

STUDY OF ELECTROMAGNETIC BEHAVIOR IN MULTICONDUCTOR SYSTEM BY FINITE ELEMENT METHOD

NGHIÊN CỨU ĐẶC TÍNH ĐIỆN TỪ TRƯỜNG ĐAN XEN TRONG HỆ THỐNG DÂY DẪN NHIỀU SỢI BẰNG PHƯƠNG PHÁP PHẦN TỬ HỮU HẠN

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Abstract:

This paper involves modeling and calculating the mutual electromagnetic characteristics in a multiconductor system using finite element method and equivalent energy equations. The approach is applied on a real three phase shielded cable. The finite element model of the cable is presented for calculating the mutual parameters which depend on the frequency. The high frequency phenomenas, the skin and proximity effect, are well studied.

Keywords:

Multiconductor, electromagnetic field, magnetodynamic, Maxwell's equations, finite element method.

Tóm tắt:

Bài báo đề cập đến việc nghiên cứu các đặc tính điện từ trường đan xen trong một hệ thống đa dây dẫn bằng phương pháp phần tử hữu hạn kết hợp việc giải các phương trình năng lượng. Phương pháp nghiên cứu được trình bày chi tiết và áp dụng tính toán chi tiết một hệ thống đa dây dẫn cụ thể - cáp ba pha có đai bảo vệ. Các giá trị tương hỗ giữa các dây dẫn, cũng như các hiện tượng xuất hiện ở tần số cao như hiệu ứng bề mặt và hiệu ứng gần được xác định rõ nét.

Từ khóa:

Hệ thống đa dây dẫn, điện từ trường, điện động, hệ phương trình Maxwell, phương pháp phần tử hữu hạn.

1. INTRODUCTION

Multiconductor systems are frequently used in energy transmission such as overhead lines and cables. The mutual electromagnetic effect is extremely

varied. The propagation of electromagnetic waves in transmission lines could be described by the Transverse Electromagnetic (TEM) mode. The terms of voltages and currents are calculated by using the circuit parameters of line. Moreover, the switching of semiconductor devices in power static converters can generate the

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Electromagnetic Interference (EMI). In power system, this high level of emission can produce the high frequency disturbance which propagate over the power cables [1,2]. In order to analyze the influence of transmission multiconductor system on the EMI level, it is necessary to precisely model the behavior of this system in the frequency domain. However, there are some difficulties in modeling of system due to several factors [3,5]. Firstly, the properties of materials, thicknesses of insulation and shielding are not fully known. Secondly, electrical wires and frame are twisted, sometimes in opposite sense. These physical parameters are insufficient to model a multiconductor system in the frequency domain; therefore, it is necessary to take into account the electromagnetic phenomena such as the skin effect and proximity effects [1,2,4]. To correct model, both of these effects are highly dependent on the characteristics of the materials and on the geometry; thus, the finite element method is proposed to use [4,7]. The number of simulations by finite element method will vary according to the number of conductors in the multiconductor system. Each simulation will provide an energy value that will allow us to determine the lumped parameter (resistance and inductance) matrices. Moreover, these simulations will be performed for several frequencies to capture the evolution of the skin and proximity effects.

2. METHODOLOGY

In this section, the electromagnetic

formulations used to calculate the lumped parameters are introduced. Based on energy method, the self and mutual values are obtained from the finite element model [8].

2.1. Finite Element Method and Formulations

Finite Element Method

The finite element method (FEM) is a technique for the numerical resolution of partial differential equations. This method is powerful, general, robust and widely used in engineering.

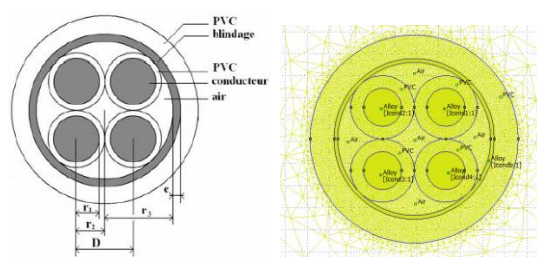


Figure 1. Decomposition of a studied object to finite elements

In reality, the FEM solves the weak form of the partial differential equations by using a mesh which serves as support for the interpolation functions.

