

A Multi-slice Field-Circuit Coupling Method for Transient Electromagnetic Field Analysis and Temperature-rise Computation of Gas-Insulated Transmission Lines

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Abstract—Precise and swift computation of the transient electromagnetic field and temperature elevation during fault conditions of GIL is essential for optimizing design and ensuring the safe operation. However, utilizing full-scale 3D finite element methods for calculating the full-scale transient electromagnetic field of GIL is impractical due to the immense computational resources and time required. The equivalent circuit method, while highly efficient, lacks the ability to intuitively depict the transient field distribution and accurately calculate ohmic loss for coupling transient thermal-fluid field computations. This paper introduces a lightweight 2D multi-slice electromagnetic field-circuit coupling model to compute the transient electromagnetic field and ohmic loss within GIL. This approach enables the transient analysis of GIL devices spanning up to tens of kilometers to be practically feasible, improving efficiency in optimization design, and providing a fast and convenient means to improve operational safety and reliability.

Keywords—Field-circuit coupling, GIL, multi-slice, ohmic loss, temperature rise.

I. INTRODUCTION

Gas-insulated transmission lines (GIL) have been widely used in power systems due to their advantages such as large transmission capacity and low electromagnetic (EM) interference [1, 2]. Achieving and maintaining low and consistent temperature levels is paramount for the efficient operation of GIL. In order to minimize the occurrence of failed qualification tests against the IEC standard 62271 validation [3], precise prediction of temperature rise within GIL systems is imperative. This necessitates accurate computation of losses, as they serve as the primary heat source for temperature rise calculations.

The allocation of losses hinges on the configuration of the GIL structure, which comprises several standardized segments. Each segment typically spans around 20 meters, while the overall project length varies from hundreds of meters to tens of kilometers. To mitigate induced voltage and disperse induced current effectively, multiple interphase shunts and grounding wires are strategically arranged along the pipeline. Solving ohmic losses through three-dimensional (3D) electromagnetic fields and subsequently computing temperature rise via thermal-fluid coupled analysis is not feasible due to the substantial numerical computation costs

associated with simulating the entire GIL system in 3D. To address this challenge, we developed a code using FreeFEM++ [2]. For a GIL model with a length of only 2 meters, the number of mesh elements can reach around 1.8 million, requiring approximately 19.82 minutes for computation on a computer equipped with an Intel Core i5-9500 CPU and 64 GB RAM. However, as the model length exceeds 5 meters, conventional personal computers struggle to manage the computational workload.

There is limited research available on Gas-Insulated Lines (GIL) that effectively tackles the computational hurdles associated with implementing the finite element method (FEM) to solve the induced eddy currents in practical, long-distance GIL systems. Current methodologies for analyzing losses and temperature rise often resort to either a two-dimensional (2D) cross-section [4] or a simplified 3D coaxial cylindrical structure of fixed length [5]. However, these approaches fail to accurately represent real-world GIL configurations, as they overlook crucial elements such as interphase shunts and grounding setups.

In this work, the system voltage source is imposed to GIL input terminals. Voltage degrees of freedom (DoF) are introduced at the solid conductor terminals. The transient magnetic field governing equations, expressed using the A - ϕ method, and Kirchhoff's voltage-current law are employed. The electromagnetic field-circuit coupling model combined with the 2D multi-slice technique for replacing 3D simulation is derived, taking into account skin effects, proximity effects, and the influence of interphase-shunts. The numerical model is then used for simulation to obtain the transient magnetic field distribution of GIL, spanning several tens of kilometers. Additionally, ohmic losses are provided for thermal-fluid coupling field calculations to obtain the transient temperature-rise.

II. PROPOSED FIELD-CIRCUIT COUPLED METHOD

A. 3D MVP Formulation for Eddy-current Fields

The thermal rise in Gas-Insulated Lines (GIL) is primarily influenced by the ohmic loss of both the conductor and the enclosure. These losses can be derived from computations of the eddy-current field. When the steady-state excitation current at power frequency is provided, the electromagnetic field distribution can be determined using frequency-domain finite element formulation. Generally, since no highly permeable iron material is used in the GIL, the eddy-current field is usually solved by the A - ϕ method with nodal

elements [2], which is also convenient for applying voltage sources and coupling with external circuit excitations.

Under short-circuit conditions of the conductive-rods with transient voltage waveform, it is necessary to solve the transient magnetic field governing equations in time-domain:

$$\nabla \times \frac{1}{\mu} (\nabla \times \mathbf{A}) - \nabla \left(\frac{1}{\mu} \nabla \cdot \mathbf{A} \right) + \sigma \frac{\partial \mathbf{A}}{\partial t} + \sigma \nabla \varphi = \mathbf{J}_s = \frac{\mathbf{I}}{S} \quad (1)$$

$$\nabla \cdot (-\sigma \frac{\partial \mathbf{A}}{\partial t} - \sigma \nabla \varphi) = 0 \quad (2)$$

where $\mathbf{A}$ is the magnetic vector potential (MVP), φ is the electric scalar potential, μ is the magnetic permeability, σ is the electrical conductivity, ω is angular frequency, and $\mathbf{J}_s$ is the source current density of the conductive-rod. And $\mathbf{J}_s$ will not appear explicitly at the right hand side if the voltage source or external circuit is given.

