage is below 63 kV, the average amplitude increases slightly with AC voltages, and as the DC voltage becomes larger, the amplitude almost retains unchanged; hence AC voltage has no obvious effects on the shape of positive current pulses. The same results were obtained by previous study about the influence of DC voltage on the parameters of positive corona current pulses [22].

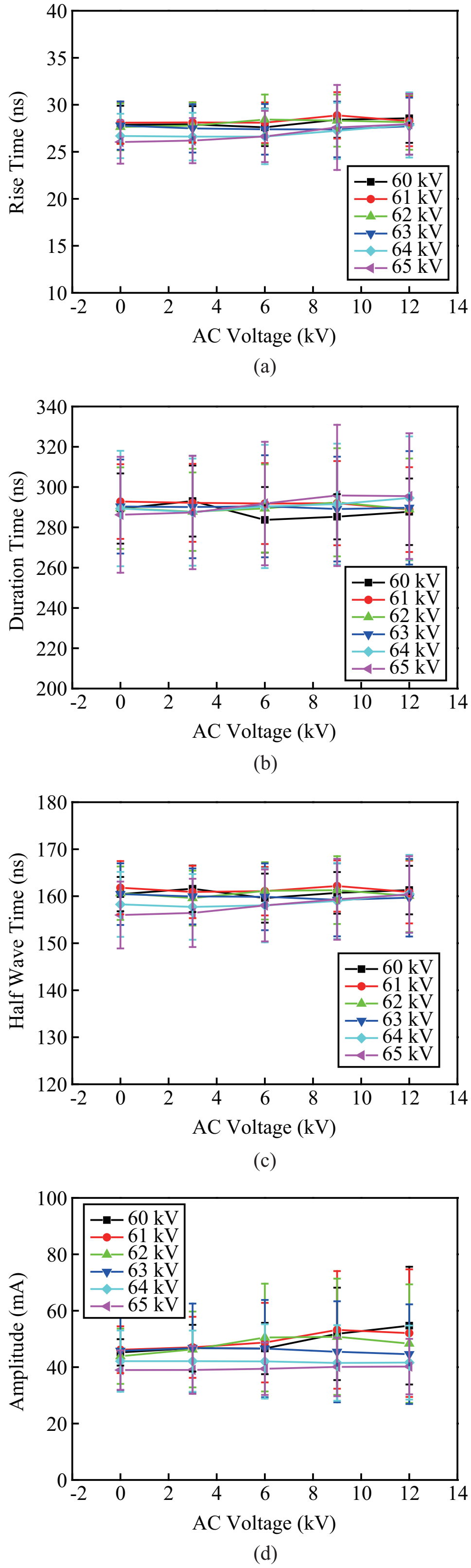

Fig. 4. Temporal characteristics of positive corona current pulses. (a) Rise time. (b) Duration time. (c) Half-wave time. (d) Amplitude.

C. Repetition Frequency

The repetition frequency is defined as the number of pulses dividing the corresponding recording time. Fitting curves for the repetition frequency with different AC voltages are shown in Fig. 5. When AC voltage is below 9 kV, the trend of fitting curves is of the same form as that of only DC voltage exists [23]. That is first increasing slowly then rapidly with the rise of DC voltage. However, with the increase of AC voltage, a linear relationship exited between the repetition frequency and the DC voltage. On another side, under fixed DC voltage the AC voltage has a dual effect on the repetition frequency. That is when DC voltage is below 64 kV, the repetition frequency increases with AC voltage and when DC voltage exceeds 64 kV the repetition frequency decreases with the increase of AC voltage.