The weak formulation is also called variational formulation. This formulation can be defined by considering a differential operator R and a function f such as finding u on Ω checking $\int_{\Omega} R(u)v = \int_{\Omega} fv$ for any adapted function v .

The distribution of electric field and magnetic field is described by Maxwell's equations. The studied object can be discretized by the nodes, the edges, the

facets and the volumes.

Solving the final electromagnetic equations in a complex object, such as a multiconductor system, is extremely difficult. Therefore, the author used the finite element method and solved the problem by using its numerical tool as Salome software [6]. This is a software which provides a generic platform for numerical simulation. It is based on an open and flexible architecture made of reusable components. Salome can be used as standalone application for generation of Computer-aided design (CAD) model, its preparation for numerical calculations and post-processing of the calculation results. Salome can also be used as a platform for integration of the external third-party numerical codes to produce a new application for the full life-cycle management of CAD models.

In this study, the value of the capacitance matrix is supposed not to be frequency dependent and not to be examined. However, for the resistance and inductance matrices which vary with the frequency, the two magnetodynamic potential formulations are used [9,10].

Magnetodynamic problem

As mentioned above, the purpose is to determine the resistance and inductance matrices which depend on the skin and proximity effects. These resistance and inductance matrices are calculated in function of the frequency by solving the magnetodynamic formulations.

The magnetic vector potential A and the

electric scalar potential ϕ are identified such that the magnetic field B and vector A are related by $B = \text{curl}A$ and the electric field E is equal to $E = j\omega A - \text{grad}\phi$. Combining the previous equations with the Ampere's law ($\text{curl}H = J$, H as the magnetic field and J as the current density) and with the behavior laws ($B = \mu H$ and $J = \sigma E$ with μ as the permeability and σ as the conductivity), the partial differential equation to be solved is:

$$\text{curl} \frac{1}{\mu} \text{curl}A = J_s - \sigma(j\omega A + \text{grad}\phi) \quad (1)$$

The boundary conditions indicated on B ($B \cdot n = 0$) and E ($E \times n = 0$) are imposed on the application of $A \times n = 0$ on Γ_B and $A \cdot n = 0$ and $\phi = 0$ on Γ_E respectively.

There is another potential formulation. The electric vector potential formulation T and the magnetic scalar potential formulation Ω are introduced such that:

$$J = J_s + J_{\text{ind}} = \text{curl}T_s + \text{curl}T \quad (2)$$

Where the source term $J_s = \text{curl}T_s$ and the unknown term $J_{\text{ind}} = \text{curl}T$. Consequently the equation to solve is given by a conductive part

$$\text{curl} \frac{1}{\sigma} (\text{curl}T_s + \text{curl}T) = -j\omega\mu(T_s + T - \text{grad}\Omega) \quad (3)$$

The boundary conditions of type J and H on the boundary Γ_H by imposing $T \times n = 0$ and $\Omega = 0$ on Γ_H . The main purpose when solving both formulations is to obtain two values of lumped parameters, one for each formulation.

2.2. Determination of impedance matrices

Based on the calculation of the energy, Joule losses and magnetic energy, the values of R and L matrices can be found. In general, if the conductors are flown by an electric current, the Joule losses and the magnetic energy are expressed as follows :

$$\begin{cases} P_{Joules} = \sum_{i=1}^n I_i^2 R_{ii} + \sum_{i,j=1;i \neq j}^n I_i I_j R_{ij} \\ W_{mag} = \frac{1}{2} \left(\sum_{i=1}^n I_i^2 L_{ii} + \sum_{i,j=1;i \neq j}^n I_i I_j L_{ij} \right) \end{cases} \quad (4)$$

where R_{ii} , L_{ii} are respectively the self resistance and inductance of conductor i ; and R_{ij} , L_{ij} are the mutual resistance and inductance between conductor i and conductor j .

To take into account the evolution of the resistance according to the skin and proximity effect, the simulations must be carried out at several frequency values. It should be noted that self resistance values corresponds to Joule losses in the three conductors when only one is supplied.

