Prediction of radio interference from HVDC transmission lines based on corona discharge characteristics

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Abstract: Many research works have proved that it is viable to predict the radio interference (RI) of high-voltage alternating current transmission lines by corona cage test. However, it is uncertain whether the same method can be adopted for RI prediction of high-voltage direct current (HVDC) transmission lines, since the corona performance of HVDC lines is obviously affected by the widely distributed space charge. In this study, the detailed corona current characteristics, such as the current pulse amplitude, rise time, half-wave time, and repetition frequency are systematically studied by the reduced-scale experiment and the relationship between the average corona current and the RI excitation current is confirmed. Furthermore, based on the experimental study, a method for predicting the RI level of HVDC transmission lines by the corona cage test is proposed. The RI level of a ±800 kV bipolar HVDC transmission line is predicted and compared with the measured result, which verifies the validity of the proposed method.

1 Introduction

CORONA performances such as radio interference (RI) and audible noise (AN) are important restrictions for constructing new transmission lines [1]. Corona cages are usually used to study and predict the corona performance of high-voltage (HV) transmission lines. As there is no widely distributed space charge existing around the HV alternating current (HVAC) conductors, an excitation function, which is independent of conductor configurations, is defined to evaluate the RI generation quantities of HVAC transmission lines [2–4]. Therefore, the cage result is available for RI prediction of actual HVAC lines [5, 6]. However, since the space charge greatly affects the corona discharge of direct current (DC) conductors, it is hard to define a configuration-independent excitation function for HVDC transmission lines [7], which means that the cage result cannot be directly used.

Thus some scholars have tried to make the RI prediction by monitoring overhead transmission lines [8–12]. However, using a corona cage is the most convenient and economical way to study corona performance. So lots of scholars, till now, have conducted researches on the corona cage test of HVDC conductors. Djeumen et al. [13] measured the space charge distribution in a corona cage under the influence of different atmospheric conditions. Liao et al. [14] also measured space charge in negative corona on a laboratory-scale corona cage. Nakano and Sunaga [7] proposed that corona cage tests were available for RI prediction based on the assumption that RI quantities were determined by the maximum bundle gradient in the presence of space charge. Otto and Reader [15] found that a small corona cage could not be used to accurately predict the RI performance of actual HVDC transmission lines. These studies in some extent proved that it was difficult to convert the corona cage result to actual line result under DC voltage.

The characteristic of corona current pulse is the foundation in studying the relationship between corona cage corona and actual line corona. This characteristic has been studied by many scholars. Trichel [16] first discovered the periodically regular corona pulse waveform which is called Trichel pulse. Loeb [17] further developed the theory of Trichel pulse and categorised the negative corona mechanism and positive corona mechanism into three phases and four phases, respectively. Denholm [18] studied the positive corona current features, the peak value and pulse repetition frequency. However, these studies were limited to qualitative descriptions of the corona current characteristics.

Recently, more and more specific corona currents were studied. Li et al. [19] studied the statistical characteristic in time-domain of DC corona and AN from the conductor in corona cage. Bian et al. [20, 21] studied the corona current characteristics under different air pressures and humidities. Yin et al. [22] made a research on the detailed characteristics of positive corona current for coaxial geometry electrodes, such as the current pulse amplitude, rise time, half-wave time and repetition frequency. Liu et al. [23] found the characteristics of intermittent positive corona current pulse and provided a reasonable explanation for this intermittent characteristics. Liu et al. [24] measured a large amount of corona current waveforms based on the largest outdoor HVDC corona cage, and found related statistical regularities between a corona current spectrum and an AN spectrum. Liang et al. [25] measured corona discharge characteristics for HVDC conductors with different height to the ground, but he mainly focused on the relationship between corona inception voltage, conductor structure and height. Mo et al. [26] studied the corona characteristics between the stranded and the shaped wires of HVDC transmission lines. Pfeiffer and Frank [27], Pfeiffer et al. [28] studied the relationship between the corona and the rain drop in raining condition.