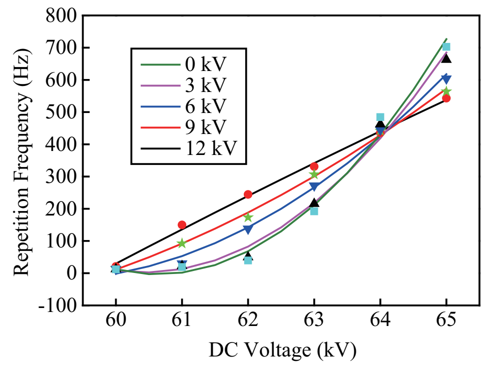

Fig. 5. Repetition frequency of current pulses.

When AC voltage is below 12 kV, the repetition frequency can be expressed as

$$f = K(V_{\mathrm{DC}} - V_0)^2 \tag{2}$$

where K is the proportional constant, V_0 is the coefficient obtained by numerical fitting, V_{DC} is the DC applied voltage. The fitting curves are shown by the solid lines in Fig. 5. When AC voltage is up to 12 kV, a linear relationship can better describe the variance of repetition frequency with the increase of DC voltage. The parameters of empirical formulas are listed in Table I. With the increase of AC voltage the proportional constant K and coefficient V_0 become smaller, and the fitting curve is inclined to be a straight line.

TABLE I
NUMERICAL FITTING RESULT OF THE RELATION BETWEEN REPETITION FREQUENCY AND DC VOLTAGE

AC Voltage (kV)	K (Hz/MV^2)	V_0 (kV)
0	38.3	60.6
3	32.7	60.4
6	17.4	58.9
9	7.96	55.5

When AC voltage is 12 kV, the empirical formula for the repetition frequency is

$$f = 101.49V_{\mathrm{DC}} - b \tag{3}$$

where b is 605.5 Hz.

D. Secondary Pulse Time Intervals

Fig. 6 shows the relationship between time intervals of secondary pulses and the AC voltage.

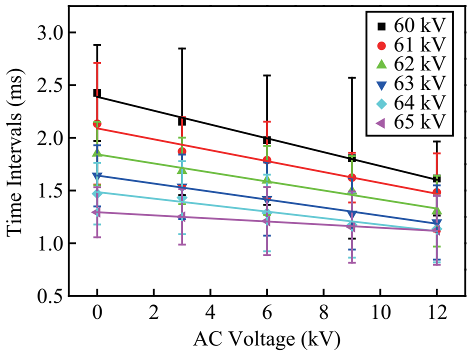

Fig. 6. Time intervals between secondary pulses.

We can see that the secondary pulse time interval decreases linearly with AC voltage and they are in the range of 1 ms to 3 ms. With the increase of DC voltage, the slope of the fitted lines becomes smaller. The linear relationship between the time intervals and the AC voltage can be expressed as

$$T_i = kV_{\text{AC}} + c \tag{4}$$

where V_{AC} is the AC applied voltage, c is the numerical fitting coefficient in millisecond. The associate parameters are listed in Table II.

TABLE II
NUMERICAL FITTING RESULT OF THE RELATION BETWEEN SECONDARY PULSE TIME INTERVALS AND AC VOLTAGE

DC Voltage (kV)	k (ns/kV)	c (ms)
60	−0.066	2.39
61	−0.052	2.09
62	−0.043	1.84
63	−0.038	1.64
64	−0.030	1.48
65	−0.015	1.29

In previous study about the effect of DC voltage on the secondary pulse intervals, the following empirical formula was obtained [22]

$$T_i = \frac{\alpha}{(V_{\text{DC}} - V_0)} \tag{5}$$

where a is the proportional constant, V_0 is the coefficient obtained by numerical fitting, which is believed to be the inception voltage. It shows that the adjacent AC voltage has much more uniform effects on the secondary time intervals of positive corona current pulses.

