Calculation of Ion-Flow Field of HVDC Transmission Lines in the Presence of Wind Using Finite Element-Finite Difference Combined Method with Domain Decomposition

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A new combined method adopting the domain decomposition is proposed for analyzing the ion flow field of HVDC transmission lines including the effect of the transverse wind. The calculation process of the Poisson equation is iterated with Dirichlet-Neumann algorithm to coordinate the solution between adjacent subdomains. The upstream finite element method is used with dense triangle mesh in the vicinity of bundles conductors to guarantee the accuracy where the electric field strength changes severely.The upstream finite difference method is proposed and the larger uniform quadrilateral grid is applied to simulate the ion flow field in the rest of the region to reduce the amount of the mesh elements with a satisfactory precision. Suitable methods and reasonable distribution of the grid can be used in different subdomains to improve the calculation efficiency. Finally calculations are well compared with experimental data and results in the presence of wind in the previous literature.

***Index Terms*—Finite difference methods, finite element analysis, HVDC transmission, nonlinear equations, space charge**

I. Introduction

The wind velocity has a significant influence on the ion-flow field of HVDC transmission lines. Considering the impact of the wind on the ion trajectory, the electric field-space charge coupled problem becomes more complex. In this paper, the ionized field is analysed using the domain decomposition method (DDM) including the wind velocity. The computed region is split into several subdomains and Dirichlet-Neumann algorithm [1] (D-N algorithm) is used to calculate the Poisson equation. The small domains near bundle conductors are solved by the upstream finite element method (FEM) and the triangular elements are used. The rest of the region is decomposed into quadrilateral mesh and the upstream finite difference method (FDM) is introduced. The electric field on one node can be easily obtained and the upstream element is determined conveniently with the FDM. The distribution of the mesh could be arranged properly with the DDM and the number of elements is limited in a reasonable extent. The results show reasonable agreement with the measured and computed values in previous literature.

II. Calculation Method

A. Bipolar Ion-Flow Field Problem

For the bipolar lines, the unknowns of the ionized field, i.e. the electric potential Φ, the absolute value of the space charge densities ρ_+ and ρ_- are determined by Poisson equation

$$\Delta\Phi = -(\rho_+ - \rho_-)/\varepsilon_0 \tag{1}$$

and the continuity equations for ion densities

$$\nabla \cdot \boldsymbol{j}_\pm = \mp R\rho_+\rho_-/\mathrm{e} \tag{2}$$

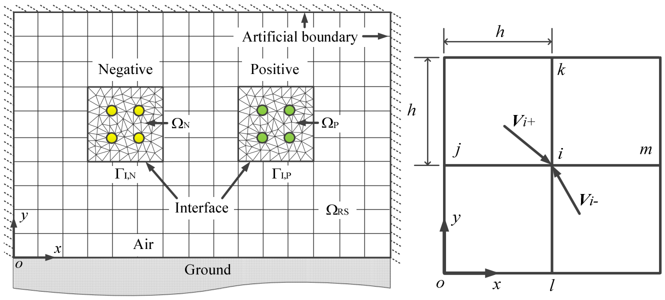
where R is the recombination coefficient and e is the elementary charge. The current density $\boldsymbol{j}_\pm$ is defined as

$$\boldsymbol{j}_\pm = \rho_\pm(-k_\pm\nabla\Phi \pm \boldsymbol{W}) \tag{3}$$

where k_+ and k_- are positive and negative ion mobilities respectively and $\boldsymbol{W}$ is wind velocity. The following boundary conditions are required: The potentials on the conductor surface and the ground are the corresponding values; the electric field on the conductor surface remains at the corona onset value E_{on}; the potentials on the artificial boundary are same as the case of the space-charge-free electric field.

B. Finite Element-Finite Difference Combined Method with Domain Decomposition for Solving Ionized Field

The size of the computed region is several orders of magnitude greater than the area of bundle conductors. A more reasonable mesh distribution could be obtained by the DDM rather than an automatic mesh generation. Let the whole region Ω be portioned into three non-overlapping subdomains, i.e., Ω_P, Ω_N and Ω_{RS} as shown in Fig.1 (a). Ω_P and Ω_N are the small areas surrounding the positive and negative conductors, respectively. Ω_{RS} is the rest of the calculation space. The interfaces between two subdomains are $\Gamma_{I,P}$ and $\Gamma_{I,N}$, respectively. In Ω_P and Ω_N, the upstream FTM is used with the dense triangular meshes. The larger and uniform grid can be applied in the domain Ω_{RS} and the upstream FDM (discussed in Section II-C) is introduced. The D-N algorithm (present in Section II-D) is carried out to solve the Poisson equation in the whole domain.



(a) (b)

Fig. 1. Combined method with domain decomposition. (a) Computed domain of ionized field. (b) Upstream element for FDM.

The computational process is described as follows: Firstly, the initial charge densities on the conductor surface are set [2] and the space-charge-free electric field is calculated. Next, the space charge densities are updated with the upstream FEM in Ω_P and Ω_N and using the upstream FDM in Ω_{RS}, respectively. According to the new charge densities, the potential of the whole region is calculated with D-N algorithm [1]. The charge densities on the conductor surface are then modified by the approach in [3]. This process is repeated until the Kaptzov's assumption is met and the errors of the ion densities between two iterative steps are within the limits.

