Research on Electromagnetic Radiation Model of Corona Discharge with UHV AC Transmission Lines

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Abstract. The corona discharge pulse current has double exponential distribution characteristics. On this basis, the electromagnetic radiation model of corona discharge is established by using the theory of electric dipole. The corona discharge characteristics are analysed and compared with the measured results of 1000kV UHV ac transmission line. The results show that the electromagnetic field strength increases first and then decreases with time, and at the same time, the electromagnetic field strength decreases exponentially with distance. The simulated and predicted corona discharge radiation characteristics have the same variation law as the measured data, which verifies the correctness of the model.

1. Introduction
At present, the research work of corona discharge mainly focuses on the mechanism of corona generation, harmfulness, influencing factors and preventive measures [1]. Lack of in-depth theoretical research on electromagnetic radiation from corona [2]. Aiming at the time-domain characteristics of corona discharge pulse current, a radiation model of dipole antenna is established to study the correlation of radiation field produced by a single corona source with time and distance in this paper.

2. Corona Current

2.1. Formation and Characteristics of Corona Current
Corona discharge is a common form of gas discharge. When corona discharge occurs, free electrons, ions and charged particles are formed in space. An increasing current will be generated in conductors. When the instantaneous current reaches its peak, the ion velocity will be increased due to relatively large stable space charge clouds [3]. Degree reduction leads to the decrease of electric field and the decrease of electric current. Therefore, a pulse current with a shorter peak time and a longer descent time will be generated during Corona discharge [4].

The corona current of transmission line is mainly positive polarity corona [5], and usually flows in the form of pulse clusters in the transmission line. Its current intensity mainly depends on the conductance of the gas space outside the electrode [6], that is, on the applied voltage, the shape of the electrode, the distance between the electrodes, the nature of the gas, etc. [7].

2.2. Corona current calculation
The time domain characteristics of the pulse current can be described by the current expression in double exponential form [8], as shown in formula (1). The main form of corona in transmission line is positive corona [9]. The typical time-domain variation curve of positive corona current is shown in Figure 1.

\[ i(0,t) = K_i e^{-\alpha t} - e^{-\beta t} \]  

(1)

Where \( K, \alpha \) and \( \beta \) are coefficients, \( I_0 \) is the peak current, and \( t \) is generally in nanoseconds (ns).

The average value of pulse characteristics, as shown in Table 1. Coefficients \( K, \alpha \) and \( \beta \) can be estimated by the following formula on the premise of a given peak time and a 50\% time required to reach the tail value [10].

If \( x = \beta / \alpha \), \( y = t_i / t_p \), the desired results can be obtained from the following equations.

\[ x(y - 1) \ln(x) = (x - 1) \ln(2(x' - 1)/(x - 1)) \]  

(2)

\[ \alpha = \ln(x) / (x - 1) \]  

(3)

In the above formula (2), formula (3) can be obtained by experiment, while errors \( x \) and \( \alpha \) can be obtained by formula (3), so that the values of \( \alpha, \beta \) and \( K \) can be calculated from \( \beta = x \alpha \), known peak time \( t_p \), and finally the expression of corona current under this condition can be obtained.

| Type          | Peak to peak time | Time to reach the 50\% of tail of the pulse | Peak current | Repetition time of pulse per second |
|---------------|-------------------|--------------------------------------------|--------------|-----------------------------------|
| Positive polarity | 50ns              | 150ns                                      | 100mA        | power frequency                   |
| Negative polarity | 20ns              | 50ns                                       | 10mA         | 100\times power frequency         |

3. Corona discharge EMI model

3.1. Antenna radiation model

The pulse current generated by corona discharge contains a wide frequency band and high frequency component. The energy is radiated in the form of electromagnetic waveform. The radiation field can be analyzed and calculated by dipole antenna model. Therefore, this paper uses the electric dipole antenna model to analyze the radial radiation field intensity of the conductor. The radiation field of the electric dipole is shown in Figure 2.

Let the current element \( I \) be at the origin of spherical coordinates, the sinusoidal variation of \( I \), and the electromagnetic field produced by the electric dipole be

\[ E_r = \frac{\Delta I}{2\pi \varepsilon_0 c} \left( \frac{k^2}{r^2} + \frac{1}{r} \right) \cos \theta e^{jk \cdot \mathbf{r}} \]  

\[ E_\theta = \frac{\Delta I}{4\pi \varepsilon_0} \left( \frac{k^2}{r^2} + \frac{1}{r} \right) \sin \theta e^{jk \cdot \mathbf{r}} \]  

\[ H_\phi = \frac{\Delta I}{4\pi} \left( \frac{k^2}{r^2} + \frac{1}{r} \right) \sin \theta e^{jk \cdot \mathbf{r}} \]  