E. Distribution of Pulse Amplitude

Under DC voltages positive current pulse amplitude roughly has a bell-shaped pulse height distribution [24], [25]. Yin *et al*. observed a lognormal distribution of positive current pulse amplitude [23]. In our experiment, the histogram of pulse amplitudes at 65 kV DC voltage and 9 kV AC voltage is shown in Fig. 7. The red line is the fitted normal distribution and it can be seen that the distribution of pulse amplitude agrees quite well with Gaussian distribution. The probability density distribution function can be defined as

$$P(A) = \frac{1}{\sigma\sqrt{2\pi}} \exp\left(-\frac{(A-\mu)^2}{2\sigma^2}\right) \tag{6}$$

where μ and σ are the mean and variance of pulse amplitudes. Fig. 8 shows the fitted probability density distribution functions with different AC and DC voltages. The fitted bell curves have similar peak and average values. It can be concluded that the AC voltage has no obvious influence on the distribution of positive current pulse amplitude. When DC voltage is lower than 61 kV, due to the randomness and the low repetition frequency of current pulses, no suitable functions can be found to describe the distribution of current pulse amplitudes.

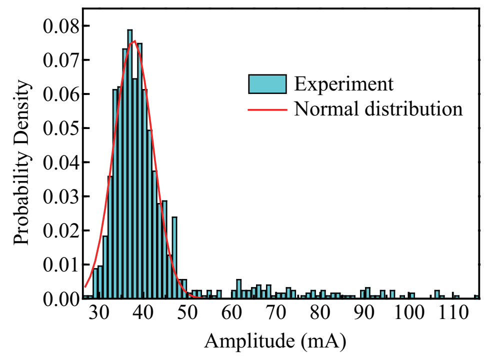

Fig. 7. Probability density distribution of corona pulse amplitudes (DC voltage = 65 kV, AC voltage = 9 kV).

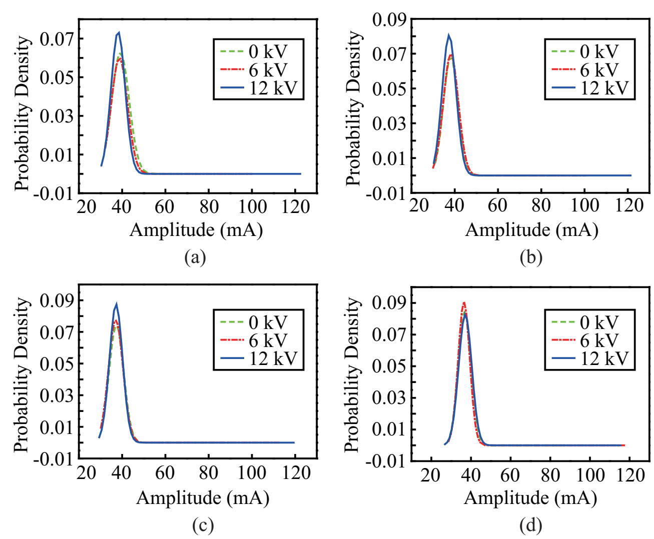

Fig. 8. Fitted probability density distribution of current pulse amplitudes with different AC and DC voltages. (a) DC voltage: 62 kV. (b) DC voltage: 63 kV. (c) DC voltage: 64 kV. (d) DC voltage: 65 kV.

IV. DISCUSSION

Due to the complexity of an accurate model to describe the process of positive DC corona discharge, a simplified ion clouds model proposed in [22] is used to interpret the characteristics of the positive corona current pulses in this experiment. As shown in Fig. 9, once one current pulse exists, a quantity of positive ions proportional to the amplitude of current pulses emerges in the ionization region (adjacent to vicinity of corona point) and is driven to the outer space by the electric field force. For the low mobility of positive ions, the ion cloud corresponding to respective pulses coexists in the interspace between electrodes. On the other side, the presence of positive space charges weakens the electric field on the surface of corona point; thus it blocks the development of successive current pulses.

