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An improved method to calculate the radio interference of a transmission line based on the flux-corrected transport and upstream finite element method

Deng Jun [a, b, *], Hao Yanpeng [a], Li Licheng [a]

[a] School of Electric Power, South China University of Technology, Guangdong 510640, China
[b] Maintenance & Test Center, EHV, China Southern Power Grid, Guangzhou, Guangdong 510663, China

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A B S T R A C T

The radio interference (RI) from HVDC transmission lines can block communication systems. In this paper the RI of a HVDC transmission line has been analyzed by the superposition of the electromagnetic field generated by the corona current based on phase-model transformation, where the corona current can be solved by the flux-corrected transport and finite difference method combining the upstream finite element method for bipolar conductor model instead of corona cage or excitation function. Our calculated values for 0.5 MHz RI from the proposed method compare well with measured values from a 800 kV HVDC test line established in China. With this validation, we find that RI should increase with temperature, increase with altitude, and vary in a complex way with relative humidity. Therefore, the proposed method can be adopted in transmission lines design and electromagnetic environment evaluation.

Introduction

High voltage direct current (HVDC) transmission technology has been developed for the demand of long distance and large capacity power transmission. However, the radio interference (RI) due to the corona of HVDC transmission lines can degrade the performance of receive devices, cause the signal error or even block the communication system. Consequently, the RI of different atmospheric parameters should be accurately analyzed during the design for electromagnetic environment limit.

Theoretical studies and experimental were carried out to analyze the characteristic of RI for transmission lines. The empirical formula and excitation function recommended by the International Special Committee on Radio Interference (CISPR) have been popularly employed to calculate the RI limit and to select of the conductor type [1–3]. Using the recommended empirical formula and excitation function is restricted when calculating the RI for given atmospheric conditions such as humidity, temperature, altitude, etc. Consequently, the corona cages or short test conductors have been proposed for the analysis of the atmospheric parameters on the RI investigation by EPRI of China and CSG, respectively [4,5]. However, the huge difference between the corona cage and the natural environment of a practical transmission line have resulted in RI calculation defects and restricted the applicability of experimental methods. Hence, the simulation method should be developed for the RI of given atmospheric conditions.

In this paper, the corona current is simulated for different environment parameters by finite-difference and flux-corrected transport method. Furthermore, the phase-model transformation is employed to decouple corona current propagation of bipolar HVDC conductors. Moreover, the RI for the given environment parameters can be obtained by the superposition of negative and positive conductor. Finally, the actual transmission line model and measurement data should be present to verify the proposed method.

Mathematical model

To calculate the RI of DC transmission lines for different environmental conditions, first the corona current must be found. Ion movements in the ionization region are analyzed to find the corona current. The ground RI is then found from the field strength generated by the bipolar corona.

* Corresponding author.
E-mail addresses: reacherempire@163.com, 165284950@qq.com (D. Jun).

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Basic equation for ionization region of DC conductor

According to charge continuity equations, the corresponding differential equations for densities of the electron, positive and negative ions and the electric potential for the vertical section of transmission lines can be defined by

$$\begin{aligned}
&\frac{\partial N_e}{\partial t} + \nabla\cdot(\mu_e N_e E - D_e \nabla N_e) = (\alpha - \eta)N_e - \beta_{ep} N_e N_P + S \\
&\frac{\partial N_P}{\partial t} + \nabla\cdot(\mu_P N_P E) = \alpha N_P - \beta_{ep} N_e N_P - \beta_{PN} N_e N_P + S \\
&\frac{\partial N_N}{\partial t} + \nabla\cdot(\mu_N N_N E) = \alpha N_N - \beta_{PN} N_e N_P \\
&\nabla^2\cdot\phi_1 = -\frac{(N_P - N_N - N_e)}{\varepsilon_0}
\end{aligned} \tag{1}$$

where N_P, N_N and N_e are densities of the positive ions, negative ions and electron, respectively. μ_e, μ_P, μ_N are the drift velocity of electrons, positive and negative ions, respectively. D_e is the diffusion coefficient of electrons, α and η are the ionization and attachment coefficients, β_{ep} is the electron-positive ion recombination coefficient, β_{PN} is the negative-positive ion recombination coefficient. S denotes the generation of the electrons and positive ions through ionization of photo and background radiation. ϕ_1 and ε_0 are the electric potential and the air permittivity. However, the above parameters can be obtained from Ref. [6]. α, η and atmospheric pressure p can be defined as follows.

$$\begin{aligned}
&p = 101.3e^{-0.12h} \\
&\alpha = \frac{p_w}{p}\alpha_w + \frac{p_d}{p}\alpha_d \\
&\eta = \frac{p_w}{p}\eta_w + \frac{p_d}{p}\eta_d
\end{aligned} \tag{2}$$

where h is the altitude height, p_w, α_w, η_w are atmospheric pressure, the ionization and attachment coefficients for the wet air while p_d, α_d and η_d are parameters for dry air [7].