For example, a simple two-conductor system can be seen as below:

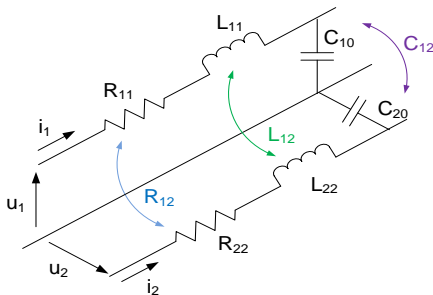


Figure 2. The mutual relationship in the two conductor system

In the magnetodynamic problem, the relationship of resistance and inductance between the conductors can be defined as follows :

$$R = \begin{bmatrix} R_{11} & R_{12} \\ R_{21} & R_{22} \end{bmatrix}; L = \begin{bmatrix} L_{11} & L_{12} \\ L_{21} & L_{22} \end{bmatrix} \quad (5)$$

where R_{11} , L_{11} , R_{22} , L_{22} are respectively the self resistance and inductance of conductor 1 and conductor 2; and R_{12} , L_{12} (or R_{21} , L_{21}) are the mutual resistance and inductance between conductor 1 and conductor 2. R_{12} represents the effect of proximity of conductor 1 to conductor 2 and L_{12} is the mutual inductance between these two conductors.

The energy equations (4) in this case become:

$$\begin{cases} P_{Joules} = I_1^2 R_{11} + I_2^2 R_{22} + 2I_1 I_2 R_{12} \\ W_{mag} = \frac{1}{2} I_1^2 L_{11} + \frac{1}{2} I_2^2 L_{22} + I_1 I_2 L_{12} \end{cases} \quad (6)$$

The approach principle is the variation of input currents in FEM model to calculate the energy equations. The findings of P_{Joules} and W_{mag} values are based on this FEM model.

Thus, in order to calculate the resistance and inductance of conductor 1 (R_{11} and L_{11}), the established FEM model is applied to the currents on two conductors (I_1 , I_2) as (1,0) A. Based on P_{Joules} and W_{mag} of FEM model, the energy equations (6) are calculated to obtain the resistance and inductance of conductor 1. In order to get the mutual values (R_{12} , L_{12}), the two applied currents have to be different and non-zero.

3. CASE STUDY

3.1. Geometry and parameters

This cable has three cores, and each conductive core consists of 61 non-insulated copper wires. Each core is also surrounded by a semi-conductive tape and a XLPE insulation, and then there is the jam, the sealing sleeve, the armature as well as the outer sheath as being shown in Figure 3.

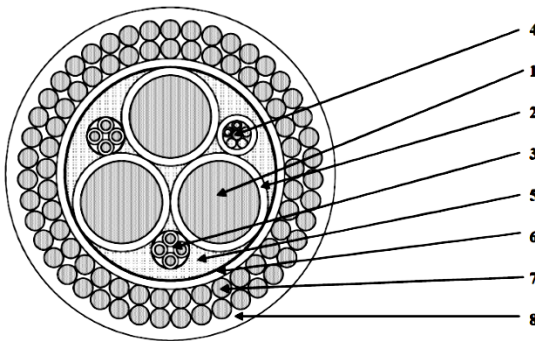


Figure 3. Configuration of the cable

Table 1. Parameters of the cable

No	Description	Material	Thickness (mm)	Diameter (mm)
1	Conductor 300mm ²	Copper, cable class 2 with longitudinal sealing	61 wires	20.8
2	Insulation	PRS/XLPE	2.0	25.0
3	Assembly of 4 conductors 4mm ²	Copper, cable class 2 Insulation PRS/XLPE	7 wires	2.55
4	Optical fibers	8 monomode fibers G652	0.7	4.01
5	Jams	Polypropylen ropes		
6	Inner sheath	Sheath PEBD	2.2	59.9
7	Amor double layer	Galvanized steel wires	Diameter 5.0	79.9
8	Outer sheath	Sheath PEBD	3.2	86.3

As a part of the study, all of the copper strands are assimilated to a uniform section. This assumption is valid as far as the strands are not insulated from each other and are wrapped by an insulating sheath which contributes to increasing the contact areas. Each conductor is surrounded by semiconductor layers. As a part of this work, these semiconductor layers are considered playing a role of

insulation. Therefore, they are modeled in the case of magnetodynamic model by a non-conductive and non-magnetic material in the case of electrostatic model by a dielectric material $\epsilon_r = 2,4$ corresponding to the XLPE insulation surrounding the conductor. The studied system is simulated for 1 m of length.

