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Near field coupling to shielded cable due to switching operation in substation

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Abstract It is vital to study the electromagnetic coupling to shielded cable for improving electromagnetic anti-interference ability of secondary equipment in a substation. As a hybrid of method of moment (MoM) and transmission line method, a frequency domain model is put forward to study the near field coupling to shielded cable due to the switching operation in substation. Compared with the results of EMTP, the proposed method has been proven correct. Furthermore, this method overcomes the disadvantage of EMTP, which is only applicable for transient analysis of parallel conductors. As an example, the presented method is applied to evaluating the electromagnetic interference (EMI) to the shielded cable, whose shield is grounded at both ends, due to the switching operation in 500 kV air insulation substation (AIS).

Keywords electromagnetic coupling, shielded cable, switching operation, substation

1 Introduction

Due to the switching operation in a substation, strong spatial electromagnetic field will be generated by high voltage and large current along the busbar. The transient electromagnetic field will induce interference voltage and current at the port of the secondary equipment through transfer impedance and admittance of the shielded cable. To reduce external electromagnetic interference (EMI) with the relay and control equipment, the shielded cable is arranged in the cable tunnel and its metal shield is generally connected to the grounding grids at both ends.

A number of time domain and frequency domain models are proposed in Refs. [1,2] for evaluating induced volt-

age and current of the overhead conductor excited by an external electromagnetic field. However, the incident wave is assumed to be far field (i.e., plane wave) and the computation is simplified in these models. The spatial electromagnetic field due to the switching operation in a substation is considered as near field and cannot be formulated analytically. As a frequency domain numerical method, the method of moment (MoM) is widely used to model the thin wire structure and calculate the electromagnetic field distribution in a substation in Refs. [3–5].

In this paper, MoM is combined with transmission line method to evaluate near field coupling to shielded cable due to the switching operation in a substation. First, with the shielded cable removed, MoM is used to calculate the electric field distribution along the shielded cable at different frequencies. Second, based on the wide-frequency models of transfer impedance and admittance of shielded cable, the Agrawal transmission line model proposed in Ref. [2] is adopted to predict the electromagnetic interference with the shielded cable. Compared with the results of EMTP, the proposed method is verified correct. Finally, as an application, this method is performed to calculate the current flowing in the cable shield grounded at both ends and the voltage between the cable shield and the cable core due to the switching operation in the 500 kV air insulation substation.

2 Methodology

As illustrated in Fig. 1, the cable core together with the cable shield forms the inner transmission line system. The cable shield together with the ground forms the outer transmission line system. Both systems are coupled by transfer impedance and admittance of the shielded cable. For the outer transmission line system, the location at infinity under the earth's surface is considered as the zero-voltage reference point. The transmission line models for describing the field-line coupling involve [6]:

1) Taylor model that includes distributed voltage and current sources on the line.

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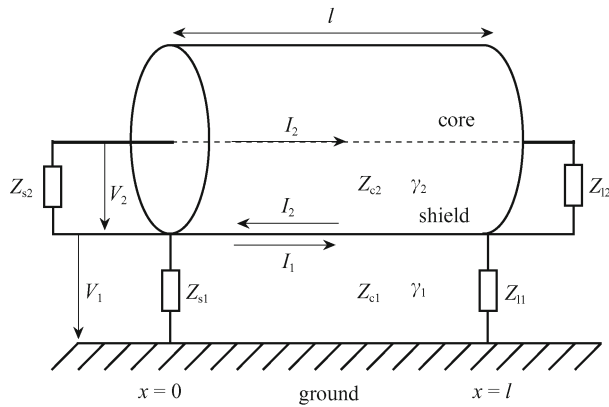


Fig. 1 Inner and outer transmission line models

2) Rachidi model that only includes distributed current sources.

3) Agrawal model that only includes distributed voltage sources.

