Numerical Calculation Method of EHV/UHV AC Corona Loss Based on Streamer Theory

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Abstract. For the selection and design of Ultra/Ultra High Voltage (EHV/UHV) transmission lines, the calculation of corona losses is very important content of the research. A numerical calculation method of corona losses of EHV/UHV alternating current (AC) transmission lines based on streamer theory is proposed in this paper. In this method, Peek's formula is not used to calculate the corona onset electric field. Instead, the corona onset electric field is calculated from the physical process of corona production on the surface of the line, and the influence of raindrops on the corona onset electric field is considered according to the law of deformation of raindrops in the electric field. After the corona onset electric field was obtained, corona losses of the wire can be obtained by calculating the ion flow field of the bundled conductors. The result of the example shows that the calculation result of this method is accurate relatively compared with the measured values. The calculation method of this paper has certain practical application value for the calculation and study of EHV/UHV AC corona loss in rainy days.

1. Introduction

At present, China's long-distance transmission, like other countries in the world, mainly uses EHV/UHV transmission networks. According to measurements and studies have shown that corona loss of 500 kV and above transmission lines in UHV/UHV power grid is sensitive to line voltage, a large proportion of the total loss in the rain and snow and rime inclement weather. All of the electromagnetic energy released must be supplied by the power plant, thus causing a great waste of electrical energy [1-5].

For numerical analysis corona loss, J.J. Clade et al. first made a comprehensive study of AC corona lines, the calculation of corona losses is very important content of the research. A numerical calculation method of corona losses of EHV/UHV alternating current (AC) transmission lines based on streamer theory is proposed in this paper. In this method, Peek's formula is not used to calculate the corona onset electric field. Instead, the corona onset electric field is calculated from the physical process of corona production on the surface of the line, and the influence of raindrops on the corona onset electric field is considered according to the law of deformation of raindrops in the electric field. After the corona onset electric field was obtained, corona losses of the wire can be obtained by calculating the ion flow field of the bundled conductors. The result of the example shows that the calculation result of this method is accurate relatively compared with the measured values. The calculation method of this paper has certain practical application value for the calculation and study of EHV/UHV AC corona loss in rainy days.
areas on the surface of the split wire are prone to halo and some areas are not even halo. However, the method uses the Peek formula to calculate the field strength of the halo. In the past, the selection of the roughness coefficient in the Peek formula is empirical, especially for the selection of the surface roughness coefficient of the rainy days transmission line, and there is no uniform standard up to now.

To solve this problem, based on the method of Wei et al., one kind of numerical calculation method for corona loss of UHV/UHV AC lines based on streamer theory is presented in this paper. This method is no longer using the corona onset field strength Peek formula, and the corona onset field strength is calculated based on the physical process of the surface halo, and the influence of raindrops on the surface of the rainy day on the height of the halo field is considered.

2. Streamer theory
Stream theory believes that the main factors for maintaining self-sustaining discharge are electron impact ionization and space photoionization.

Figure 1. Development of electron avalanche on negative half cycle

Figure 2. Primary electron avalanche on positive half cycle

In the negative half cycle, when the field strength around the conductor reaches the critical value of the ionization of air molecules generated by the collision of free electrons, the initial electron avalanche forms and begins to develop forward, as shown in Figure 1, where \( l \) represents the distance from the centre of a wire to a point in the space. When the head of electron avalanche gradually extends to the ionization boundary \( l_i \), if the photons generated by the initial electron avalanche collide with the conductor surface and the number of photoelectrons released has reached \( N_{eph} \geq 1 \), the corona discharge starts. In the positive half cycle, the initial electron avalanche occurs at the boundary of the ionization region. As shown in Figure 2, when the electron number \( K \) of the initial electron avalanche head reaches \( e^{20} \), the corona discharge starts.
3. Calculation method

3.1. Calculation method description and process

The numerical calculation method of corona loss used in this paper is based on the analogue charge method, which places 8 analogue charges in each sub-wire of the split wire, and the position of the simulated charge is located at 0.7 × R at the centre of the sub-wire, and R is the split wire radius. Then, the AC ion flow field around the wire under the split conductor and the multi-phase line is calculated by the corona onset field strength obtained by the streamer theory, and the final result is obtained. The specific calculation process is shown in Figure 3.