3.2. Mesh

Since there are three conductors and conductive armature (Figure 4), the linear parameters to be determined will be expressed in a matrix form of around 4*4.

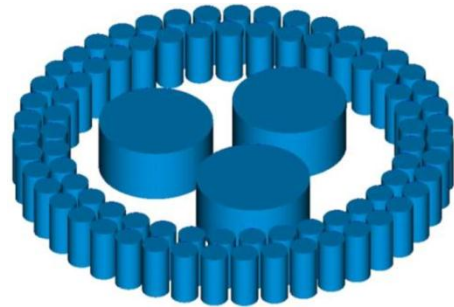


Figure 4. Representation of conductive parts in modeling cable

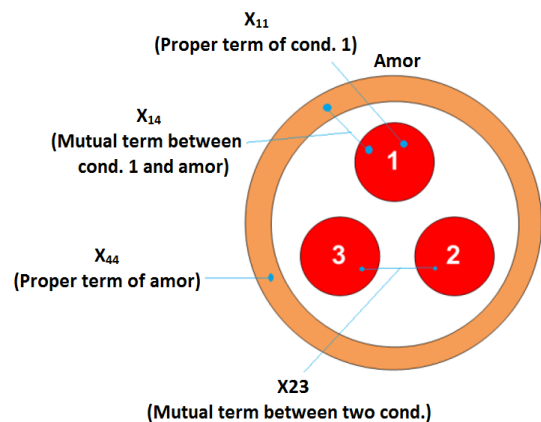


Figure 5. Index of matrix [R] and [L]

The numbering of the various conductors is given in Figure 5, and in Figure 6, the

equivalent circuit of this cable is represented by the coefficients of the matrices [R] and [L].

Instead, the magnetodynamic model will present well the distribution of induced currents of cable. The calculations are carried out with the amor connection condition as in Figure 6.

This figure shows the equivalent circuit of the multiconductor system. The values R_{11} , R_{22} , R_{33} , R_a and L_{11} , L_{22} , L_{33} , L_a are respectively the resistance and inductance of conductor 1, 2, 3 and of the amor. The values R_{12} , R_{13} , R_{23} , R_{1a} , R_{2a} , R_{3a} are respectively the mutual resistance between the conductors as well as between a conductor with the amor of cable. The rule of inductance is similar.

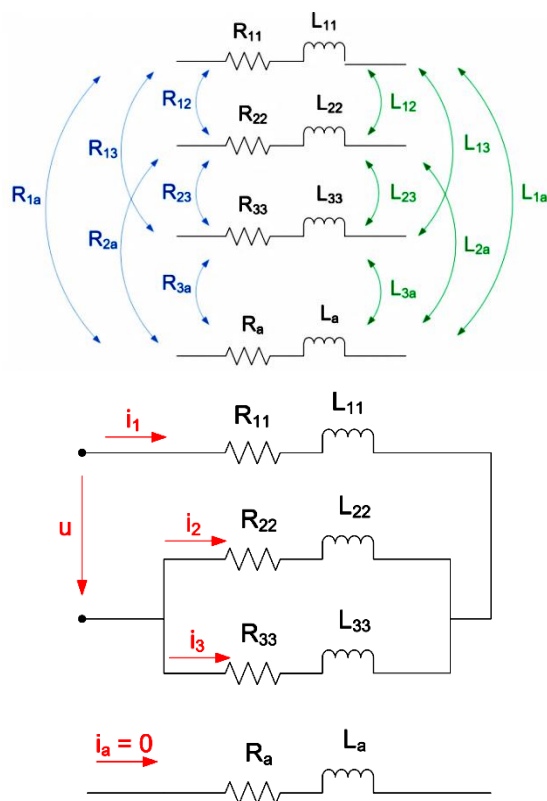


Figure 6. Equivalent circuit of studied cable

The Figure 6 (bottom) represents the equivalent circuit in case of forward current in conductor 1 and back current in two conductors 2 and 3. In this case, the amor of cable is open circuit ($i_a = 0$).

