Research on characteristics of electromagnetic radiation of corona discharges from high voltage transmission lines

Lei Wang*, Shang-he Liu, Ming Wei, Xiao-feng Hu
Electrostatic and Electromagnetic Protection Research Institute, Ordnance Engineering College, Shijiazhuang, 050003, China.

E-mail: wl810603@sina.com

Abstract. With the development and application of ultra high voltage electric power transmitting technology, harmful effects of corona discharges to the safe and stable operation of the ultra high voltage (UHV) transmission lines should be considered. In this paper, the radiation law of corona discharges was studied by theoretical analysis and laboratory simulation. Correlated conclusions include that the waveform of corona discharges is in attenuated oscillation mode, the signal of the radiation field increases with increasing charging voltage, whereas the signal amplitude the antenna receives is attenuated with the distance from 3 m to 24 m.

1. Preface
In the field of power systems, the UHV transmission has become the development trend of the power transmission. With the increase in the transmission voltage level, the corona discharge is inevitable, and it has become an important factor which can affect the safe and stable operation of the high-pressure and UHV transmission lines [1-4]. It is a new topic on detecting the fault of high-voltage transmission line through remote detection of the signal radiated from corona discharge, which requires the study of radiation law of corona discharge.

2. Theoretical analysis
The corona discharge radiation field of high voltage transmission line includes two parts: one is the electromagnetic field radiated outward by the rapid charge transfer within the channel of the air corona district, which can be equivalent to the radiation field from a short electric dipole antenna; the other part is radiated by the pulse current generated from the corona discharge excitation conductor, where the high voltage transmission line can be equivalent to pulse transmission line that radiates electromagnetic fields. Both corona discharge radiation fields can be calculated by the electric dipole model and the thin straight antenna model [5].

2.1 Short electric dipole
The dipole with a length of L was set up in the Z-axis, and its center is coincident with the origin (as shown in Figure 1). From figure 1, it can be seen that the current on the dipole is not always acting on the field point P, but there is a delay caused by the difference of the shoot diameter (s) and the distance (r). The current (I) was expressed as a transient form [5] by formula (1).

* To whom any correspondence should be addressed.
Figure 1. Field strength at any point of short electric dipole.

\[ I = I_0 e^{j\omega t} \quad \text{(1)} \]

The instantaneous propagation effects of the current can be expressed by using the Lorentz spread or lag time notation, which is written as follows:

\[ [I] = I_0 e^{j\omega t} \quad \text{(2)} \]

In the practical application, we are interested only in the far field, but the distance of the far-field point and the dipole is much greater than the dipole length (\( r \gg L \)), and its wavelength is much larger than its length (\( \lambda \gg L \)). The calculation of the electromagnetic field by the short dipole in the far-field point is as follows:

\[
\begin{align*}
E &= E_\phi = \frac{j \omega I_0 L \sin \theta e^{j\omega [r-(\frac{L}{\lambda}) \cos \theta]}}{4\pi \varepsilon_0 c^2 r} = j \frac{I_0 \beta L}{4\pi \varepsilon_0 c} \sin \theta e^{j\omega [r-(\frac{L}{\lambda}) \cos \theta]} \\
H &= H_\phi = \frac{j \omega I_0 L \sin \theta e^{j\omega [r-(\frac{L}{\lambda}) \cos \theta]}}{4\pi c r} = j \frac{I_0 \beta L}{4\pi} \sin \theta e^{j\omega [r-(\frac{L}{\lambda}) \cos \theta]}
\end{align*}
\quad \text{(3)}
\]

The general radiation power of non-uniform current dipole can be calculated using the formula (3) and the Poynting vector formula

\[ P = \frac{\mu}{\varepsilon} \left( \frac{L}{\lambda} \right)^2 \frac{L^2}{12\pi} = \frac{1}{2} I_0^2 R_r \quad \text{(4)} \]

For free space (\( \mu = \mu_0, \varepsilon = \varepsilon_0 \)), the availability radiation resistance of electric dipole can be gotten formula (5).

\[ R_r = 197\left( \frac{L}{\lambda} \right)^2 = 197L^2_0 \quad (\Omega) \quad \text{(5)} \]

For example, when \( L_0 = 0.1, R_r \) will be 1.97 \( \Omega \); when \( L_0 = 0.01, R_r \) will be 0.02\( \Omega \). At the same time, the wavelength is much larger than the length of the electric dipole under normal circumstances (\( \lambda \gg L \)), visibility, the radiation resistance of electric dipole is quite small. In certain circumstances, the radiation power radiated by the corona discharge current is also very small.
2.2 The thin straight antenna

The far-field formula of the symmetrical and thin straight antenna with a length of $L$ is derived using figure 2. Taking into account that the antenna is consisted of a string of infinitesimal dipole with length of $dz$, the field of the antenna can be gotten by integration of all of the dipole field, the result is as follows[5].

\[
E = E_0 = \frac{jIe^{j[r-(r/l)]}}{2\pi r} \left[ \frac{\cos\left(\frac{\beta L \cos \theta}{r} - \frac{\beta L}{2}\right)}{\sin \theta} \right] \\
H = H_0 = \frac{j60Ie^{j[r-(r/l)]}}{r} \left[ \frac{\cos\left(\frac{\beta L \cos \theta}{r} - \frac{\beta L}{2}\right)}{\sin \theta} \right]
\]

(6)

These results show that the radiation resistance of thin straight line is much larger than that of the electric dipole. For the same current, the radiation power of thin straight line is much larger than the electric dipole.