![Figure 3. Corona loss calculation method flow](image)

3.2. Raindrop model

The corona discharge phenomenon of transmission lines in rainy days is more serious. The main reason is that the raindrops on the transmission line will cause distortion of the electric field around the line [11]. This paper does not consider the process of gathering and rupture of raindrops. It is considered that the change of the intensity of the corona onset field on the rainy day is only caused by the raindrops on the surface of the line and its deformation. It is considered that the larger the rainfall, the higher the maximum raindrop radius of a section of the line surface. Based on this, this paper proposes a simplified calculation model of raindrop corona onset field strength. As shown in Figure 4, the field strength at the tip of the raindrop will be significantly greater than the field strength at the surface of the transmission line. At a certain operating voltage, the tip of the raindrop will first satisfy the halo condition. This paper considers the working voltage at this point is the corona voltage at that point. The field strength is that the field is the corona onset field strength.

![Figure 4. Raindrop model](image)
In this paper, the derivation process of water droplet deformation in oil under high voltage electric field in [12] is modified, and the effect of raindrop gravity is considered. It is considered that the raindrop is in equilibrium under the combined action of internal pressure, gravity, electric field force and surface tension. The deformation of the raindrop is mainly related to the electric field strength $E_0$ (V/m) and the raindrop radius $R_0$, which is expressed as follows:

$$E_0^2 = \frac{(1 - \lambda^2)(6\gamma_1 \lambda^{1/3} - 3\gamma_1 - 2\rho g \lambda^{2/3} R_0^2)}{1 + 2\lambda^2 - 2(\lambda^{1/3} - 1) \ln(\lambda + \sqrt{\lambda^2 - 1})} R_0^2 \left(\frac{3\epsilon_0 \epsilon_2 (\epsilon_1 - \epsilon_2)}{2\epsilon_0^3 \epsilon_2^2 \lambda^2}ight)$$  \hspace{1cm} (1)

Where: $\gamma_1$ is the tensile stress per unit length at the interface between air and raindrop; $\epsilon_0$ is the vacuum dielectric constant, $\epsilon_0 = 8.8542 \times 10^{-12}$ F/m; $\epsilon_1$ is the relative dielectric constant of the raindrop, $\epsilon_1 = 81$; $\epsilon_2$ is the relative dielectric constant of air, $\epsilon_2 = 1.0006$; $\lambda$ is the deformation stretch ratio of the raindrop, $\lambda = a/b$, $a$ is the long semi-axis of a semi-ellipsoid raindrop, $b$ is the short semi-axis of a semi-ellipsoid raindrop; $n_s = \frac{1}{1 - \lambda^2} \left[1 - (\lambda^2 - 1)^{1/2} \ln(\lambda + \sqrt{\lambda^2 - 1})\right]$; $g_1$ is the acceleration of gravity; $\rho$ is the density of the raindrops.

The maximum field strength of the semi-ellipsoid raindrop surface is located in the long semi-axed head, and its expression is as in [13]:

$$E_{\text{max}} = E_0 e_1 / e_2 \left(1 + \frac{e_1 - e_2}{2e_0^3 e_2^2 \lambda^2} (\ln \frac{1 + e_0 - 2e_0}{1 - e_0})\right)^{-1} = kE_0$$  \hspace{1cm} (2)

Where: $e_0$ is the eccentricity of raindrops, $e_0 = (1 - \lambda^{-2})^{1/2}$, $k = e_1 / e_2 \left(1 + \frac{e_1 - e_2}{2e_0^3 e_2^2 \lambda^2} (\ln \frac{1 + e_0 - 2e_0}{1 - e_0})\right)^{-1}$

3.3. Calculation of positive halo field strength and negative halo field strength

Taking the middle phase of the three-phase transmission line shown in Figure 5 as an example, when there is no raindrop on the surface of the line, the point $P_1$ is the minimum point of the halo voltage. When the raindrop is attached, considering the actual situation of the surface of the transmission line, the point $P_0$ is considered to be the minimum value of the halo voltage is calculated from this point to calculate the field strength of the three-phase transmission line under rainy conditions. Under rainy conditions, it is considered that the maximum field strength at the tip of the raindrop at point $P_0$ reaches the corona self-sustaining discharge condition, and the field strength at $P_0$ is the height of the halo field.

Based on corona discharge mechanism of positive half-period, when the number of electrons $K$ of initial electron collapse head reaches $e^{20}$, it turns into a discharge to form a corona self-sustaining discharge.