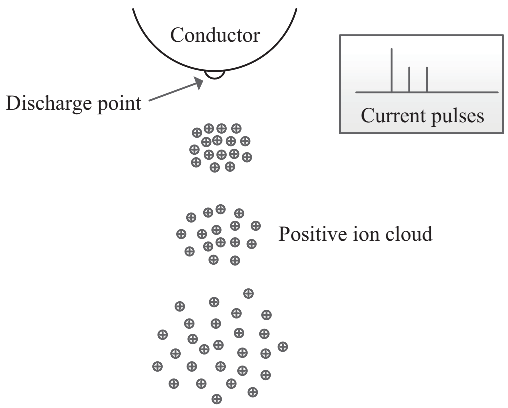

Fig. 9. Schematic diagram of the ion cloud model.

The repetition frequency of current pulses for positive DC corona discharge has been studied extensively [23], [26]. They are in the same form as represented by the green line in Fig. 5, which shows that the repetition frequency increases first slowly and then rapidly with DC voltage. With further increase of DC voltage, the positive corona discharge will go into a steady corona mode that the repetition frequency changes slightly with DC voltage [22]. It can be explained that at relatively lower DC voltage, the electric field in the space is not strong enough to rapidly clear the positive space charges produced by preceding current pulses; hence, the repetition frequency increases slowly with DC voltage. When DC voltage becomes higher, the space charge quickly clears and many more current pulses appear. In steady corona mode, the current pulses emerge with small time intervals, and a large quantity of positive space charges exist, which further obstructs increase of current pulses.

Combined with AC voltage, the surface electric field on the corona discharge point is superimposed with the AC component, as illustrated in Fig. 10, where the corresponding AC and DC voltage is -63 kV and 12 kV, respectively. The electric field is calculated using the finite element method (FEM) based software COMSOL. The green dotted line denotes the

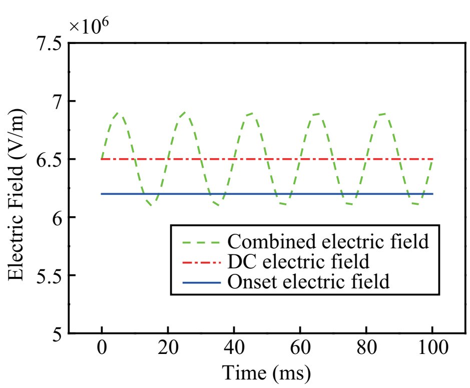

Fig. 10. Illustration of electric field on the surface of DC conductor.

combined electric field, and the red dash dot line and blue solid line are, respectively, the DC component and the onset value. Here, the onset is defined as the occurrence of isolated corona current pulses. It is observed that the surface electric field of the corona discharge point is reduced and strengthened corresponding to the opposite half cycles of the AC voltage and may traverse below the onset electric field.

As concluded from Fig. 5, the repetition frequency increases first slowly and then rapidly with DC voltage, representing a nonlinear relationship. Consequently, in a full cycle of the combined electric field, the positive half cycle will produce more current pulses than that reduced in the negative half cycles, which results in the overall increase of repetition frequency observed in Fig. 5 when DC voltage is below 64 kV.

With increase of DC voltage, the electric field is considerably above the corona onset critical value, and the repetition frequency changes linearly with the electric field. Thus, there is a balance between the promotion and reduction effects corresponding to the negative and positive half cycles of the AC voltage that the repetition frequency changes slightly with different AC voltages, as shown in Fig. 5 where the DC voltage is 64 kV. When DC voltage is up to 65 kV, as shown in Fig. 2(f), the positive corona discharge is in steady corona mode, which shows that the increase of electric field on the surface of corona point barely promotes the generation of current pulses. Consequently, in negative half cycles of AC voltage, there is a small increase in the repetition frequency. On other hand, in positive half cycles much more current pulses are depressed. This explains the decrease in repetition frequency caused by AC voltage when DC voltage is 65 kV. The decreasing proportional constant K can be ascribed to the above dual functions of AC voltage. In addition to the effect of periodic electric field, the AC conductor also absorbs and repels the positive ion space charges in negative and positive half cycles, which in turn affects the distribution and clearance of positive ion space charges. This phenomenon needs further detailed study. The dual effect of AC voltage on the repetition frequency of positive corona current pulses reveals that by depending on the intensity of positive corona discharge, the adjacent AC voltage can increase or reduce the radio interference level from DC transmission lines.

