A Method of Finite Difference Time Domain Combined with Electromagnetic Field and Transmission Lines

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Transmission structures of gas insulated switchgear (GIS) were mainly composed of uniform transmission line structures and three-dimensional non-transmission line structures. In order to accurately and efficiently calculating very fast transient overvoltage (VFTO) generated by switch operation in GIS, this paper presented a method of finite difference time domain (FDTD) combined with electromagnetic field and transmission lines (3D-1D FDTD). Three-dimensional electromagnetic field computation with FDTD and uniform transmission line computation with FDTD were respectively used to model three-dimensional non-transmission line structures and uniform transmission line structures in GIS. In this paper, coupled boundary conditions connected with electromagnetic field and transmission lines, and stability conditions of iterative calculation were discussed. A long straight GIS busbar as an example, transient voltages and transient currents at different locations were calculated by 3D-1D FDTD and one-dimensional transmission line equivalent circuit model, both calculation results were contrasted to verify the effectiveness of 3D-1D FDTD.

Index Terms**—gas insulated switchgear, very fast transient overvoltage, combined with electromagnetic field and transmission lines, finite difference time domain, modeling and calculating.**

I. INTRODUCTION

Equivalent circuit models [1], [2], [3] or three-dimensional electro-magnetic field models [4], [5] are commonly used to simulate and calculate very fast transient overvoltage (VFTO) in gas insulated switchgear (GIS). Equivalent circuit models are widely adopted because of some characteristics such as simple model, easy to extract parameters, etc., in particular, equivalent circuit models of each component of GIS were proposed and recommended by Working Group WG33/13.09 on International Council on Large Electric systems (CIGRE) [1]. However, equivalent circuit models are difficult to simulate electromagnetic ware transient propagation in complex structures of GIS in addition to using three-dimensional electromagnetic field models which existence model complexity, split difficulty, consumption large amounts of computer memory and computing time.

Vast majority part of GIS are considered as transmission line structures such as busbar, branch busbar, etc., three-dimensional non-transmission line structures such as disconnector, casing, breaker are accounted for minority part of GIS. Therefore, considering calculation accuracy and computational cost, fully demonstrating advantages of equivalent circuit models and three-dimensional electro-magnetic field models, this paper presents a modeling method combined field-circuit, namely, a method of finite difference time domain combined with three-dimensional electro-magnetic field and one-dimensional transmission lines (3D-1D FDTD). Then, some simple transmission line structures of GIS can be obtained higher calculation accuracy by one-dimensional transmission lines computation with finite difference time domain method (1D FDTD); complex non-transmission line structures of GIS are calculated by three-dimensional electro-magnetic field computation with finite difference time domain method (3D FDTD).

II. 3D-1D FDTD METHOD

A. Calculation formula

Assuming distribution voltage source and distribution current source generated by incident electromagnetic wave in transmission lines were $\boldsymbol{U}_F$ and $\boldsymbol{I}_F$, equations of transmission lines in time domain are shown in formula (1), calculation formulas of 1D FDTD are first-order central difference discrete formula (1) in time and space [6].

$$\begin{cases} \dfrac{\partial \boldsymbol{U}(l,t)}{\partial l} + \boldsymbol{L}\dfrac{\partial \boldsymbol{I}(l,t)}{\partial t} + \boldsymbol{rI}(l,t) = \boldsymbol{U}_F(l,t) \\ \dfrac{\partial \boldsymbol{I}(l,t)}{\partial l} + \boldsymbol{C}\dfrac{\partial \boldsymbol{U}(l,t)}{\partial t} + \boldsymbol{gU}(l,t) = \boldsymbol{I}_F(l,t) \end{cases} \tag{1}$$

Curl equations of Maxwell equations are shown in formula (2), calculation formulas of 3D FDTD are discrete formula (2) in the form of finite difference time domain. Uniaxial perfectly matched layer (UPML) is used to absorbing boundary of 3D FDTD [7].

$$\begin{cases} \nabla \times \boldsymbol{H} = \dfrac{\partial \boldsymbol{D}}{\partial t} + \boldsymbol{J}_e \\ \nabla \times \boldsymbol{E} = -\dfrac{\partial \boldsymbol{B}}{\partial t} \end{cases} \tag{2}$$

B. Coupled boundary

1D FDTD and 3D FDTD are connected to coupled boundary, coupled boundary must be met conditions of transverse electromagnetic wave (TEM) or quasi-TEM wave propagation. Interrelation of current $\boldsymbol{I}$, voltage $\boldsymbol{U}$, electric field strength $\boldsymbol{E}$ and magnetic field strength $\boldsymbol{H}$ in Different moments is shown in Fig. 1. Seen, at the moment of $t_{i+1/2}$, $\boldsymbol{H}$ is calculated by its value of previous moment and adjacent electric field strength, $\boldsymbol{I}$ is calculated by loop integrals of $\boldsymbol{H}$. At the moment of t_{i+1}, $\boldsymbol{U}$ is calculated by its value of previous moment and adjacent current, ***E*** is calculated by potential distribution in coupled boundary.