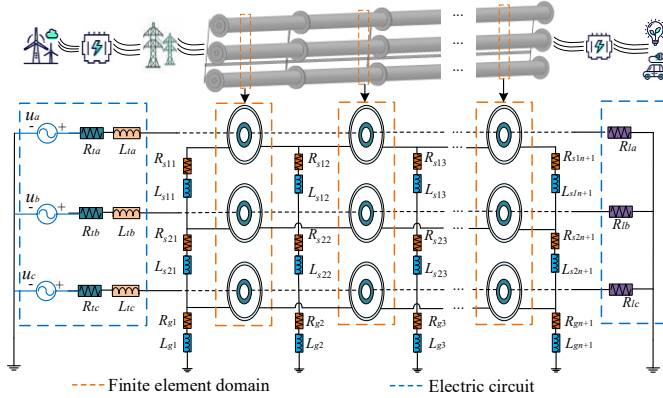


Fig. 1 Multi-slice field-circuit coupling model of 1000-kV GIL.

B. 2D field-circuit coupling Multi-slice FEM

Fig. 1 depicts the schematic diagram of the GIL's cross-section-based multi-slice field-circuit coupling model derived from the actual 3D model. The conduction current and ohmic loss of the conductive rod and enclosure are determined by external power supply excitation, transmission-line impedance, load impedance, and other electric network parameters. The governing equation for the 2D transient magnetic field can be derived from equations (3) and (4). In the 2D planar field associated with the cross-section extracted from the solution domain, the magnetic vector potential (MVP) exhibits only its axial component on the selected cutting surface, satisfying the Coulomb gauge automatically, and simplifying the double-curl operator to the Laplace operator.

Taking the MVP for each slice corresponding to each segment, the loop currents and the node voltages as unknown variables, combining the magnetic field equation and the circuit balance equations from using KCL and KVL, the final discretized equations of the GIL's transient magnetic field-circuit coupled equation can be established. The transient loss $P(t)$ per unit length of the conductive region can be calculated from the solution of coupled field-circuit model:

$$P(t) = \sum_{i=1}^n P_i = \sum_{i=1}^n \int_{S_i} \frac{\mathbf{J}_i \cdot \mathbf{J}_i^*}{2\sigma_{20}/(1+\alpha(T-20))} dS_i \quad (4)$$

$$P_C = \sqrt{\frac{1}{C} \int_0^C P^2(t) dt} \quad (5)$$

where P_i is the ohmic loss inside i -th element, $\mathbf{J}_i$ and $\mathbf{J}_i^*$ are the current density and its conjugate inside the element, n is

the total number of elements in the conductive region, $\sigma(T)$ is the electric conductivity when the absolute temperature is T , and S_i is the area of element i . σ_{20} is the electrical conductivity of the aluminum alloy at 20 °C, and α is the temperature coefficient of resistivity, generally taken as 0.0042. P_C is the effective value of loss within a power frequency cycle.

C. Temperature Rise Calculation Model

To accommodate its potential length spanning several kilometers axially, the GIL is segmented into standardized sections using external interphase-shunts. These segments are sealed with insulators at both ends, containing the insulation gas flow within each segment. Consequently, heat transfer occurs via natural convection within a closed cavity without inlet or outlet. Apart from the electrical connection structure at the segment ends, the temperature gradient along the axial direction approaches zero. The heat balance equation for the radial section is as follows:

$$\begin{cases} P_c = Q_{cc} + Q_{cr} \\ P_c + P_e = Q_{ec} + Q_{er} \end{cases} \quad (6)$$

P_c and P_e are the ohmic losses on the conductor and the enclosure, respectively, Q_{cc} and Q_{cr} are the heat transferred by convection and radiation from the conductor, respectively, and Q_{ec} and Q_{er} are that of the enclosure.

III. CONCLUSIONS

Utilizing the 2D multi-slice electromagnetic field-circuit coupling model, induced current, and ohmic loss of GIL under transient conditions are calculated. These losses are then incorporated into the thermal-fluid coupling field for temperature-rise computations. Compared with existing methods, the proposed one tackles challenges related to the huge cost of using full-scale 3D finite element simulations. Additionally, it surpasses the limitations of the fully pure equivalent circuit method, offering a solution to the difficulty in obtaining transient electromagnetic field distributions and accurately calculating ohmic loss for the thermal field.

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