Basic equation for ion movement region of DC conductor

In this region, ions move towards oppositely charged ions or towards conductors having the opposite polarity. Therefore, the Poisson and current continuity equations governing the bipolar ion field are [8].

$$\begin{aligned}
&\nabla^2\cdot\phi_2 = (\rho_+ - \rho_-)/\varepsilon_0 \\
&E_s = -\nabla\phi_2
\end{aligned} \tag{3}$$

$$\begin{aligned}
&\nabla\cdot(\rho_+ k_+ E_s) = -R\rho_+\rho_-/e \\
&\nabla\cdot(\rho_- k_- E_s) = R\rho_+\rho_-/e
\end{aligned} \tag{4}$$

where ρ_+ and ρ_- are positive and negative space charge density, respectively. k_+ and k_- are positive and negative ion motilities, j^+ and j^- are the positive and negative current density, e and R are the electron charge and coefficient of recombination, respectively. E_s is the total electric field.

The corona current for bipolar conductor

The corona current can be computed by integrating the particle current densities going into the bipolar surface. Hence, the corona current for bipolar sub-conductor is expressed by the term of I_s

$$I_s = \frac{\iint\limits_{S_a} e(\mu_P N_P - \mu_N N_N - \mu_e N_e)dS}{S_3} \tag{5}$$

where S_a and S_3 are the integration surface and its area of the positive or negative polar conductor, respectively.

The phase-model transformation for corona current of bipolar conductors

A HVDC transmission line is a parallel, multi-conductor system where the corona current propagation on any one conductor is electromagnetically coupled to the other conductors. However, the current propagation on any one conductor may be decoupled by the phase-model transformation. Hence, every conductor current can be calculated by the single wave process in model domain, and the corona current can be obtained by the model to phase domain transformation.

The basic equations of transmission lines are

$$\frac{d^2[I_{ph}]}{dx^2} = [Y][Z][I_{ph}] \tag{6}$$

where The element of the vector $[I_{ph}]$ is corona current of every polar conductor from the Eq. (5). $[Z]$ and $[Y]$ are per unit length series impedance and shunt admittance matrices at same the frequency, respectively. The element of $[Z]$ and $[Y]$ can be defined by

$$\begin{aligned}
&z_{ij} = \begin{cases} j\omega\dfrac{\mu_0}{2\pi}\ln\dfrac{2(h_i + P)}{r_i} & i = j \\ j\omega\dfrac{\mu_0}{2\pi}\ln\dfrac{\sqrt{(h_i + h_j + 2P)^2 + d_{ij}^2}}{\sqrt{(h_i - h_j)^2 + d_{ij}^2}} & i \neq j \end{cases} \\
&y_{ij} = \begin{cases} \dfrac{1}{2\pi\varepsilon_0}\ln\dfrac{2h_i}{r_i} & i = j \\ \dfrac{1}{2\pi\varepsilon_0}\ln\dfrac{D_{ij}}{d_{ij}} & i \neq j \end{cases}
\end{aligned} \tag{7}$$

where h_i and r_i are the conductor height and radius, d_{ij} is the distance between the conductor i and j, D_{ij} is the distance between the conductor i and j's ground mirror. The complex penetration depth P can be obtained in Ref. [9]. μ_0 and ω are the air permeability and the frequency.

If the diagonal matrix λ^2 is composed of the eigenvalues for matrix $[Y][Z]$, the corresponding eigenvectors matrix and its inverse matrix are S and S^{-1}, respectively. Therefore, the Equation (6) can be written as

$$S^{-1}S\frac{d^2[I_{ph}]^m}{dx^2} = S^{-1}[Y][Z]S[I_{ph}]^m \quad = \lambda^2[I_{ph}]^m [I_{ph}]^m = S^{-1}[I_{ph}] \tag{8}$$

The Eq. (8) is second-order ordinary differential equations with constant coefficients. Hence, the solution of Eq. (8) and the corona current $[I_{ph}]^k$ decoupled by phase-model transformation will be

$$\begin{aligned}
&[I_{ph}]^m = \frac{1}{2}e^{\lambda x}S^{-1}[I_{ph}] \\
&[I_{ph}]^k = S^{-1}[I_{ph}]^m
\end{aligned} \tag{9}$$