Although a large amount of valuable work has been reported on the corona current characteristics, few scholars investigated the corona current characteristic relationship between corona cage and actual line, which may be the key to investigating the RI of HVDC transmission line based on the corona cage test. In this paper, a reduce-scale experimental platform is set up and the detailed corona current features such as current pulse amplitude, rise time, half-wave time and repetition frequency are systematically studied in both corona cages and actual lines. Furthermore, the correlations among the average corona current, the RI excitation current and pulse repetition frequency are discovered and confirmed based on the experimental results. Finally, based on the corona cage test results, a method for predicting RI from HVDC lines is proposed and validated by the measurement on Xiangjiaba-Shanghai ±800 kV bipolar HVDC transmission line.
As for HV AC conductors, the equivalence between the RI quantity measured in the cage and those on the line is based on the Shockley–Ramo theorem, the current induced in the electrode due to a particular excitation function. Therefore, the current on the line can be predicted as

\[ i_l = \frac{C_c}{C_c + \Gamma_l} \cdot i_c \]

(6)

However, as for HVDC lines, the existence of space charge region will significantly affect the electric field around the conductor. The space charge distribution around conductors in the corona cage is significantly different from that above the ground [31]. Therefore, the excitation functions \( \Gamma_l \) and \( \Gamma_c \) cannot be simplified as the same. Equation (6) is not valid for HVDC conductors, more studies should be carried out.

3 Reduced-scale test

3.1 Experimental platform

The experimental platform consists of two systems as shown in Fig. 2a, one is the scaled conductor-plane test system and the other is the scaled cage test system. Both systems contain one corona onset section and two conjunct sections. The corona onset section is used to produce corona in both cage and line-to-plane experiments; the two conjunct sections are the power supply section providing energy for coronas and current measuring section, respectively. The measuring section can measure as well as record the corona pulse characteristics in both time domain and frequency domain. The photo of the real platform is illustrated in Fig. 2b.

The corona onset section for corona cage tests include a series of one-meter long corona cages, whose radii are 10, 20 and 30 cm, respectively. The corona onset section for corona line tests includes two insulating brackets designed to fix the reduced-scale lines so that the line-to-plane height can be adjusted from 20 cm to 1 m. The conductors used in both cage and line tests are the same and the radii are 0.4, 0.6 and 0.8 mm. The power supply section consists of a rectified DC supply which can provide high DC voltages and an inductive trap providing high DC voltages and blocking the interference from the power source. The current measuring section is the most complicated section in the experiment facilities, comprising a coupling circuit to decouple the radio frequency components of corona currents, an electromagnetic interference (EMI) receiver containing the CISPR standard and the peak (P), quasi-peak (QP) as well as root-mean-square (RMS) detectors, a Faraday's cage to protect a high-speed data acquisition card and a non-inductive resistor in its interior, a photoelectric conversion device with an optical fibre to transfer as well as deliver.
the current signals, and a computer to record the corona current characteristics. The high-speed data acquisition card has two channels and a 200 MHz sampling frequency which is high enough to analyse the radio frequency components of corona currents. The non-inductive resistor, whose resistance is 400 Ω, is connected in series with the line conductor to measure the corona currents. In order to verify the validity of the measurement system, measured waveforms of a typical positive corona current pulse from the non-inductive resistor and a current sensor are compared in Fig. 3. In the figure, \( A \) represents the peak value of the current amplitude, \( t_r \) is the rise time, \( t_h \) is the half-wave time. The similar waveforms show that the measurement system has a good performance in measuring corona current.

As demonstrated by Maruvada et al. [31], the RI is mostly induced by positive corona on bipolar HVDC transmission lines, therefore the focus point in this paper is the positive corona discharge.

