Effect of Ion Flow Field on Insulator Potential Distribution Characteristics in 500kV HVDC Transmission Lines: Postprint

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Abstract

Due to the presence of space charge around ultra-high voltage DC transmission lines, the electric field distribution in the vicinity of DC transmission lines is complex, exerting an influence on the flashover of nearby insulators. This paper presents computational simulations of the ion flow field near a 500kV monopolar high-voltage DC line based on the upwind finite element method, adopts an iterative convergence control algorithm to ensure convergence, and investigates the effect of space charge on the surface parameters of 500kV DC insulators.

Full Text

Impact of the 500kV Ion Flow Field of High Voltage DC Transmission Lines on Insulator Potential Distribution Characteristics

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Abstract

The presence of space charge around ultra-high voltage DC transmission lines creates a complex electric field distribution near the lines, which significantly affects insulator flashover behavior. This paper simulates the ion flow field near a 500kV single-pole high-voltage DC transmission line using the upstream finite element method, employing an iterative convergence control algorithm to ensure computational stability. The study investigates how space charge influences the surface electrical parameters of 500kV DC insulators.

Keywords: Ultra-high voltage, space charge, DC power transmission, insulator, flashover, ion flow field
Classification: TM85

1 Introduction

High-voltage DC transmission technology offers significant advantages for long-distance, large-capacity power delivery and plays a crucial role in China' s power grid infrastructure. However, HVDC development faces substantial technical challenges. Compared with AC transmission lines, the space charge surrounding HVDC lines creates distinctly different electric field characteristics, substantially affecting the field distribution of nearby electrical equipment. Since insulators are located in close proximity to transmission lines, they experience particularly pronounced effects, and the electric field potential values on insulator surfaces have critical practical significance for grid stability. Therefore, research on the ion flow field near DC transmission lines is essential.

During HVDC line operation, corona discharge occurs when the electric field intensity at the conductor surface exceeds the breakdown strength of air, generating space charge. These charges produce an electric field in space, resulting in different field distributions for DC and AC lines. When corona discharge occurs on HVDC lines, the resulting space charge significantly impacts insulator performance, severely affecting grid safety. To ensure safer DC transmission operation, research on calculation methods for voltage and electric field distribution along DC insulator strings is necessary. Such studies provide deeper understanding of insulator performance in DC lines, facilitate optimized design specifically for DC insulators, and support further research on surface discharge and pollution flashover. This work is significant for the optimized design and stable operation of DC line insulators, ultimately helping to resolve HVDC technical challenges.

This paper solves the Poisson equation and current continuity equation that describe the ion flow field of DC transmission lines, proposes an improved iterative method, and investigates the ion flow field and wind speed effects based on the Kapzov assumption. Using Matlab programming and the finite element method, the influence of space charge on the electric field and potential distribution along 500kV insulator surfaces is calculated.

2 Mathematical Model

2.1 Ion Flow Field Control Equations

During operation of ultra-high voltage DC transmission lines, corona phenomena generate numerous charged ions, whose movement forms an ion flow. Considering wind speed effects and based on the specific operating environment of HVDC lines and Maxwell' s equations, the governing equations for the ion flow field are:

! 2!= “(” + ““”) /#0
E = ! “!
J + =!+ (K+E + w)
J ! =!! (K !E ! w)
!” J + = #R!+!! / e
!” J # = #R!+!! / e

where is the electric potential; and are positive and negative space charge densities, respectively; is the permittivity of air; E is the resultant electric field intensity; J and J are positive and negative ion current densities; K and K are positive and negative ion mobilities; w is wind speed; R is the ion recombination coefficient; and e is the elementary charge.

2.2 Basic Assumptions

To facilitate ion flow field analysis, this study adopts the following assumptions:

(1) The space around HVDC transmission lines contains two polarity charges. Since the ionization layer thickness is much smaller than the conductor height above ground and inter-electrode distances, its thickness is neglected.

(2) The conductor corona is considered stable during calculation, with transient processes ignored.

(3) The corona near conductors remains stable, with constant corona onset field strength (Kaptzov assumption).

(4) Ion mobility k and recombination coefficient r are treated as constants independent of other variables.

(5) Space charge diffusion is neglected, as it is negligible compared to the electric forces acting on charges, thus ignoring diffusion introduces no significant error.

(6) When considering wind conditions, wind speed variations are ignored, with wind treated as constant and stable.

(7) Tower effects and non-uniform corona distribution are neglected, reducing the three-dimensional problem to two dimensions.

The ground-level synthetic electric field constraint equation is:

n =!i (n!1) 1+µ
Emax ! Ec

where i is a correction factor and Emax is the maximum field strength at the conductor surface.

The corona onset field strength is calculated by:

Ec = 29.8m! 1+

where r is the conductor radius, m is the conductor surface roughness coefficient, and is the relative air density.

2.3 Model Solution

Solving the ion flow field of DC transmission lines requires boundary conditions for the Poisson equation and current continuity equations (1)-(6). Since the space charge densities , and potential at each node are unknown, this paper employs an iterative solution method. Initially, approximate charge density values at each node are determined using the coaxial cylinder charge density formula. Based on these values and boundary conditions, the potential and field strength at each node are calculated. Subsequently, the current continuity equation is solved using these field strengths to obtain updated space charge densities at all nodes. New potentials and field strengths are then calculated from the updated charge densities. This process repeats until both the electric field strength and space charge density at all nodes simultaneously satisfy the specified convergence criteria, at which point the solution is obtained. The calculation flowchart is shown in [Figure 1: see original paper].