Each coupling formulation gives the same response to the transmission line. As an effective frequency domain method to solve the telegraph equations describing the field-line coupling, Green's function method is widely used since it can obtain voltage and current along the transmission line. In this paper, the Agrawal model is adopted, and the corresponding formulations of Green's function method are as follows [2]:

$$I_1(x) = \int_0^l G_I(x, x_s) E_t(x_s) dx_s, \quad (1)$$

$$V_1(x) = \int_0^l G_V(x, x_s) E_t(x_s) dx_s, \quad (2)$$

$$G_I(x, x_s) = \frac{[e^{\gamma_1(x < -l)} - \rho_1 e^{-\gamma_1(x < +l)}][e^{\gamma_1(l - x_s)} - \rho_2 e^{\gamma_1(x_s - l)}]}{2Z_{c1}(1 - \rho_1 \rho_2 e^{-2\gamma_1 l})}, \quad (3)$$

$$G_V(x, x_s) = \frac{\delta[e^{\gamma_1(x < -l)} - \delta \rho_1 e^{-\gamma_1(x < +l)}][e^{\gamma_1(l - x_s)} + \delta \rho_2 e^{\gamma_1(x_s - l)}]}{2(1 - \rho_1 \rho_2 e^{-2\gamma_1 l})}. \quad (4)$$

Here,

$$\begin{cases} \delta = \begin{cases} 1, & x > x_s, \\ -1, & x < x_s, \end{cases} \\ Z_{c1} = \sqrt{\frac{Z_1}{Y_1}}, \\ \gamma_1 = \sqrt{Z_1 Y_1}, \\ \rho_1 = \frac{Z_{s1} - Z_{c1}}{Z_{s1} + Z_{c1}}, \\ \rho_2 = \frac{Z_{l1} - Z_{c1}}{Z_{l1} + Z_{c1}}, \end{cases} \quad (5)$$

where I_1 and V_1 are line current and voltage of the outer transmission line system respectively; G_I and G_V are

Green's functions for the line current and voltage; E_t is tangential component of the electric field along the line; x is location of the line current and voltage; x_s is location of the distributed voltage source; $x_>$ and $x_<$ are the maximum value and the minimum value of x or x_s respectively; Z_{s1} and Z_{l1} are load impedances; Z_{c1} and γ_1 are characteristic impedance and propagation constant; Z_1 and Y_1 are per-unit length series impedance and shunt admittance. The formulations of Z_1 and Y_1 are deduced in detail in Ref. [2]. Since the cable is laid on the earth's surface, the normal component of the electric field perpendicular to the earth's surface is ignored in Eqs. (1) and (2).

As for the inner transmission line system formed by the cable core and the cable shield, the voltage and current at the ports can be obtained by the following Baum-Liu-Tesche (BLT) equations [2]:

$$\begin{bmatrix} I_2(0) \\ I_2(l) \end{bmatrix} = \frac{1}{Z_{c2}} \begin{bmatrix} 1 - \rho_3 & 0 \\ 0 & 1 - \rho_4 \end{bmatrix} \begin{bmatrix} -\rho_3 & e^{\gamma_2 l} \\ e^{\gamma_2 l} & -\rho_4 \end{bmatrix}^{-1} \begin{bmatrix} S_1 \\ S_2 \end{bmatrix}, \quad (6)$$

$$\begin{bmatrix} V_2(0) \\ V_2(l) \end{bmatrix} = \begin{bmatrix} 1 + \rho_3 & 0 \\ 0 & 1 + \rho_4 \end{bmatrix} \begin{bmatrix} -\rho_3 & e^{\gamma_2 l} \\ e^{\gamma_2 l} & -\rho_4 \end{bmatrix}^{-1} \begin{bmatrix} S_1 \\ S_2 \end{bmatrix}. \quad (7)$$

The source vector is given by

$$\begin{bmatrix} S_1 \\ S_2 \end{bmatrix} = 0.5 \begin{bmatrix} \int_0^l e^{\gamma_2 x} [Z_t I_1(x) + Z_{c2} Y_t V_1(x)] dx \\ \int_0^l e^{\gamma_2(l-x)} [-Z_t I_1(x) + Z_{c2} Y_t V_1(x)] dx \end{bmatrix}. \quad (8)$$