3.2 Time-domain results

The typically measured corona pulses when the conductor radius is 0.4 mm are shown in Figs. 4 and 5. In order to provide a common basis for any comparison, instead of using applied voltage to the conductor as the independent variable, the corresponding space-charge free surface electric field is considered as the independent variable. When the static electric field is 100 kV/cm, the corona current pulses change obviously with the size of the electrode. As demonstrated in Figs. 4a–c, with the increases of line-to-plane height \( h \), the repetition frequency of the current pulses reduces evidently. The explanation for this observation might be that the space charge movement distance for larger \( h \) is longer than that in smaller \( h \), and the larger one accumulates more charges resulting in the decrease of the total electric field. This decrease in total electric field weakens the discharge on the conductor surface. From another perspective, the average charge velocity is smaller due to the decrease of the total electric field, the region between line and plane can accumulate more charges, leading to further decrease of total electric field and the attenuation of discharges on the conductor surface. These two factors, together, result in less current pulses in a larger \( h \) model. For the same reasons, with the increases of corona cage radius \( R \), the repetition frequency of the current pulses reduces apparently which has been demonstrated in Figs. 5a–c. Moreover, the current pulse repetition frequency in the corona cage is usually much higher than that on the actual line.

Although the pulse repetition frequency decreases apparently with the increase in the line-to-plane height or the corona cage radius, the average pulse amplitude almost keeps unchanged at a constant value of a little >20 mA in both actual lines and corona cages, as illustrated in Figs. 4 and 5. Experiments are repeated more than ten times and the statistical deviations are illustrated in Fig. 6.

As shown in Fig. 6a, the maximum amplitude of corona pulses increases with the electric field but the average amplitude remains almost the same. As either the line-to-plane height or the cage radius increases, the maximum amplitude reduces to some extent, however, the average amplitude changes on a negligible scale.
As the electrode spacing changes, the average rise time and half-wave time of corona currents change slightly, as shown in Figs. 6b and c. The average rising time is about 50 ns and the average half-wave time is around 160 ns.

As demonstrated in Fig. 6d, when the electric field increases, the repetition frequency increases obviously. Additionally, the electrode size greatly affects the repetition frequency of corona pulses. When either the line-to-plane height or the cage radius increases, the repetition frequency reduces evidently under the same electric field condition. The repetition frequency of corona currents in the cages is much larger than that on the reduced-scale lines. However, this disparity grows smaller as the cage radius increases.

The effect of the conductor radius on the corona characteristics is also studied. Similarly, the average amplitude, rising time and half-wave time of corona pulses change slightly with the variation of the conductor radius. However, the repetition frequency changes obviously with the conductor radius, as shown in Fig. 7. The reason for this observation can be explained in two aspects. On one hand, the conductor with a larger radius may have more discharge points on the conductor surface when the conductor surface roughness and conductor surface electric field are the same. On the other hand, the electric field is stronger in the surrounding area of larger radius conductors when the conductor surface electric field is identical, leading to a higher velocity of the ambient electrons and thus the ionisation process is easy to engender. Similar corona cage test results are also mentioned in [32].

In conclusion, the electrode configuration greatly affects the repetition frequency of corona pulses. Therefore, the corona currents measured in the cage cannot be directly equivalent to those on the actual line. In the meanwhile, the statistics of a single corona pulse including the average amplitude, rising time and half-wave time are slightly affected by the electric field and the electrode configuration.

3.3 Frequency-domain result

The radiofrequency components measured by the EMI receiver with the P, QP and RMS detectors are shown in Fig. 8. The correction factors for the circuit attenuation and resistive network are considered. As shown in the figure, the RMS responses are much smaller than the P and QP responses. For the purpose of comparison, the corresponding FFT values are also given. The RI results measured with a 200 Hz bandwidth, which are much lower than that with a 9 kHz bandwidth, are closer to the FFT value. According to the CISPR standard [32], QP values are recommended to evaluate the RI level. However, the excitation function, which is defined to describe the power spectral density of corona currents on the transmission line, should be expressed only in terms of RMS values. In the past two decades, RMS detectors have been widely adopted in the RI measurement [33]. In this paper, evaluating the RI performance of the transmission line by RMS values is recommended.