C. Calculation of Current Continuity Equation in Ω_{RS} Using Upstream Finite Difference Method

Substituting (2) into (3), we have

$$\boldsymbol{V}^{\pm}\cdot \mathrm{grad}\rho_{\pm} = -\frac{k_{\pm}}{\varepsilon_0}(\rho_{\pm})^2 + \left(\frac{k_{\pm}}{\varepsilon_0}-\frac{R}{\mathrm{e}}\right)\rho_{+}\rho_{-} \qquad (4)$$

where $\boldsymbol{V}^{+}=-k_{+}\cdot\mathrm{grad}\Phi+\boldsymbol{W}$ and $\boldsymbol{V}^{-}=k_{-}\cdot\mathrm{grad}\Phi+\boldsymbol{W}$ are respectively the mobility velocity of the positive and negative ions. The upstream FEM has been present in [2]-[3] with the triangle element. For the quadrilateral mesh, the FDM is proposed. The nodes j and k are defined as the upstream nodes in Fig.1 (b) and for the positive ion density on node i

$$\mathrm{grad}\rho_{i+} \approx \mathrm{sgn}(\boldsymbol{V}_{ix}^{+})\frac{\rho_{i+}-\rho_{j+}}{h}\hat{\boldsymbol{x}} + \mathrm{sgn}(\boldsymbol{V}_{iy}^{+})\frac{\rho_{i+}-\rho_{k+}}{h}\hat{\boldsymbol{y}}\ . \qquad (5)$$

Therefore (4) can be expressed as

$$\begin{aligned}&(\rho_{i+})^2 + \left[\frac{\varepsilon_0}{k_+}\left(\frac{|\boldsymbol{V}_{ix}^{+}|}{h}+\frac{|\boldsymbol{V}_{iy}^{+}|}{h}\right) + \left(\frac{\varepsilon_0 R}{k_+\mathrm{e}}-1\right)\rho_{i-}\right]\rho_{i+} \\ &-\frac{\varepsilon_0}{k_+}\left(\frac{|\boldsymbol{V}_{ix}^{+}|}{h}\rho_{j+}+\frac{|\boldsymbol{V}_{iy}^{+}|}{h}\rho_{k+}\right)=0\end{aligned} \ . \qquad (6)$$

The non-smaller root ρ_{ir} of (6) is selected as the positive space charge density. During the calculation, the ion densities on the nodes in the domain Ω_{RS} are solved one by one from the interface to outward nodes. The solution of the negative density is similar to the positive case. It is obvious that the search of upstream nodes is simple to implement. Moreover, when calculating the mobility velocity of the ions, the electric field strength on node i can be obtained directly by adopting the central difference scheme with high accuracy rather than by averaging the values of adjacent elements in the FEM [2].

D. D-N Algorithm for Calculating Poisson Equation in Ω

The Dirichlet-Neumann algorithm is introduced on the account of the application of the difference meshes and methods in the subdomains. Firstly, the initial values on the interface Γ_I (i.e. $\Gamma_{I,P}$ and $\Gamma_{I,N}$) are set as the potentials of the space-charge-free electric field. Then the electric fields in the subdomains Ω_P and Ω_N are calculated with the FEM in the presence of space charges, respectively. The normal derivative on Γ_I is modified to be the Neumann boundary condition in Ω_{RS}. Next, the potential in Ω_{RS} is analysed by the FDM as a mixed Neumann-Dirichlet problem and the new values of the potentials on Γ_I will be obtained. The iteration loop will be carried out until the deviations of the potentials on Γ between two steps are within the allowable limit.

III. Validation and Application

The influences of the wind on the ion current density for a ±900kV bipolar line and a reduced-scale unipolar model are analysed, respectively. The line configurations are seen in [4]-[5]. The comparisons of the measured data, the previous results of the flux tracing method (FTM) and the calculations are shown in Fig.2. It indicates that the results of the proposed method have reasonable agreements with the measurement.

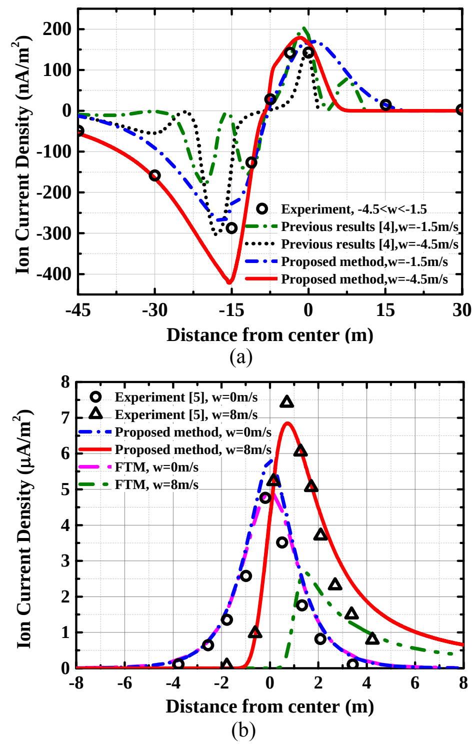


Fig. 2. Ground-level ion current density. (a) Full-scale. (b) Reduced-scale.

IV. Conclusion

The ion flow field in the presence of wind is analysed with the proposed combined method. Proper grids and methods are respectively used in different subdomains to reduce the amount of the meshes and increase the efficiency of the calculation, which will be discussed in the full paper.

V. References

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