Here,

$$\begin{cases} Z_{c2} = \sqrt{\frac{Z_2}{Y_2}}, \\ \gamma_2 = \sqrt{Z_2 Y_2}, \\ \rho_3 = \frac{Z_{s2} - Z_{c2}}{Z_{s2} + Z_{c2}}, \\ \rho_4 = \frac{Z_{l2} - Z_{c2}}{Z_{l2} + Z_{c2}}, \end{cases} \quad (9)$$

where I_2 and V_2 are line current and voltage of the inner transmission line system respectively; Z_{s2} and Z_{l2} are load impedances; Z_{c2} and γ_2 are characteristic impedance and propagation constant; Z_2 and Y_2 are per-unit length series impedance and shunt admittance; Z_t and Y_t are per-unit length transfer impedance and admittance of the cable shield. Z_2 and Y_2 can be measured using the method proposed in Ref. [7], while Z_t and Y_t can be acquired by that in Ref. [8].

With the help of the inverse fast Fourier transformation (IFFT), corresponding transient response can be achieved from the above frequency domain formulations.

3 Validation

To validate the proposed method, we select parallel over-ground conductors shown in Fig. 2 as the computational

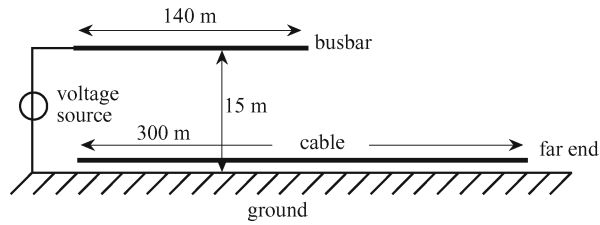


Fig. 2 Computational model for parallel conductors

model. The busbar is 140 m long, 15 m high with a radius of 5.8 cm. A 300 m single-core shielded cable (Model: RG58A/U; Nominal impedance: 50 Ω) under the busbar is laid on the earth’s surface. The inner radius and outer radius of the cable shield are 1.48 mm and 1.6 mm, respectively. The soil resistivity is 100 Ω·m and the busbar

is excited by a unit step voltage source with a rise-time of 1 μs. Figure 3 gives the transient and spectral density responses of the voltage between the cable shield and the ground at the far end when the cable shield is left open at both ends. Figure 4 gives the transient and spectral density responses of the current flow in the cable shield at the far end when the cable shield is grounded at both ends through the grounding resistance of 1 Ω. The solid line represents the results derived by using the proposed method and the dotted line denotes the results obtained by EMTP. We can find a good agreement for both transient and spectral density responses. Thus the proposed method is validated and can be applied to effectively evaluate the near field coupling to the shielded cable with different arrangement modes (e.g., parallel or perpendicular to the