The conductor surface charge equation used in this paper is:

4” 0U 0Eg (U !U 0) rHEcU 5!

where Eg is the nominal field strength near the ground directly below the conductor, r is the conductor radius, H is the conductor height, and U is the corona onset voltage.

The charge density iteration formula is:

$\times 10$

The value is selected as (Emax - Ec)/Emax, enabling the program to automatically adjust the surface charge variation speed based on results. This allows rapid convergence when surface errors are large while slowing variations near convergence to maximize accuracy. After each iterative correction, the next iteration is performed. Once convergence conditions are met, the iteration terminates.

4 Results and Analysis

4.1 Space Charge Distribution Under Ion Flow Field

This paper uses self-programmed Matlab software with the finite element method to calculate space charge near transmission lines. The model parameters are: conductor radius of 0.02 m, height above ground of 20 m, corona onset field strength of 35 kV/m, and corona onset voltage of 329 kV [6].

Calculations were performed for wind speeds of 2 m/s, 4 m/s, 6 m/s, and 8 m/s along the positive x-axis. The spatial charge density distributions under different wind speeds are shown in [Figure 2: see original paper] through [Figure 5: see original paper]. The results demonstrate that as horizontal wind speed increases from 0 m/s to 4 m/s, wind exerts a noticeable influence on space charge distribution near conductors. The maximum charge density is proportional to wind speed, increasing with wind velocity, and the overall distribution shifts significantly in the wind direction.

4.2 Influence of Space Charge on Insulator Surface Field Parameters

In ultra-high voltage DC transmission systems, numerous environmental factors can degrade insulator electrical performance, causing operational failure. Therefore, in-depth study and analysis of insulator surface electric fields and potentials is necessary. This section calculates insulator electric field and potential distributions in the presence of space charge and compares them with AC line operation conditions. The insulator model parameters are listed in .

** Insulator Main Dimensions and Parameters**

Parameter	Value
Rated mechanical load (kN)	[value]
Disc diameter (mm)	[value]
Core rod diameter (mm)	[value]
Leakage distance (mm)	[value]
Insulation length (mm)	[value]
Single-side metal end length (mm)	[value]

The electric field and potential distributions without space charge are shown in [Figure 6: see original paper] and [Figure 7: see original paper], respectively. Under space charge conditions, the distributions are shown in [Figure 8: see original paper] and [Figure 9: see original paper]. The spatial potential is determined by both transmission line potential and space charge, showing a significant overall potential increase due to space charge effects.

In post-processing, electric field and potential values at insulator shed edges were extracted. [Figure 10: see original paper] compares the potential distribution with and without space charge, while [Figure 11: see original paper] compares the electric field distribution. The results show that space charge substantially increases shed potential values. Comparing the two conditions reveals that with space charge, the electric field strength at the high-voltage end increases significantly, while the field at the low-voltage end decreases slightly. Space charge thus substantially affects both potential and electric field strength on insulator surfaces. This occurs because the corona layer around conductors contains charges of the same polarity, which contribute to the spatial potential distribution.

5 Conclusions

This paper simulates and analyzes the influence of space charge distribution around 500kV UHVDC transmission conductors on insulator surface electric field distribution, yielding the following conclusions:

1. For ±500kV single-pole lines, wind speed effects on space charge distribution near conductors were analyzed. Wind speed increases the maximum space charge density and causes offset in the wind direction. The spatial charge distribution characteristics were determined.
2. The potential and electric field distributions along suspension insulators were studied and analyzed under space charge conditions. The electric field strength at the insulator high-voltage end is lower than in the electrostatic field, while the low-voltage end field strength is higher, increasing by approximately 8%.

References

[1] Wang Feng, Fan Jingmin, Li Min, et al. Application of the high precision upstream FEM to calculation of the Ionized field of HVDC transmission line. High Voltage Engineering, 2016(4): 1061-1067.
[2] Wang Feng, Li Min, Lü Jianhong, et al. Effect of wind speed on ion flow field under UHVDC transmission lines. High Voltage Engineering, 2016(9): 2897-2901.
[3] Yuan Haiyan, Fu Zhengcai. Calculation of ion flow for UHV bipolar DC transmission lines. National Doctoral Academic Forum, 2008.
[4] Qiao Ji, Zou Jun, E Tianlong, et al. Calculation of ground-level electric field and ion flow of HVDC transmission lines with shield wires. Power System Technology, 2017, 41(7): 2386-2392.
[5] Hu Q, Shu L, Jiang X, et al. Influence of air pressure and humidity on positive direct current corona discharge performances of the conductor in a corona cage. International Transactions on Electrical Energy Systems, 2014, 24(5): 723-735.
[6] Liu Zhenya. UHV Grid. Beijing: China Economic Publishing House, 2005: 1-10, 267-289.
[7] Liu Zhenya. UHV DC Transmission Lines. Beijing: China Electric Power Press, 2009: 1-17, 114-143.
[8] Wu Zhancheng, Zhang Xijun. Gas Discharge. Beijing: National Defense Industry Press, 2012.
[9] Dai Xijie. Fundamentals of DC Transmission. Beijing: Water Resources and Electric Power Press, 1990: 230-264.

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