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Analysis of Electromagnetic Field Effects Using FEM for Transmission Lines Transposition

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***Abstract*—**This paper presents the mathematical model of electric field and magnetic field in transmission system, which performs in second-order partial differential equation. This research has conducted analyzing the electromagnetic field radiating to atmosphere around the transmission line, when there is the transmission line transposition in case of long distance distribution. The six types of 500 kV transposed HV transmission line with double circuit will be considered. The computer simulation is applied finite element method that is developed by MATLAB program. The problem is considered to two dimensions, which is time harmonic system with the graphical performance of electric field and magnetic field. The impact from simulation of six types long distance distributing transposition will not effect changing of electric field and magnetic field which surround the transmission line.

***Keywords*—**Transposition, Electromagnetic Field, Finite Element Method (FEM), Transmission Line, Computer Simulation

I. INTRODUCTION

FOR decades, due to the increasing of electrical power demands in Thailand, Electricity Generating Authority of Thailand (EGAT) decides to enlarge transmission capacity by installing 500-kV extra high-voltage power transmission lines in both AC and DC. In the AC system, double-circuit transmission lines consist of 6 conductors running in parallel. Transposition in case of long distance distribution of the 6 conductors results in electric and magnetic field distribution that may cause some serious harm to surround the transmission line. From literature, basic electromagnetic theory [1] or image theory [2] are widely used for electromagnetic field calculation in high voltage power transmission lines. So far, there is no report on electric and magnetic field calculation in this scope by using Finite Element Method (FEM).

The FEM is one of the most popular numerical methods used for computer simulation. The key advantage of the FEM over other numerical methods in engineering applications is the ability to handle nonlinear, time-dependent and circular geometry problems. Therefore, this method is suitable for solving the problem involving electric and magnetic field effects around the transmission line caused by circular cross-section of high voltage conductors.

In this paper, 500-kV, double-circuit, extra high-voltage power transmission lines are studied with 6 conductors transposition in case of long distance distribution in order to troubleshoot the voltage drop unbalance problem. Computer-based simulation utilizing the two dimensional finite element method in the time harmonic mode, instructed in MATLAB programming environment with graphical representation for electric and magnetic field strength have been evaluated. In general, electric field strength of the system depends on operating voltage level applied to phase conductors. Due to the voltage regulation of the transmission systems, the conductor surface potential does not change to result in remarkable difference of the electric field contours. In the same manner, magnetic field strength of the system depends strongly on the phase currents flowing through the phase conductors. As mentioned where a normal steady-state operation is assumed, the current does not suddenly change its value. Therefore, both field distribution are quasi-static.

II. MODELING OF ELECTROMAGNETIC FIELDS INVOLVING TRANSMISSION LINES

A mathematical model of electric fields (**E**) radiating around a transmission line is usually expressed in the wave equation (Helmholtz's equation) as in (1) [3], [4] derived from Faraday's law.

$$\nabla^2\mathbf{E} - \sigma\mu\frac{\partial\mathbf{E}}{\partial t} - \varepsilon\mu\frac{\partial^2\mathbf{E}}{\partial t^2} = 0 \qquad (1)$$

…, where ε is the dielectric permittivity of media, μ and σ are the magnetic permeability and the conductivity of conductors, respectively.

A mathematical model of magnetic fields (**B**) for transmission lines is performed in form of the magnetic field intensity (**H**), which related to the equation, $\mathbf{B} = \mu\mathbf{H}$. This model can be characterized by using the wave equation (Helmholtz's equation) as in (2) [3], [4] derived from the Ampere's law.

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$$\nabla^2 \mathbf{H} - \sigma\mu \frac{\partial \mathbf{H}}{\partial t} - \varepsilon\mu \frac{\partial^2 \mathbf{H}}{\partial t^2} = 0 \qquad (2)$$

Due to the similarity between (1) and (2), formulation of the FEM used for the magnetic field problems is mathematically the same. One can point out this similarity by replacing the electric field (**E**) with the magnetic field intensity (**H**).

This paper has considered the system governing by using the time harmonic mode and representing the electric field in complex form, $\mathbf{E} = Ee^{j\omega t}$ [5], therefore,

$$\frac{\partial \mathbf{E}}{\partial t} = j\omega E \quad \text{and} \quad \frac{\partial^2 \mathbf{E}}{\partial t^2} = -\omega^2 E$$

…, where ω is the angular frequency.