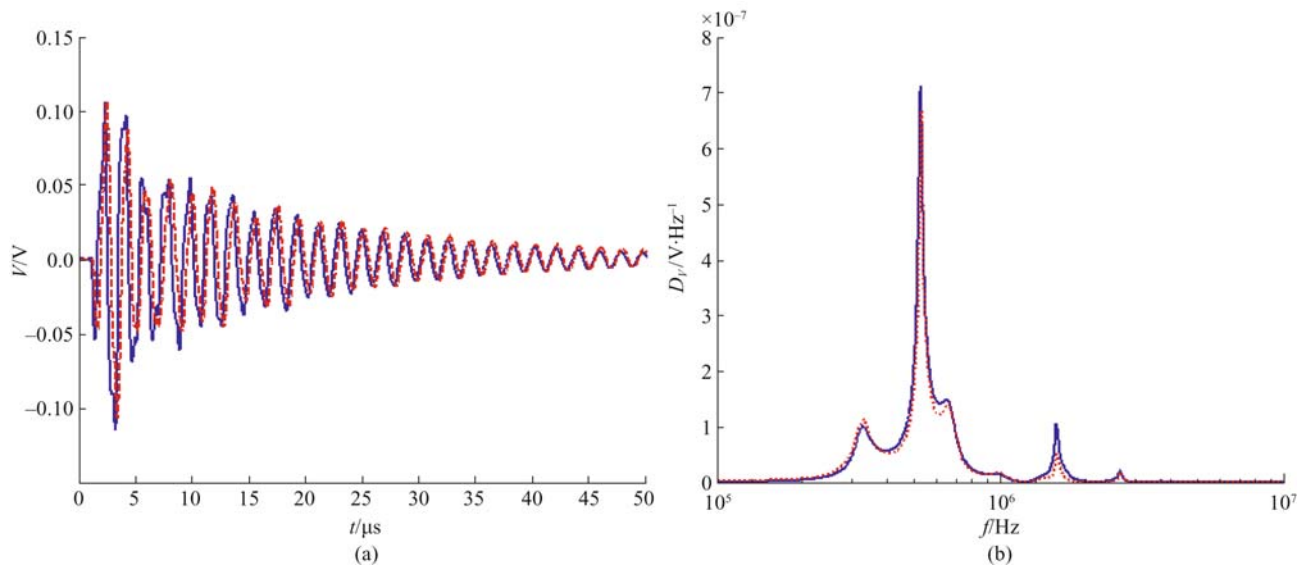


Fig. 3 Voltage response at shield’s far-end. (a) Transient response; (b) spectral density response

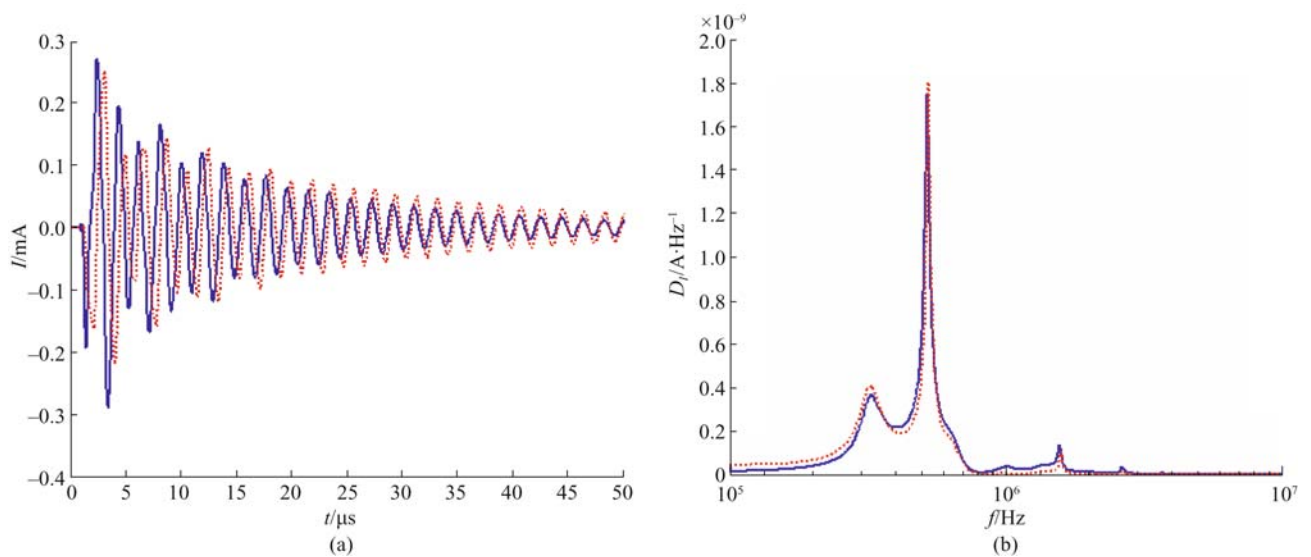


Fig. 4 Current response at shield’s far-end. (a) Transient response; (b) spectral density response

busbar) due to the switching operation in a substation. As an advantage, this method overcomes the disadvantage of EMTF, which is only applicable to parallel conductors.

From Figs. 3(b) and 4(b), we can see that both the voltage and current frequency spectrum is below 10 MHz, and the maximum spectral density is about at 0.524 MHz. In this model, the length of the busbar is 140 m and the period of the voltage and current wave process along the busbar is

$$T = \frac{4l}{c} = \frac{4 \times 140}{3 \times 10^8} = \frac{28}{15} \times 10^{-6} \text{ s.} \quad (10)$$

The corresponding dominant frequency is

$$f = \frac{1}{T} = \frac{15}{28} \times 10^6 \text{ Hz} = 0.536 \text{ MHz.} \quad (11)$$

Apparently, the dominant frequency of 0.536 MHz fits well with 0.524 MHz.