By calculation of the equivalent antenna radiated field, it can be obtained that the radiated field of corona discharge is inversely proportional to the distance, and the radiated field strength increases with the discharge current. In addition, the radiation power of space is much smaller than that of the line.

3. Laboratory simulations for radiation law of corona discharge

In order to get a clearer understanding of the radiation field by corona discharge, a test experimental platform was constructed to test the signals radiated from corona discharge and to study its radiation law by testing of signals radiate from corona discharge in different conditions.

3.1 Platform of experiment

Considering that the electromagnetic field produced by corona discharge high voltage transmission line is equivalent to radiation field of dipole and the conductor pulse transmission line, the long straight line is used to simulate the corona discharge, and the experimental layout is shown in figure 3. The corona discharge simulation system in laboratory is divided into two parts.
(1) Discharge system. The discharge system consists of a long straight line, high voltage static power (300 kV, 3 mA) and high-voltage towers, etc. The main purpose is to simulate the corona discharge of high-voltage line.

(2) Test system. The test system consists of a log-periodic antenna, a corona discharge test system of Tek 7404B high-speed digital storage oscilloscope and a signal pre-amplifier. The signal pre-amplifier is used to test the discharge radiation signal.

The high voltage source with radiation signal seriously interferes with the discharge signal test, so in this experimental system the high-pressure source is set in the shielded room. A high voltage line insulated by high performance material output the high voltage outside the shielded room through a window, and some distance from the walls of the shielded room was left to prevent high-voltage breakdown. The high-voltage line outside shielded room was mounted on the wood bracket and with the distance of 1.5 m to the ground.

One end of the high-voltage line was connected to the high voltage source; the other end was fixed on an insulating stand. The length of high-voltage line outside the shielded room was the effective radiation length of the transmission line. The distance of the antenna and discharge point was d. The high voltage was adjusted by the high voltage pressure control switch.

3.2 The characteristics of corona discharge signal

![Figure 3. Experimental layout.](image3)

![Figure 4. Waveform of 60 kV corona discharging.](image4)

![Figure 5. Spectrum of 60 kV corona discharging.](image5)

The experiments were conducted under a temperature of 26 °C, a relative humidity of 35%, and a charging voltage of 60 kV. The receiving antenna in horizontal polarization direction was log-periodic antenna, and the digital filters were used to capture the discharge signal.
The length of the high-voltage line outside the shielded room was 150 cm; the test distance was 6 m. When the voltage of corona discharge was 60 kV, the time domain and frequency domain waveforms measured by the receiving system were shown in figure 4 and 5. From figure 4 it can be seen that the rise time of the corona discharge waveform was about 1~5 ns, and the duration time of the waveform was about tens of ns. Also, figure 5 pointed that the corona discharge spectrum distribution was extremely wide, the frequency ranged up to 1.5 GHz, and the main energy concentrated below 1 GHz.

3.3 The radiation law of different voltage
Under the same conditions, the discharge voltage was selected from 30 kV to 100 kV by the step of 10 kV, the maximum amplitude of radiation signal was recorded in figure 6. It can be seen from the figure that the signal radiation field increases with increasing the charging voltage. The discharge current would increase with the discharge voltage, which was consistent with the radiation field calculation of the equivalent antenna.

3.4 Discharge radiation law of different distance
Under the same experimental conditions, the distance of the test antenna and high-voltage line was changed from 3 m to 24 m by the step of 3 m. The relation between the maximum amplitude of domain waveform and the test distance was shown in figure 7. From figure 7 it can be seen that the signal amplitude that the antenna received was attenuated with the increase of the distance, which pointed that the received signal power was inversely proportional to the propagation distance, and the result was also consistent with the theoretical analysis.

4. Conclusion
Through the theoretical analysis and experimental study of radiation law by high voltage transmission line corona discharge, the following conclusions can be drawn: (1) the waveform of corona discharge was attenuated oscillation mode. The waveform rise time was about 1~5 ns, the frequency ranged up to 1.5 GHz, and the main energy concentrated below 1 GHz; (2) with the increase of charging voltage, the signal radiation field increases; (3) the signal amplitude that the antenna received was attenuated with the distance, which showed that the received signal power was inversely proportional to the propagation distance.
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