Refer to (1), by employing the complex form of the electric fields and assuming that the system is excited with a single frequency source, Equation (1) can be transformed to an alternative form as follows.

$$\nabla^2 E - j\omega\sigma\mu E + \omega^2 \varepsilon\mu E = 0$$

When considering the problem of two dimensions in Cartesian coordinate *(x,y)*, hence

$$\frac{\partial}{\partial x}\left(\frac{1}{\mu}\frac{\partial E}{\partial x}\right) + \frac{\partial}{\partial y}\left(\frac{1}{\mu}\frac{\partial E}{\partial y}\right) - \left(j\omega\sigma - \omega^2\varepsilon\right)E = 0 \qquad (3)$$

Analytically, there is no simple exact solution of the above equation. Therefore, in this paper the FEM is chosen to be a potential tool for finding approximate electric field solutions for the PDE described as in (3) [6].

III. SYSTEM DESCRIPTION WITH THE FEM

A. Discretization

This paper determines a four-bundled, double-circuit, 500-kV power transmission line. Fig. 1 shows the power transmission line with the low-reactance orientation type. Height of conductors shown in the figure is the maximum sag position. The lowest conductors are C and A′ at the height of 13.0 m above the ground level [7]. Each phase conductor is 795 MCM (0.02772 m - diameter). The overhead ground wire has 3/8 inch - diameter. Fig. 2 displays the domain of study discretizing by using linear triangular elements.

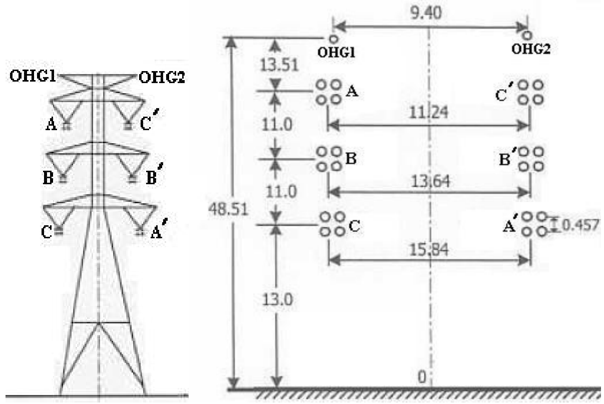

Fig. 1 500-kV double-circuit, four-bundled power transmission line with low-reactance orientation

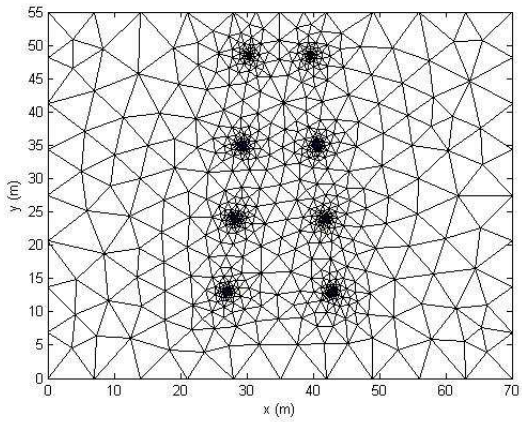

Fig. 2 Discretization of the system given in Fig. 1

B. Finite Element Formulation

An equation governing each element is derived from the Maxwell's equations directly by using Galerkin approach, which is the particular weighted residual method for which the weighting functions are the same as the shape functions [8], [9]. According to the method, the electric field is expressed as follows.

$$E(x,y) = E_i N_i + E_j N_j + E_k N_k \qquad (4)$$

…, where N_n , $n = i, j ,k$ is the element shape function and the E_n , $n = i, j ,k$ is the approximation of the electric field at each node (i, j ,k) of the elements, which is

$$N_n = \frac{a_n + b_n x + c_n y}{2\Delta_e}$$

…, where Δ_e is the area of the triangular element and,

$$a_i = x_j y_k - x_k y_j \,, \quad b_i = y_j - y_k \,, \quad c_i = x_k - x_j$$
$$a_j = x_k y_i - x_i y_k \,, \quad b_j = y_k - y_i \,, \quad c_j = x_i - x_k$$
$$a_k = x_i y_j - x_j y_i \,, \quad b_k = y_i - y_j \,, \quad c_k = x_j - x_i .$$

The method of the weighted residue with Galerkin approach is then applied to the differential equation, refer to (3), where the integrations are performed over the element domain Ω.