4 Application

Figure 5 shows the field-line coupling model due to the switching operation in a 500 kV air insulation substation. The three-phase busbar is 140 m long, 16 m high with a radius of 5.8 cm and an interval of 10 m. The three-phase leading wire is 50 m long, 10 m high with a radius of 6.5 cm and an interval of 10 m. The 300 m shielded cable (Model: RG58A/U) under the *A*-phase leading wire is arranged on the earth's surface. The cable shield is grounded through the grounding resistivity of 1 Ω at the switching field side and control room side. The cable core is left open at both ends. The soil resistivity is 100 Ω·m. The busbar is excited by three-phase cosine voltage source

and θ is the initial phase angle of the *A*-phase voltage source.

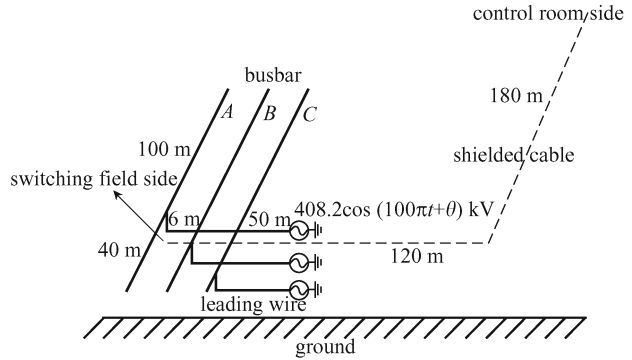


Fig. 5 Field-line coupling model in 500 kV air insulation substation

Figure 6 gives the amplitude-frequency characteristics of per-unit length transfer impedance and admittance of the shielded cable using the method proposed in Ref. [8]. The transfer admittance can be neglected over the frequencies of 0.1 to 10 MHz. Figures 7 and 8 show the current flow in the cable shield and the voltage between the cable core and the cable shield at the control room side when θ is zero, respectively. In Fig. 8, the solid line represents the results that consider the transfer impedance and admittance and the dotted line denotes the results that only consider the transfer impedance. We can find a good agreement for both the transient response and spectral density response. From Figs. 7(b) and 8(b), it can be seen that the main frequency spectrum is below 10 MHz and the dominant frequency is 0.46 MHz, which is consistent with 0.48 MHz by Eq. (11).