The 0.5 MHz RMS components of corona pulse current which is defined as the RI excitation current, measured in corona cages as well as actual lines, are shown in Fig. 9. When the electric field is

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Fig. 6 Statistics of corona current pulses
(a) Pulse amplitude, (b) Rise time, (c) Half-wave time, (d) Repetition frequency

Fig. 7 Repetition frequency of current pulses in reduced-scale line corona of different conductor radii

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line test, the RI level is higher when the conductor height is lower.

RMS values decrease rapidly. As for the cage test, the RI level is

According to the previous conclusion, the waveform of a single
corona pulse remains unchanged. It is assumed there are
consecutive corona pulses; \( n \) is the number of pulses in the sequence,
then (7) can be modified as

\[
I_c = \frac{\int_0^{nT} i(t) dt}{T_{all}}
\]

where \( n \) is the number of pulses in the sequence, \( t_s \) is a single
corona pulse duration time; \( i(t) \) is the single corona pulse waveform function; \( T_{all} \) is the average time interval between two
consecutive corona pulses; \( f \) is the pulse repetition frequency and \( A \) is the scale factor. The factor \( A \) represents the average charge
provided by a single corona pulse. From (8), it can be seen that a
single corona pulse waveform can be used to calculate the \( I_c \) of the
entire pulse sequence. The relationship between the average corona
current \( I_c \) and the pulse repetition frequency \( f \) is acquired.

The RI excitation current, an important characterisation of the
corona discharge intensity, is generally measured by EMI receivers. To find out the relationship between the RI excitation current and the
current repetition frequency, a simulation for the receivers’
measurement process is established. Substantially, this
measurement process is a filtering process and furthermore, the
receiver can be simplified to a Hanning band pass filter [34] whose
characteristic function is given as

\[
H(f) = \begin{cases} 
0.5 - 0.5\cos\left(\frac{2\pi(f - f_L + \frac{f_B}{2})}{2f_B}\right) & f_L \leq f \leq f_U \\
0, f \notin (f_L, f_U) & \end{cases}
\]

where \( f_B = 0.5 \text{ MHz} \) is the filter centre frequency; \( f_L = 9 \text{ kHz} \) is the
lower cut-off frequency and \( f_U = 0.5045 \text{ MHz} \) is the upper cut-off frequency.

The filtered current \( i \) is defined as

\[
i_t = \text{Re}(\mathcal{F}^{-1}(H(f_s)\mathcal{F}(i)))
\]

where \( \mathcal{F} \) is the fast Fourier transform, \( \mathcal{F}^{-1} \) is the inverse fast
Fourier transform. Similarly as (8), the RMS value of \( i_t \) can be expressed as

\[
I_{RMS} = \sqrt{\frac{\int_0^{nT} i_t^2(t) dt}{T_{all}}} = \sqrt{\frac{n \int_0^{T} i_t^2(t) dt}{nT_{av}}} = \sqrt{\frac{\int_0^{T} i_t^2(t) dt}{T_{av}}} = B \sqrt{f}
\]

where \( I_{RMS} \) is the RMS value of RI excitation current; \( T_{all} \) is the
duration time of the pulse sequence, \( n \) is the number of pulses in the sequence, \( T_I \) is the duration time of filtered current \( i_t \); \( f \) is the
repetition frequency of \( i_t \), which is also the repetition frequency of corona current \( i(t) \); \( B \) is the scale factor and \( B^2 \) represents the RI
component of average power provided by a single corona pulse.