As to the time intervals between secondary pulses, a linear relationship is obtained. When only DC voltage exists and with increase of the DC voltage, the electrostatic field near the discharge point becomes larger and speeds up the clearance of space charges. Hence, the time intervals become smaller. However, the smaller time interval means more current pulses, namely, more space charges produced in the air gap, which results in the relation denoted by (5). When AC voltage exists, the positive half cycles obstruct the occurrence of positive current pulses, which reduces the amount of space charge. The offset effect of the space charge on the electric field becomes smaller. Accordingly, the time interval between secondary pulses is more sensitive to the increase of AC voltage, which results in a linear decrease of secondary pulse intervals with AC voltage.

V. Conclusion

The influence of adjacent AC conductors on positive corona current pulses is studied. The AC voltage has no obvious effect on the temporal characteristics of positive current pulses, such as rise time, duration time, half wave time, and amplitude. As to the repetition frequency, depending on the DC voltage, the AC voltage first raises the repetition frequency and then depresses it, which means that the AC voltage has two sides effect on the intensity of positive corona discharge. The distribution of current amplitude is a good fit to normal distribution and the AC voltage has little influence on the parameters of the distribution. A theoretical explanation based on ion cloud model is presented to reveal the mechanism of the positive DC corona discharge under the influence of AC voltage.

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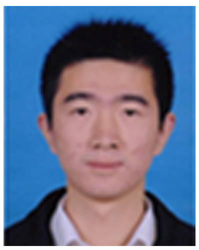
Zhenguo Wang received his B.Eng. degree in electrical engineering in Dalian Maritime University, Dalian, China, in 2012. He is currently pursuing the Ph. D. degree in North China Electric Power University. His main research interest is electromagnetic compatibility in power systems.

Tiebing Lu received his B.Eng. and M.Eng. degrees in electronic engineering from Xian Jiaotong University, in 1991 and 1994, respectively, and the Ph.D. degree in electrical engineering from North China Electric Power University in 2002, Baoding, China. He is currently a Professor in the School of Electrical and Electronic Engineering, North China Electric Power University. His research interests are electromagnetic compatibility in power systems and the numerical methods of the electromagnetic fields.

Xiang Cui (M'97–SM'98) received his B.Eng. and M.Eng. degrees in electrical engineering from North China Electric Power University, Baoding, in 1982 and 1984, respectively, and the Ph.D. degree in accelerator physics from China Institute of Atomic Energy, Beijing, China, in 1988.

He is currently a Professor and the Head of the electromagnetic fields and electromagnetic compatibility laboratory, North China Electric Power University. His research interests include computational electromagnetics, electromagnetic environment and electromagnetic compatibility in power systems, insulation, and magnetic problems in high-voltage apparatus. Prof. Cui is a Standing Council Member of the China Electro-technical Society, a Fellow of Institution of Engineering and Technology, a member of CIGRE C4.02.01 Working Group (electromagnetic compatibility in power systems). He is also an Associate Editor of IEEE Transactions on Electromagnetic Compatibility and a member of the Editorial Advisory Board of the International Journal for Computation and Mathematics in Electrical and Electronic Engineering.



Xuebao Li received his B.Eng. and Ph.D. degrees from North China Electric Power University, Beijing, China, in 2011 and 2016. His main research interest is electromagnetic compatibility in power systems.

Huseyin Hiziroglu (M'80–SM'02) received his B.Eng. degree in electrical engineering from Gazi University, Teknikokullar, Turkey and M. Eng. degree from Middle East Technical University, Ankara. He received his doctoral degree from Wayne State University, Detroit, USA. His research interests include gas discharge and dielectric insulation.