(4)
Where \( k \) is propagation coefficient, \( k = 2\pi/\lambda \) without considering loss, \( r \) is the distance from the observation point to the field source, \( \varepsilon_0 \) is permittivity of free space. Near field of electric dipole: when \( r < \lambda / 2\pi \), then \( k_r < 1 \), at this time, \( e^{jkr} \approx 1 \), \((-1/kr)\) high order term, \((-1/kr)^2\) and \((-1/kr)^3\) account for the main component. Low order term can be ignored. \( E \) and \( H \) are simplified as

\[
H_y = j\frac{kMl}{4\pi r} \sin \theta \quad E_y = \frac{kMl}{4\varepsilon_0 r^2} \sin \theta \quad E_z = \frac{kMl}{2\varepsilon_0 r^2} \cos \theta
\]

Far field of electric dipole: when \( r >> \lambda / 2\pi \) then \( k_r >> 1 \). Thus, the higher order terms of \((1/kr)\) in \( E \) and \( H \) become secondary components, and the field strength depends on the lower order terms. At this time, \( E \) and \( H \) are simplified as follows:

\[
H_y = j\frac{kMl}{4\pi r} \sin \theta e^{-jkr} \quad E_y = \frac{kMl}{4\varepsilon_0 r^2} \sin \theta e^{-jkr}
\]

3.2. Calculation of the EMI of corona discharge

3.2.1. Computational procedure

1) Mathematical expression of corona current

As shown in Table 1, for positive conductors, the average peak time of double exponential pulse is \( t_p = 50\text{ns} \), and the average time to reach the tail value of 50% is \( t_{90} = 150\text{ns} \). The calculations of \( \alpha, \beta \) and \( K \) are as follows: \( y = t/t_p = 3 \), so \( x = 3.45 \) is calculated by formula (2):

\[
\alpha = \ln(x)/(x-1)t_p = \ln(3.45)/(3.45-1) \times 10^{-9} = 10 \times 10^6
\]

\[
\beta = 0.50546, K = 3.45 \times 10^6
\]

So the current pulse is:

\[
i(t) = 2.335 \cdot i_p \left( e^{-10t} - e^{-3.45t} \right)
\]

2) Determining relevant parameters

Because of the symmetry of transmission lines, \( \theta \) is chosen from 0 to 90°. Suppose that \( \Delta l = 0.005\text{m} \), the peak current \( i_p = 0.1\text{A} \). \( c=3 \times 10^8 \), \( \varepsilon_0=8.85 \times 10^{-12} \), \( \omega_0=2\pi f \), \( k=\omega_0/c \).

3.2.2. Spectrum analysis of corona radiation

![Figure 3. The time domain graph of corona current](image)

![Figure 4. Spectral analysis diagram of corona current](image)

According to the selected parameters, the time-domain waveform of corona current and its spectrum are established, as shown in Figures 3 and 4. From Figure 3, we can see that the maximum amplitude of corona current is 0.1A when the corona current \( t=0.5 \times 10^7 \text{s} \). Then, as time goes on, the corona current gradually decreases and is relatively smooth, that is to say, a pulse with a relatively long falling time and a relatively long peak time is formed. From the spectrum analysis chart of Figure 4, it can be seen that the basic frequency of electromagnetic radiation produced by corona discharge is within 30MHz, and the general AM broadcasting band is also within this frequency band, which shows that it will have a serious impact on the radio signal. The corona interference spectrum of overhead power lines is wider, and the main energy is concentrated below 10MHz. With the increase of frequency, the amplitude of the interference component decreases rapidly [11]. When calculating the radiation field, 10MHz can be chosen as the reference frequency.
3.2.3. Radiation field calculation

![Figure 5](image1.png)  ![Figure 6](image2.png)

The reference frequency $f = 10$ MHz is selected for calculation, and then the frequency is as follows:

$$\frac{\lambda}{2\pi} = \frac{c}{2\pi f} = \frac{3\times 10^8}{2\pi \times 10^9} \approx 4.8$$  \hspace{1cm} (10)

It can be seen that the region of $r \ll 4.8$m is near field, and the region of $r \gg 4.8$m is far field. The selected parameter $r=0.05$m is near field, and the selected parameter $r=100$m is far field. The function curves of electric field intensity and magnetic field intensity varying with time in near and far field regions are obtained as shown in Figures 5 and 6 respectively.