The number of electrons $K$ of the initial electron collapse head is:
\[ K = e^{\alpha \cdot \eta \cdot dx} \]  

(3)

Where: \( d \) is the thickness of the corona layer; \( \alpha \) is the first ionization coefficient; \( \eta \) is the electron adhesion coefficient. The ionization coefficient \( \alpha \) and the adhesion coefficient \( \eta \) are related to the electric field strength \( E(\text{kV/cm}) \) and the relative density \( \delta \) of the air. The specific expression is as follows [14]:

\[
\alpha = \begin{cases} 
3631.28e^{-167.96(\delta/E)} & 19.0 < \frac{E}{\delta} < 45.6 \\
7358.32e^{-200.79(\delta/E)} & 45.6 < \frac{E}{\delta} < 182.4 
\end{cases}
\]  

(4)

\[
\eta = 9.8648 - 0.541 \frac{E}{\delta} + 1.1447 \times 10^{-3} \left( \frac{E}{\delta} \right)^{3/2} 
\]  

(5)

\[
\delta = \frac{p}{101.3 \times 10^{5}} + \frac{293}{293 + T} 
\]  

(6)

Where: \( p \) is atmospheric pressure (Pa); \( T \) is air temperature (°C).

Mechanism according corona discharge negative half-cycles can be seen, form a self-sustaining corona discharge to generate conditions of photoelectrons at the cathode surface of a photon, it is shown as (7)

\[
N_{\text{eph}} = \gamma_{p} \frac{1}{h} \int_{0}^{r} \alpha(t) g_{2}(r) e^{-\mu_{p} r} \int_{0}^{\theta} (\alpha(\xi) - \eta(\xi)) \, d\xi \, dr \gg 1
\]  

(7)

Where: \( g_{2} \) is the adsorption photon geometric coefficient; \( \mu_{p} \) is the photon absorption coefficient; \( \gamma_{p} \) is the photoelectron emission coefficient. The adsorption photon geometry \( g_{2} \) is expressed as:

\[
g_{2}(r) = g_{\alpha}(r) g_{\text{rad}}(r) 
\]  

(8)

\[
g_{\alpha} = \frac{1}{\pi e^{\mu_{p}(r-R)}} \int_{0}^{r} e^{-\mu_{p}(r-R)/\text{cond}} dq 
\]  

(9)

\[
g_{\text{rad}} = \frac{1}{\pi e^{\mu_{p}(r-R)}} \int_{0}^{r} e^{-\mu_{p}(r-R)^{2}} dq 
\]  

(10)

3.4. Calculation of halo and charge emission

Conductors disposed inside the analogue sum of the charges is \( M \), the total number of space charge is \( N \), the sub-surface of the wire when the wire split point \( r \) from halo space charge of the conductor surface field strength of the impact, satisfies the following equation [15-16]:

\[
R_{\text{cond},r} \cdot Q_{\text{cond}} + R_{\text{space},r} \cdot Q_{\text{space}} = E_{\text{onset}} 
\]  

(11)

Where: \( R_{\text{space},r} \) (1×N dimension) is the matrix of the field strength coefficient of the space charge versus point \( r \); \( R_{\text{cond},r} \) (1×M dimension) is the matrix of the field strength coefficient of the simulated charge pair point \( r \) of the wire; \( Q_{\text{space}} \) (N×1 dimension) is the space charge vector; \( Q_{\text{cond}} \) (M×1 dimension) is the wire simulation charge vector. Based on the formula(11), and a \( Q_{\text{space}} \) taken spend time step calculation result can be obtained at the point \( r \) blooming charge \( Q_{\text{onset},r} \). At each point of the wire to surface corona charge \( Q_{\text{onset}} \) may be calculated by repeating the above procedure at each point obtained.
Divide an AC cycle into $N$ segments. In step I, the voltage $U_{app} = U_{\text{max}} \sin[\omega(i-1)]\Delta t$, is applied to the wire, where $U_{\text{max}}$ is the voltage peak and $\omega$ is the angular frequency, $\Delta t$ is the time step, then

$$U_{\text{app}} = P_{\text{cond}} \cdot Q_{\text{cond}} + P_{\text{space}} \cdot Q_{\text{space}}$$

(12)

Where: $P_{\text{space}}$ (M×N dimension) is the matrix of potential coefficients of space charge; $P_{\text{cond}}$ (M×M dimension) is the matrix of potential coefficients of analogue charge.

Calculate the wire simulation charge vector $Q_{\text{cond}}$, compared with the elements in the halo charge vector, if $Q_{\text{cond,r}} > Q_{\text{onset,r}}$ or $Q_{\text{cond,r}} < Q_{\text{onset,r}}$, then the surface of the wire corona onset point $r$ and transmitted to the space charge $Q_{\text{space,r}} = Q_{\text{cond,r}} - Q_{\text{onset,r}}$.