3.3. Solution and Results

The distribution of the induced current in cable at $f = 1$ kHz is well presented in the Figure 7.

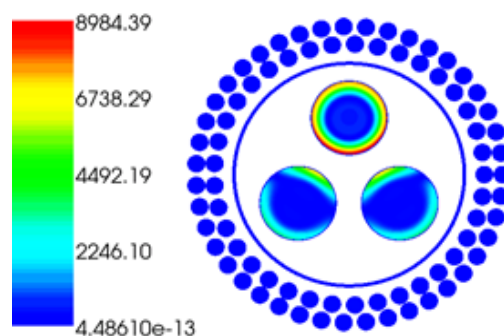


Figure 7. Density of current in cable (A/m^2)

This result is corresponding to the case of the current flowing through the conductor 1. The distribution of current in conductor 1 is according to the skin effect. At the same time, the induced currents are produced in the conductors 2 and 3. This is the proximity effect that occurs at high frequency in the multiconductor system.

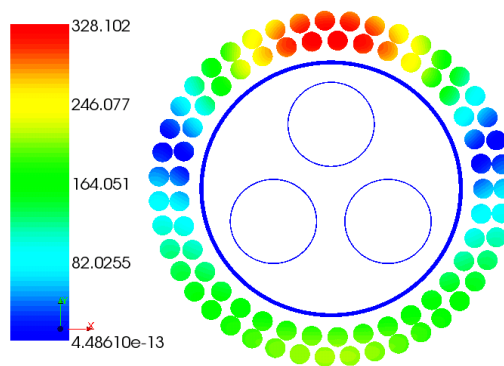


Figure 8. Density of current in amor (A/m^2)

This proximity effect also appears on the amor of cable. The Figure 8 shows that the induced current is maximum at position near conductor 1 and minimum corresponding to the farthest distance from the conductors.

Therefore, the high frequency phenomenas like the skin effect and the proximity effect in conductors and also in amor of cable are clearly demonstrated.

Solving the problem magnetodynamic by finite element method, value of Joules losses and magnetic energy are obtained according to frequency.

The equations (4) in this case become as follow:

$$\begin{cases} P_{Joules} = \sum_{i=1}^4 I_i^2 R_{ii} + \sum_{i,j=1; i \neq j}^4 I_i I_j R_{ij} \\ W_{mag} = \frac{1}{2} \left(\sum_{i=1}^4 I_i^2 L_{ii} + \sum_{i,j=1; i \neq j}^4 I_i I_j L_{ij} \right) \end{cases} \quad (7)$$

Solving equations (7) by obtained energy, values of resistance and inductance depend on frequency. The parameters variation of conductors (R_{11} , L_{11}) and shield (R_{44} , L_{44}) as well as mutual values between two conductors (R_{12} , L_{12}) and between a conductor and shield (R_{14} , L_{14}) are calculated and shown in Figure 9 and in Figure 10.

The value of resistance increases and of inductance decreases with the frequency of source. In the frequency range [0; 100kHz], the calculated resistance is relatively small. It is explained by a good conductivity material of this study cable. As the frequency increases, due to skin and proximity effect, the resistance value increases and the inductance decreases. The difference of result obtained by A-φ and T-Ω formulations is also evident at high frequency.