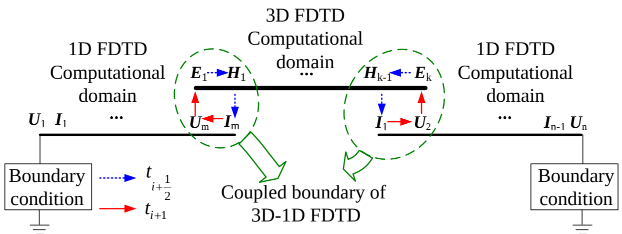


Fig. 1. Coupled boundary of 3D-1D FDTD

C. Stable conditions

Stable operation of 3D-1D FDTD method is depended on stability of FDTD format. Interrelation of time step Δt, split step Δl and signal minimum wavelength λ_{min} is expressed in formula (3). Stability factor α is generally 2 or $\sqrt{3}$, value range of dispersion factor β is from 20 to 100. Reasonable selection α and β can keep stable operation of 3D-1D FDTD method in a reasonable range of numerical dispersion.

$$\begin{cases} \alpha = \dfrac{\Delta l}{\upsilon \Delta t} \geq \sqrt{3} \\ \beta = \dfrac{\lambda_{\min}}{\Delta l} \geq 12 \end{cases} \tag{3}$$

III. Calculation Example

A long straight busbar in GIS as an example, equivalent circuit model of one-dimensional transmission lines and 3D-1D FDTD method were respectively adopted to calculate transient voltages and transient currents at different locations. Length of busbar is 1.5m, shown in Fig. 2, when using 3D-1D FDTD method, the busbar is divided into three computational domains of 0.5m length, as 1D FDTD computational domain - 3D FDTD computational domain - 1D FDTD computational domain, voltage source and load are respectively applied to both ends of busbar. Split step is 2.5×10^{-3} m, time step is 4.8×10^{-12} s. There are three observation points in the busbar, each observation point is located in the center of computational domain.

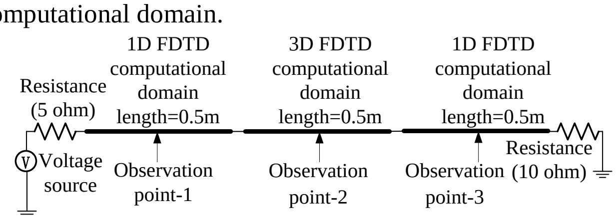
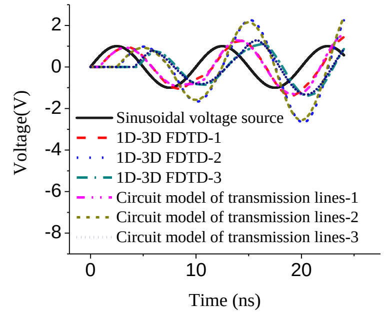
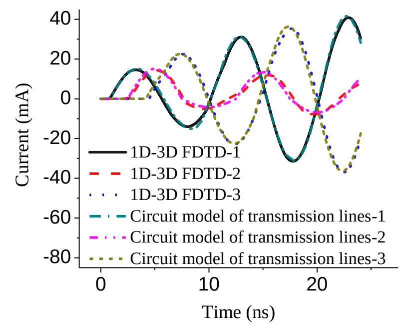


Fig. 2. 3D-1D FDTD computational model of GIS busbar

When voltage source is sinusoidal voltage source, amplitude is 1V, frequency is 100MHz, calculation time is 5000 steps, transient voltages and transient currents at three observation points are shown in Fig. 3. Seen, in the same observation point, calculated separately by equivalent circuit model of one-dimensional transmission lines and 3D-1D FDTD method, voltage and current waveforms are identical, waveforms are no divergence. Small differences between waveforms are due to 3D-1D FDTD method which is based on FDTD format, split deviation and numerical dispersion are inevitably exist in 3D-1D FDTD method. Both calculation results are contrasted to verify the effectiveness of 3D-1D FDTD method.



(a) Voltage



(b) Current

Fig. 3. Calculation results of sinusoidal voltage source as 100 MHz frequency

IV. Conclusion

This paper presents a method of finite difference time domain combined with three-dimensional electro-magnetic field and one-dimensional transmission lines (3D-1D FDTD). coupled boundary conditions, stable conditions of time-domain calculation and calculation formula of 3D-1D FDTD method are given. A long straight busbar in GIS as an example, transient voltages and transient currents at different locations are calculated by 3D-1D FDTD and one-dimensional transmission line equivalent circuit model, both calculation results are contrasted to verify the effectiveness of 3D-1D FDTD.

V. References

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