From Figures 5 and 6, it can be seen that the variation of electric field intensity and magnetic field intensity with time at fixed observation points increases rapidly at first, and then decreases gradually after reaching the peak value. The variation process is similar to that in Figure 3. When $t=50$ ns, the electric field intensity and magnetic field intensity in both near and far fields reach their peak values. When the current reaches the peak value, the electric field strength and magnetic field strength reach the maximum value, and have the same trend as the current change. The same $\theta=90^\circ$ is selected and the curves of Figures 7 and 8 are obtained. From the curves, it can be seen that the field intensity and magnetic field intensity in the near field region are much larger than that in the far field region at the same time point. Order $t=50$ ns, then $E_{\theta, \text{near}}=572.5, E_{\theta, \text{far}}=3.136 \times 10^5, H_{\phi, \text{near}}=0.01592, H_{\phi, \text{far}}=8.325 \times 10^8$. Because the impedance $Z=E/H$, then $Z_{\text{near}} \approx 3.6 \times 10^6, Z_{\text{far}} \approx 377$. That is, in the near field, the electric field is much stronger than the magnetic field, which is mainly represented by the electric field wave, which is an inductive field; in the far field, the wave impedance is approximately equal to the air wave impedance, and mainly propagates in the form of electromagnetic wave radiation, which is a radiation field.

![Figure 7](image3.png)  ![Figure 8](image4.png)

From Figure 9, it can be seen that the variation trend of electric field intensity and magnetic field intensity with distance is the same when the same $\theta$ is selected, and both of them decay with distance increasing. The farther the distance, the less affected by corona discharge. At the same time, when $r = 100$m is the far field, the attenuation of the near field radiation field is stronger than that of the far field, and the far field attenuation is relatively stable. That is to say, the intensity of electric field and
magnetic field first decays rapidly and then decreases relatively smoothly as the distance between corona sources increases.

In order to study its attenuation characteristics, the curve of Figure 10 is obtained by choosing $\theta=90^\circ$, and the fitting formulas such as formula 11 are obtained. The electric field intensity and magnetic field intensity are all exponential functions of distance. Combined with the figure, the electric field intensity and magnetic field intensity show exponential attenuation with the increase of distance. Therefore, for the same corona radiation source, the intensity of electric field and magnetic field in the near field area is much greater than that in the far field area at the same time, that is, the radiation intensity in the near field area is much greater than that in the far field area.

$$E_\theta = -80.19e^{0.001009r} + 46.37e^{-0.1464r}$$
$$H_\phi = -133.1e^{0.0008563r} + 35.2e^{-0.0836e^r}$$  \(11\)

![Figure 9. The electric field strength and magnetic field strength vary with distance](image)

**Experimental analysis.** Testing a certain point of UHV 1000 kV transmission line according to the monitoring line shown in Figure 11, the data obtained are taken as the origin under phase B of transmission line, the direction of monitoring line (phase B to phase C) as the transverse axis, and the measured value is the longitudinal axis. The magnitude of magnetic induction, electric field intensity and radio interference can be observed with time. The curve of point change are shown in Figures 12, 13 and 14 respectively.

![Figure 11. Schematic diagram of test](image)

According to the Figures 7-9, it can be seen that the electric field intensity, magnetic induction intensity and radio interference increase first and then decrease with the horizontal distance along the conductor between phase B (0m) and phase C (22m), while outside phase C (22m), they decreases exponentially with the increase of the distance. It is shown that the radial radiation intensity of the mesophase increases first and then decreases exponentially with the increase of distance.

When the observation point is larger than 22m, it is located on the right side of the whole transmission line. The linear distance between the observation point and phase A (phase B) is greater than 49.9m (32.2m). At this time, the radiation source of the observation point mainly comes from phase C. It can be concluded that for single-phase lines, the radiation field caused by corona discharge decreases exponentially with the increase of the distance between the observation points, which has the same characteristics as the curve obtained by the simulation model. At the same time, the intensity of electric field and magnetic field in the near field of radiation field is larger than that in the far field.
4. Conclusion

This paper expounds the mechanism of corona generation and describes the formation of corona current. According to the time domain pulse expression of positive corona current, assuming the peak current, the current function is calculated by the average parameters of pulse characteristics, and the radiation field is simulated and analyzed by using the electric dipole antenna model. The following conclusions can be drawn:

(1) The radiation field intensity of corona current shows induction field in the near field and radiation field in the far field. (2) When the corona current reaches its peak value, the electric field strength and magnetic field strength also reach the maximum value. (3) With the increase of observation distance (in the same direction), the radiation field intensity caused by corona decreases rapidly at first, then slowly, in an exponential form. At the same time, the radiation intensity in the near field region is far greater than that in the far field region. (4) At the same time, the radiation field in the near field decreases sharply, while in the far field the attenuation is relatively stable and weak.

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