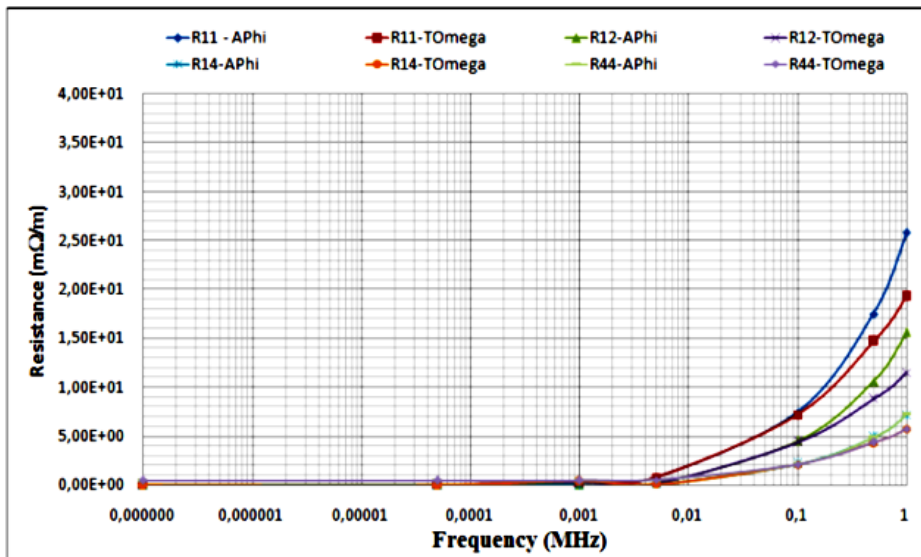


Figure 9. Evolution of resistances depends on frequency

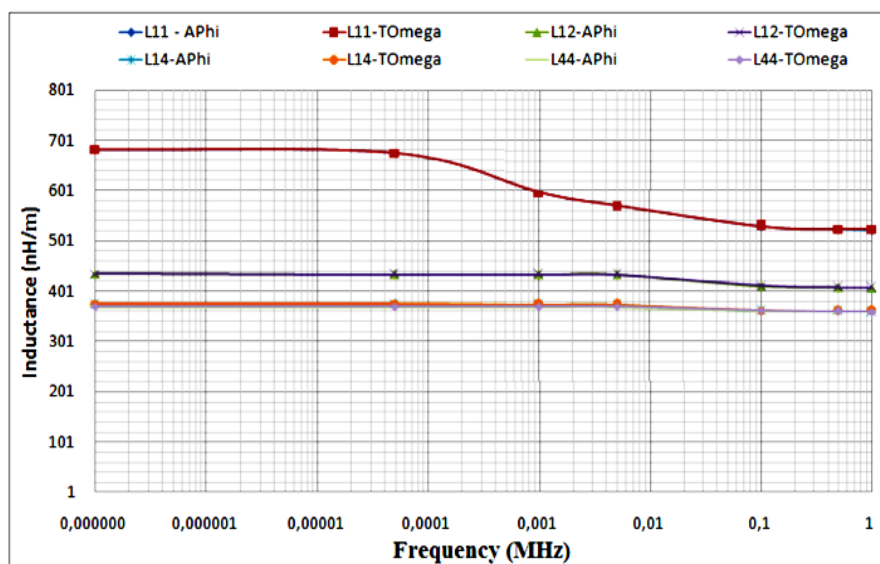


Figure 10. Evolution of inductances depends on frequency

The self values of resistance (R_{ii}) and the inductance (L_{ii}) are always greater than the mutual value between the conductors (R_{ij} , L_{ij}). However, this mutual value cannot be ignored and that is the electromagnetic interference effect in multiconductor system. It is perfectly consistent with the theory when the skin effect and the proximity effect appear to produce the induced current in the conductors of system.

4. CONCLUSION

This paper presents a method which is applied to determine the impedances of a multiconductor system according to the frequency. The results can assert greatly

the phenomena HF of the cable: the skin and proximity effect. There are two major advantages when conducting this method. Firstly, the modeling of proximity effect in high frequency is carried out successfully. Secondly, another benefit is the introduction of the connection matrix. The impedance of other configuration of system according to frequency can be determined by changing this matrix. This method can be applied in calculation, planning and operation of cable and distribution network. Furthermore, this approach will be help for the next study to determine the resonant frequency of the transmission system.

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Biography:



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