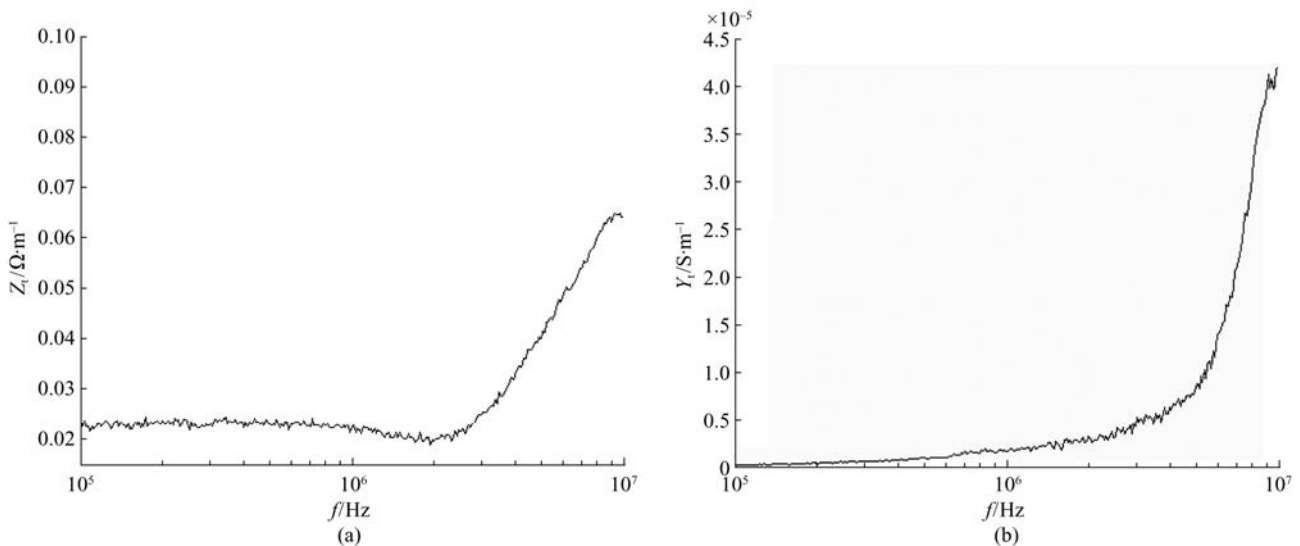


Fig. 6 Amplitude-frequency characteristics of transfer impedance and admittance of shielded cable. (a) Transfer impedance; (b) transfer admittance

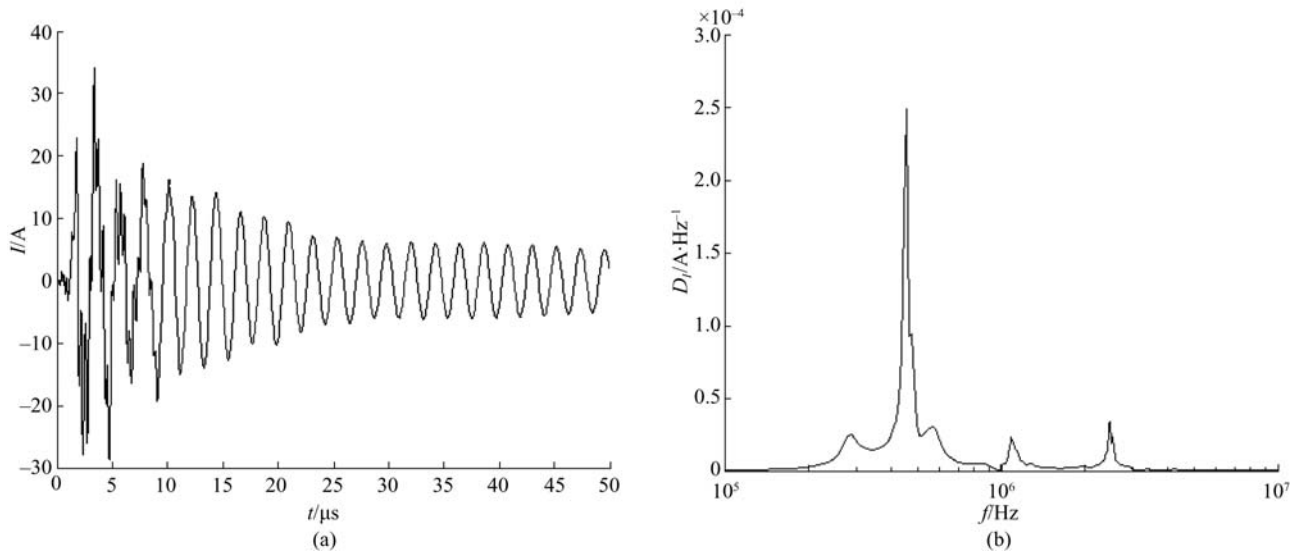


Fig. 7 Current response at control room side ($\theta = 0$). (a) Transient response; (b) spectral density response