To confirm (8) and (11), the relationships between measured
average corona current \( I_0 \), measured RMS value \( I_{RMS} \) and the
current pulse repetition frequency \( f \) are shown in Fig. 10. It is obvious that the average corona current \( I_0 \) varies linearly with the
increase of frequency and meanwhile the RMS value of filtered corona current \( I_{RMS} \) presents a linear dependence with \( \sqrt{f} \). This
relationship is universal for all electrode configurations.

Once the (8) and (11) are confirmed, the correlation between \( I_0 \)
and \( I_{RMS} \) can be rewritten as

\[
I_{RMS} = \frac{B}{\sqrt{A}} \sqrt{I_0}
\]

For corona cages and reduced-scale lines, respectively, (12) can be expressed as

\[
I_{RMS,1} = \frac{B_1}{\sqrt{A_1}} \sqrt{I_{0,1}}
\]
where $B_l, A_l$ and $B_c, A_c$ are the scale factors for reduced-scale lines and corona cages respectively; $I_{0,c}, I_{RMS,c}$ and $I_{0,l}, I_{RMS,l}$ are the average corona current and the RMS value of RI excitation current for reduced-scale lines and cage coronas, respectively.

As already mentioned in (8) and (11), the factor $A$ represents the average charge provided by a single corona pulse and the factor $B^2$ represents RI component of average power provided by a single corona pulse. Therefore, the parameters $A$ and $B$ depend only on the waveform of a single corona current pulse. Moreover, as shown in Fig. 6, whether the electric field or the electrode configuration changes, the average amplitude, rise time and half-wave time of corona pulses practically remain unchanged. Therefore, if the surface condition of the conductor and ambient conditions are same, the waveform of a single current pulse is almost the same whether in line coronas or in cage coronas. This result can be expressed as

$$A_l \approx A_c, B_l \approx B_c$$  

According to (13), (14) and (15), the relationship between $I_{RMS,l}$ and $I_{RMS,c}$ can be represented as

$$I_{RMS,l} = \sqrt{I_{RMS,c}}$$  

Based on the measured experimental results of $I_{0,c}, I_{RMS,c}$ and $I_{0,l}, I_{RMS,l}$, the further comparison between the ratio of $I_{RMS,l}/I_{RMS,c}$ and the square root ratio of $I_{0,l}/I_{0,c}$ is demonstrated in Fig. 11. The measured values with subscript $c$ are acquired from corona cage results for different radii of 20, 30 and 40 cm. The measured values with subscript $l$ are acquired based on the test results from the reduced-scale line of height 20 cm. It is obvious that among all electrode configurations, the square root ratio of average corona current matches with the corresponding ratio of RI excitation current well. Besides, the result of $C_l/C_c$ which presents the corona current relationship between the cage coronas and line coronas as shown in (6), is also provided as a contrast. As shown in Fig. 11, it has been clearly demonstrated that because the neglecting of the space charge, the traditional excitation function cannot be used directly in DC corona cage test, otherwise a misguiding of much larger line excitation current would mislead a much larger predicted corona level in transmission lines. This observation is consistent with the research of Maruvada et al. [33].

Based on the (16), steps to confirm the relationship of excitation current from corona cage to transmission lines. In order to obtain the average corona current $I_{0,c}$ and $I_{0,l}$ in step 3 and step 4, an effective numerical method should be used. The calculation process includes two parts, the first step is solving the ion-flow field around the conductor, the second step is calculating the current from corona cage to transmission lines. In order to obtain the effective method, the actual line RI excitation function can be calculated as

$$I_{RMS,l} = \frac{I_{RMS,c}}{\sqrt{I_{RMS,c}}}$$  

Step 2: Among the corona cage test results, the ones with the same space-charge-free surface electric field values as the actual lines are selected as the $I_{RMS,c}$.

Step 3: $I_{0,c}$ can be obtained by corona cage test or numerical method.

Step 4: $I_{0,l}$ can be obtained by numerical method.