$$\int_{\Omega} N_n \left(\frac{\partial}{\partial x}\left(\frac{1}{\mu}\frac{\partial E}{\partial x}\right) + \frac{\partial}{\partial y}\left(\frac{1}{\mu}\frac{\partial E}{\partial y}\right)\right) d\Omega - \int_{\Omega} N_n \left(j\omega\sigma - \omega^2 \varepsilon\right) E \, d\Omega = 0$$

, or in the compact matrix form

$$[M + K]\{E\} = 0 \tag{5}$$

$$M = \left(j\omega\sigma - \omega^2\varepsilon\right)\int_{\Omega} N_n N_m d\Omega = \frac{\left(j\omega\sigma - \omega^2\varepsilon\right)\Delta_e}{12}\begin{bmatrix} 2 & 1 & 1 \\ 1 & 2 & 1 \\ 1 & 1 & 2 \end{bmatrix}$$

$$K = \nu \int_{\Omega}\left(\frac{\partial N_n}{\partial x}\frac{\partial N_m}{\partial x} + \frac{\partial N_n}{\partial y}\frac{\partial N_m}{\partial y}\right) d\Omega = \frac{\nu}{4\Delta_e}\begin{bmatrix} b_i b_i + c_i c_i & b_i b_j + c_i c_j & b_i b_k + c_i c_k \\ & b_j b_j + c_j c_j & b_j b_k + c_j c_k \\ Sym & & b_k b_k + c_k c_k \end{bmatrix}$$

…, where ν is the material reluctivity ($\nu = 1/\mu$).

For one element containing 3 nodes, the expression of the FEM approximation is a 3×3 matrix. With the account of all elements in the system of *n* nodes, the system equation is sizable as the *n*×*n* matrix.

IV. BOUNDARY CONDITIONS AND SIMULATION PARAMETERS

In this paper, 500-kV, double-circuit, extra high-voltage power transmission lines are studied with 6 conductors transmission line transposition in case of long distance distribution, indicating in Fig. 3, there are six types of transposition as indicated by Table I. The boundary conditions applied here are that both electric and magnetic fields at the ground level and the OHGW are set as zero. In contrast, the boundary conditions at the conductor surfaces are practically different. They are strongly dependent upon the load current for the magnetic case. However, in this paper, the boundary conditions of both electric and magnetic fields of conductor surfaces in 500-kV power lines are assigned as given in [7], [10] under the maximum loading of 3.15 kA/phase [7]. This simulation uses the system frequency of 50 Hz. The power lines are bared conductors of Aluminum Conductor Steel Reinforced (ACSR), having the conductivity (σ) = 0.8×10^{7} S/m, the relative permeability (μ_r) = 300, the relative permittivity (ε_r) = 3.5. It notes that the free space permeability (μ_0) is $4\pi\times10^{-7}$ H/m, and the free space permittivity (ε_0) is 8.854×10^{-12} F/m [11].

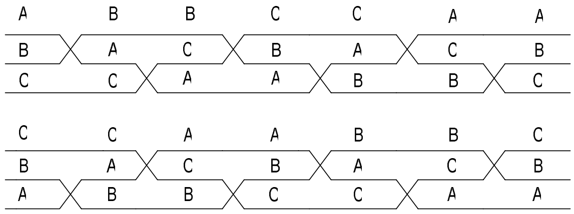

Fig. 3 Transmission lines transposition in case of long distance distribution

TABLE I
SIX TYPES OF TRANSPOSITION

type1	type2	type3	type4	type5	type6
A C′	B C′	B A′	C A′	C B′	A B′
B B′	A A′	C C′	B B′	A A′	C C′
C A′	C B′	A B′	A C′	B C′	B A′

Notes for the table, letter A, B and C reserve for each phase of the first conductor circuit, whereas A′, B′ and C′ indicate those of the second circuit.

V. RESULTS AND DISCUSSION

This paper employs MATLAB programming to simulate electric field and magnetic field distribution for six types long distance distributing transposition. Electric field simulated for all six types that same results every type can be depicted in Fig. 4. Also, simulation results of magnetic field distribution for the six types of transposition can be shown in Fig. 5.