3.5. Charge migration and loss

A moving distance of the space charge $I$ within the time $\Delta t$ in x-axis direction of $\Delta l_{xi}$ is [17]:

$$\Delta l_{xi} = \mu E_{xi} \Delta t$$

(13)

The moving distance $\Delta l_{yi}$ along the y-axis direction is:

$$\Delta l_{yi} = \mu E_{yi} \Delta t$$

(14)

The migration distance $\Delta d$ is:

$$\Delta d = \left(\Delta l_{xi}^2 + \Delta l_{yi}^2\right)^{1/2}$$

(15)

Where: $E_{xi}$ and $E_{yi}$ are the field strengths of the space charge in the x-axis and y-axis directions, respectively, and are calculated by the analogue charge method; $\mu$ is the ion mobility, and the positive and negative charges are $1.5 \times 10^{-4}$ and $1.8 \times 10^{-4} \text{m}^2/(\text{V} \cdot \text{s})$.

There is a charge recombination in ion flow field, it needs the charge density, which is defined as:

$$\rho = \frac{q_{\pm}}{e\Delta V_i}$$

(16)

Where: $e$ is the amount of electron charge $e=1.6 \times 10^{-19} \text{C}$; $\Delta V_i$ is the control volume of the charge; $q_{\pm}$ is the positive and negative line charge.

The amount of charge after the combination of positive and negative space charges is:

$$q_{\pm,\text{comb}} = \frac{q_{\pm,\text{t}}}{1 + \gamma_2 \Delta p_{\pm}}$$

(17)

Where: composite coefficient $\gamma_2 = 1.5 \times 10^{-12} \text{m}^2/\text{s}$.

Because of the combination of positive and negative charges, the space charge will disappear. Charge density that is less than a certain value, it does not consider the impact.

3.6. Stopping criterion

The generation and disappearance of space charge $I$ are always accompanied by the AC electric field. The calculation needs several cycles to achieve stability. The total space charge in one cycle is:

$$q_{\text{cycle, sum}} = \sum_{j=1}^{N} \sum_{i=1}^{N} q_{ij}$$

(18)
Two adjacent space charge cycle total amount of relative change is less than the given error tolerance \( \varepsilon \) [18], stops the calculation, namely:

\[
\left| \frac{q_{\text{cycle}, N_c} - q_{\text{cycle}, N_c - 1}}{q_{\text{cycle}, N_c - 1}} \right| < \varepsilon
\] (19)

Where: \( N_c \) is the current number of calculation cycles.

3.7. Calculation of corona loss

In the AC ion flow field, the corona loss is the energy consumed by the space charge reciprocating motion. In the \( \Delta t \) time, the energy that space charge need to move:

\[
W_i = q_i E_i \Delta d
\] (20)

The total work done by the wires in one cycle is:

\[
W = \sum_{N, \text{cycle}} q_i E_i \Delta d
\] (21)

The average power of the wire corona loss is:

\[
P = fW
\] (22)

Where: \( E_i \) is the field strength of charge I; \( Q_i \) is the charge amount of the charge I; \( f \) is power frequency.

4. Analysis of Real Example

In this paper, 500 kV three-phase transmission lines with line type 4×LGJ-630 are analysed. The total length of the line is 203.364 km. The line size is shown in Figure 6, four-splitting, sub-conductor radius \( R=1.68 \) cm, and the three-phase arrangement is an inverted equilateral triangle arrangement.

![Figure 6. Line structure](image)

In this paper, In the light rain weather, the maximum value of \( R_0 \) in 1.94mm, the maximum value of \( R_0 \) in heavy rain is 2.35mm, \( p \) is 101.3kPa, \( T \) is 20°C, \( \mu_o \) is \( 5cm^{-1} \), \( \gamma_o \) is 0.009, the calculated and measured values of corona loss are listed in Table 1.

| Weather            | Three-phase calculation value | measured value |
|--------------------|-------------------------------|----------------|
| Light rain (kW/km) | 2.19                          | 2.11           |
| Heavy rain (kW/km) | 11.45                         | 10.42          |

From Table 1, it can be seen the calculated values by this method are in good agreement with the measured values. And, the corona loss in heavy rainy days is about five times that in light rainy days.
5. Conclusion

- This paper overcomes the disadvantage of inconsistent criteria for selecting roughness coefficients in Peek's formula. Based on streamer theory, a halo model is established, and the effect of raindrops on corona field strength of conductors is considered. The calculation results of corona loss in an example are in good agreement with the measured values.

- The corona loss in rainy days is about 5 times of that in rainy days when the line model is 4 × LGJ-630.

- The numerical calculation model of corona loss in this paper is a two-dimensional spatial calculation model, which has limitations. If the influence of line sag cannot be considered, the model can be extended to three-dimensional in subsequent research.

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