Step 5: Based on (16), the actual line RMS value of RI excitation current $I_{RMS,l}$ can be calculated as

$$I_{RMS,l} = \frac{20\log_{10} I_{RMS,c}}{\frac{I_{RMS,c}}{I_{RMS,l}}} = 10\log_{10} I_{RMS,c} + 10\log_{10} \frac{I_{RMS,c}}{I_{RMS,l}}$$  

where $I_{RMS,l}$ is the decibel of $I_{RMS,c}$. In comparison, for the traditional method, the actual line RI excitation function can be calculated as

$$I_{RMS,l} = 20\log_{10} I_{RMS,c} + 20\log_{10} \frac{C_l}{C_c}$$  

5 Calculation of average corona current

Equation (17) provides a method of converting the RI excitation current from corona cage to transmission lines. In order to obtain the average corona current $I_{0,c}$ and $I_{0,l}$ in step 3 and step 4, an effective numerical method should be used. The calculation process includes two parts, the first step is solving the ion-flow field around the conductor, the second step is calculating the average corona currents based on the results from step one.

Lots of methods for solving the ion-flow field have been proposed. Liu et al. [34] calculated space charge density in negative corona based on finite-element modelling and sound pulse method. Liu and Dinavahi [35] used the finite-difference method to calculate the ionised field of HVDC lines. Other methods are improved upstream meshless method [36], finite-difference-based flux tracing method [37] and characteristic method [38].

This paper uses the time-domain finite volume method to solve the ion-flow field [39]. The ion-flow field of the HVDC transmission line and the governing equations for the model used are as follows.

The Poisson’s equation is

$$\nabla^2 \Phi(t) = -\frac{\rho'(t) - \rho(t)}{\varepsilon_0}$$  

The ion current densities satisfy

$$j'(t) = \rho'(t) \mu''(t) + W(t)$$  

The current continuity equations are

$$\frac{d\rho}{dt} = -\nabla \cdot j'(t) - R\rho'(t)$$

$$\frac{d\rho}{dt} = \nabla \cdot j'(t) - R\rho'(t)$$

The setup of boundary and convergence criterion refers to [39]. The Poisson’s equation and current continuity equations can be solved by the following approach as shown in Fig. 12. This approach has two layers of loops. The inner loop first calculates the Poisson’s equation by FEM method after initialising the charge density on the conductor surface; then uses the FVM to solve the current continuity equations and finally adjusts the charge density on conductor surface according to the Kaptzov hypothesis. The outer loop would not end until the required simulation time is
achieved or the ground-level electric field is stable. The outer loop makes this approach has a stable and accurate result.

Once the calculating of ion-flow field is completed, the average corona currents can be computed by the Shockley–Ramo theorem as

\[ I_0 = \sum_{i=1}^{K} q_i^+ E_{i0} \cdot v_i^+ - q_i^- E_{i0} \cdot v_i^- \] (24)

where \( I_0 \) is the average corona current; \( q_i^+ \) and \( q_i^- \) are the positive and negative charges in the \( i \)th element of finite-element mesh; \( E_{i0} \) is the nominal electric field in the \( i \)th element when a unit potential is applied to the conductor; \( v_i^+ \) and \( v_i^- \) are the velocities of positive and negative charge, respectively.

The experimental result and calculated result of average corona currents in all kinds of electrode configuration are compared in Fig. 13. The calculated result is in close agreement with the experimental results.

6 RI prediction of ±800 kV HVDC transmission lines

6.1 Calculation of actual line RMS value Of RI excitation current

As previously described, the RMS value of the RI excitation current can be obtained conveniently from the corona cage test and meanwhile the average corona current can be calculated by the numerical method, then the RI excitation current of the transmission line can be acquired by (16). Once the excitation current of HVDC transmission line is acquired, it is simple to calculate the RI level of transmission lines.