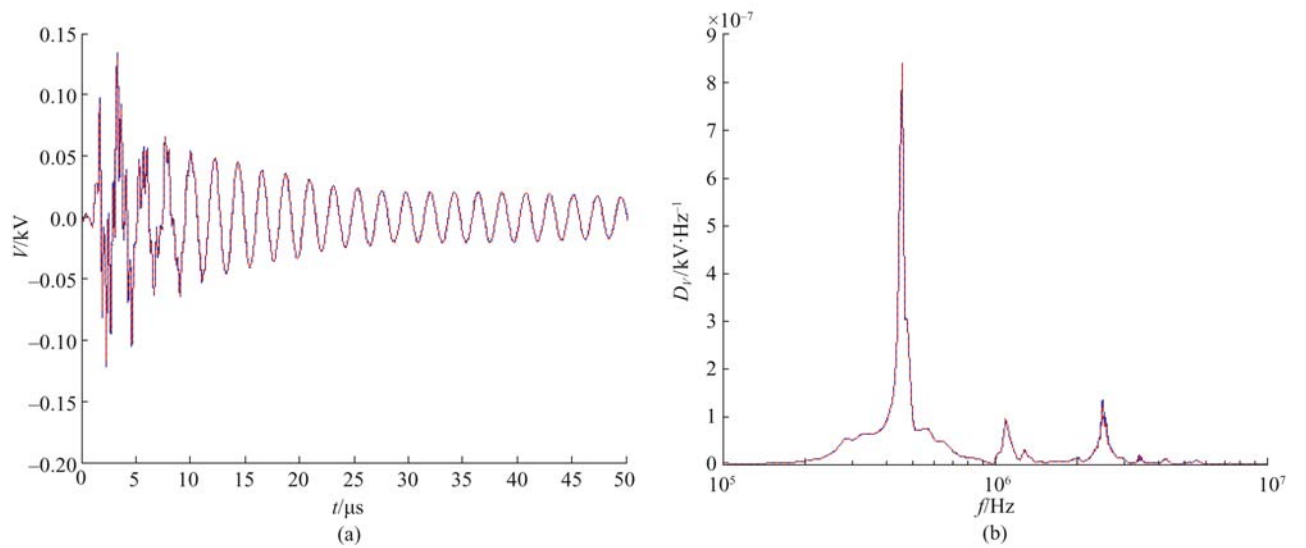


Fig. 8 Voltage response at control room side ($\theta = 0$). (a) Transient response; (b) spectral density response

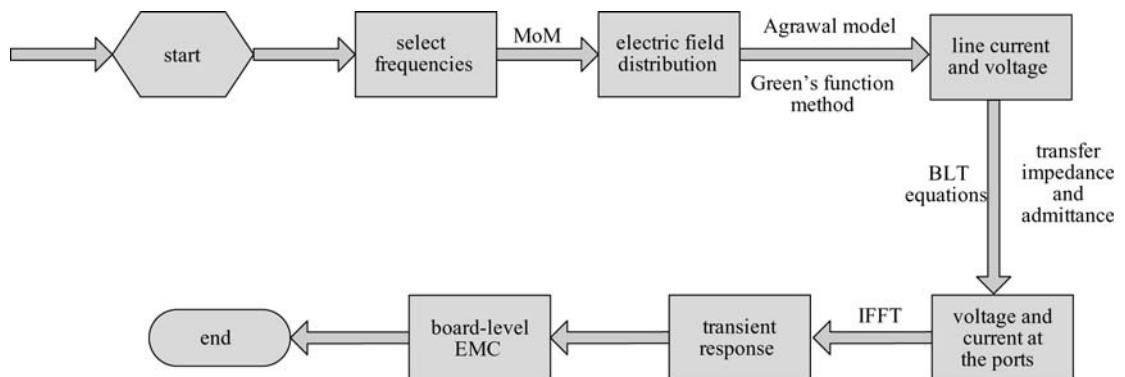


Fig. 9 Flowchart of simulation

5 Conclusions

In this paper, a frequency domain model for the near field coupling to transmission line is proposed to predict the electromagnetic interference to shielded cable due to the switching operation in a substation. The main process of the above simulation is summarized in Fig. 9. The proposed method has been proven correct in comparison with the results obtained by EMTP, and can effectively evaluate near field coupling to shielded cable with different arrangement modes (e.g. parallel or perpendicular to the busbar) due to the switching operation in a substation. An advantage of this method is that it overcomes the disadvantage of EMTP, which is only applicable to parallel conductors.

It is worth emphasizing that as an extension of the proposed method it is important for further board-level electromagnetic compatibility (EMC) study on the relay and control equipment by taking the equivalent interference source at the port of the secondary equipment as the excitation.

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