The RI tests were carried out on the Xiangjiaba–Shanghai ±800 kV bipolar UHVDC transmission line and in the UHVDC corona cage. This transmission line configuration and the photo of the actual measurement is demonstrated in Fig. 14. The parameter of the conductor is \( 6 \times 720 \text{ mm}^2 \), the sub-conductor radius is 1.8115 cm, the bundle space is 45 cm.

The RMS value of the RI component was obtained in the bipolar UHVDC corona cage whose configuration is shown in Fig. 15 [40]. The total length of this corona cage is 90 m. The cross-section is \( 21 \times 10 \text{ m} \) which comprises a middle partition whose width is 1 m, therefore, for either the positive corona cage or the negative corona cage, the cross-section is \( 10 \times 10 \text{ m} \).

The environment parameters of the HVDC transmission line and corona cage RI test are shown in Table 1. It can be seen that the environmental parameters are almost the same.

According to step 1, the corona cage test results are shown in Fig. 16. The excitation current is modified to the value with per unit length.

According to step 2–4, the voltage, maximum space-charge-free electric field, geometric capacitance and the average corona currents of the corona cage and actual lines are calculated as shown in Table 2. It can be found that when the conductor voltage in the corona cage is 550 kV, the maximum space-charge-free electric field calculation result of corona cage test and transmission line test are almost the same.

Thus, according to step 5, when the conductor voltage is 550 kV, based on the results shown in Fig. 16, the value of \( I_{\text{RMS,c}} \) is 21.62 dB \( \mu \text{A/m}^{1/2} \), the value of the second term of (17) is –10.11 dB, the value of the second term of (18) is –5.12 dB. Therefore, the actual line RMS value of RI excitation current is 16.50 and 11.51 dB \( \mu \text{A/m}^{1/2} \) based on (17) and (18), respectively.

After obtaining the RMS values of the RI excitation current on the actual lines, the propagation characteristics still need to be calculated to get the final RI level of the entire transmission line.
6.2 Calculation of the RI level of the transmission line

After obtaining the RI excitation current, the phase-mode transformation method combined with the classic transmission equations of the transmission line can be used to solve the propagation problem [41].

According to [31], for the bipolar HVDC transmission line, RI produced only by the positive polarity conductor should be concerned, the RI excitation currents of two-pole conductors per unit length can be obtained by

$$J = \left[ \begin{array}{c} J_1 \\ J_2 \end{array} \right] = \left[ \begin{array}{c} \frac{C_{21}}{C_{21}} \\ \frac{C_1}{C_{21}} \end{array} \right] \frac{I_0}{E_0}$$

(25)

where $J_1$ is the RI excitation current of positive polarity conductor, $J_2$ is the coupled RI excitation current of negative polarity conductor from positive polarity conductor, $C_{21}$ is the mutual capacitance between two pole conductors, $C_{11}$ is the self-capacitance of positive polarity conductor, $I_0$ is the RI excitation current measured from corona cage test of positive polarity conductor. All the parameters are per unit length values.

According to [41], when the current propagates along the transmission line, the transmission equation can be modified to

$$\frac{d^2}{dx^2} J = YZ I$$

(26)

where $Y$, $Z$, $I$ are the current, admittance and impedance per unit length, respectively. It is assumed that the eigenvalue diagonal matrix of $YZ$ is $\text{diag}(\lambda^2)$, the corresponding eigenvector matrix is $S$, then the decoupled phase excitation current can be calculated by

$$I_i = \frac{1}{2} S \text{diag} \left( e^{-i\lambda x} \right) S^{-1} J$$

(27)

where $I_i$ is the decoupled phase RI excitation current per unit length, $\text{diag} \left( e^{-i\lambda x} \right)$ is the diagonal matrix. The amplitude of RI field $E_x$ at a certain measure point can be calculated from (28)-(30)

$$E_x = 60KI$$

(28)

$$K_i = \frac{h_i - h_p}{(h_i - h_p)^2 + D_i} + \frac{h_i + h_p + 2\rho_d}{(h_i + h_p + 2\rho_d)^2 + D_i}$$

(29)

$$\rho_d = \sqrt{\frac{\rho}{\pi f \mu_0 J}}$$

(30)

where $K$ is a geometric parameters vector of conductors, $K_i$ is geometric parameter of conductor $i$, $h_i$ is the height of conductor $i$, $h_p$ is the height of measure point, $D_i$ is the ground projector distance of conductor $i$ and measure point, $\rho_d$ is the depth of penetration, $\rho$ is the soil resistivity, $f$ is the frequency, $\mu_0$ is the air permeability. Integrating the RI field along the entire conductor, the total amplitude of RI field $E$ at measure point produced by all the RI excitation current along the conductor can be calculated as

$$E = \sqrt{2 \int_0^{\infty} E_x dx}$$

(31)

Based on (31), the distribution of RI at the height of 1.5 m is calculated as shown in Fig. 17. The comparison of RI levels acquired from different prediction methods is also shown in Fig. 17. It is apparent that the new prediction method proposed in this paper matches the practical result well. In comparison, the prediction result by either the CISPR or the EPRI empirical formula is smaller than that of the measured result and meanwhile, the traditional excitation function method provides an apparently larger predicted RI level compared with the measured result.

7 Conclusion

In this paper, based on a current measuring system, time-domain corona current and frequency-domain responses of corona current

\[\begin{array}{|c|c|c|}
\hline
\text{Environmental parameters of HVDC transmission line test and corona cage test} \\
\text{Temperature, °C} & \text{Humidity, %} & \text{Wind speed, m/s} \\
\hline
\text{transmission line test} & 28–36 & 50–70 & 0–1.5 \\
\hline
\text{actual line test} & 27–34 & 40–69 & 0–2.2 \\
\hline
\end{array}\]

\[\begin{array}{|c|c|c|c|}
\hline
\text{Comparison of the calculated parameters between the HVDC transmission line test and corona cage test} \\
\text{Conductor voltage, kV} & \text{maximum space-charge-free} & \text{surface electric field, kV/cm} & \text{geometric capacitance, pF/m} \\
\hline
\text{transmission line test} & \pm800 & 22.47 & 11.38 \\
\hline
\text{corona cage test} & 550 & 22.45 & 20.51 \\
\hline
\end{array}\]

where $I$, $Y$, $Z$ are the current, admittance and impedance per unit length, respectively.

\[\begin{align}
\frac{d^2}{dx^2} J &= YZ I \\
I_i &= \frac{1}{2} S \text{diag} \left( e^{-i\lambda x} \right) S^{-1} J \\
E_x &= 60KI \\
K_i &= \frac{h_i - h_p}{(h_i - h_p)^2 + D_i} + \frac{h_i + h_p + 2\rho_d}{(h_i + h_p + 2\rho_d)^2 + D_i} \\
\rho_d &= \sqrt{\frac{\rho}{\pi f \mu_0 J}} \\
E &= \sqrt{2 \int_0^{\infty} E_x dx}
\end{align}\]
are measured together. The time-domain corona current characteristics indicate that if the conductor surface condition and the atmospheric condition are the same, the waveform of a single corona pulse is almost independent on the electric field and the electrode configuration, however, the repetition frequency varies obviously as the electric field and the electrode configuration change. According to this observation, the correlations between average corona current, RI excitation current and corona current pulse repetition frequency are obtained and confirmed by the time-domain as well as the frequency-domain experimental results. Furthermore, the relationship between average corona current and RI excitation current in corona cages as well as on transmission lines is achieved. This relationship presents a new way to predict the RI level of HVDC transmission lines based on the corona cage tests. The predicted RI level of Xiangjiaba-Shanghai ±800 kV bipolar UHVDC transmission line is in good agreement with the measured value.

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9 References

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