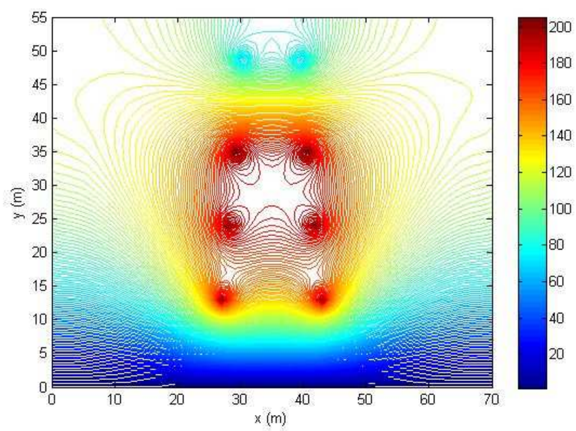

Fig. 4 Electric field distribution (kV/m) for all type transposition

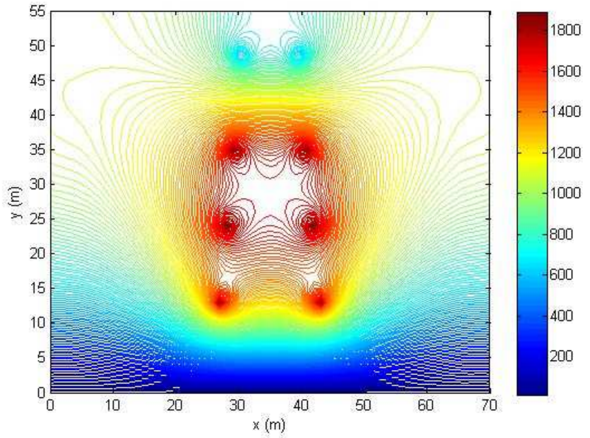

Fig. 5 Magnetic field distribution (μT) for all type transposition

When consider at some selected positions for more detail, Fig. 6-7 show the electric field plot at the height of 1 m and 10 m above the ground for all six types that same results every type, respectively. In addition, Fig. 8-9 show the magnetic field plot at the height of 1 m and 10 m above the ground for all six types, respectively.

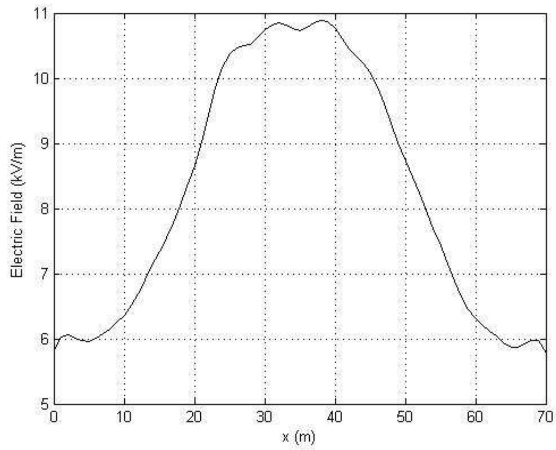

Fig. 6 Electric field distribution at 1 m above the ground for all type

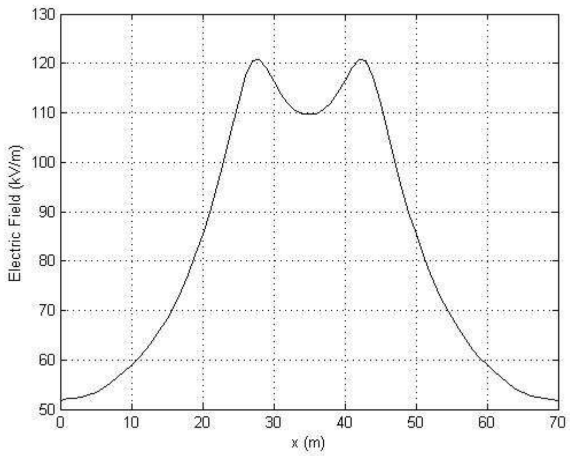

Fig. 7 Electric field distribution at 10 m above the ground for all type

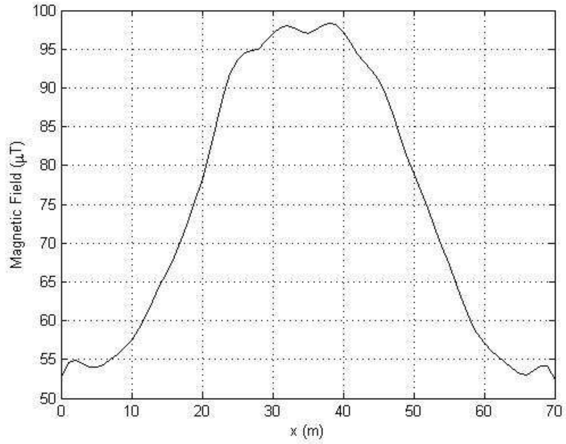

Fig. 8 Magnetic field distribution at 1 m above the ground for all type

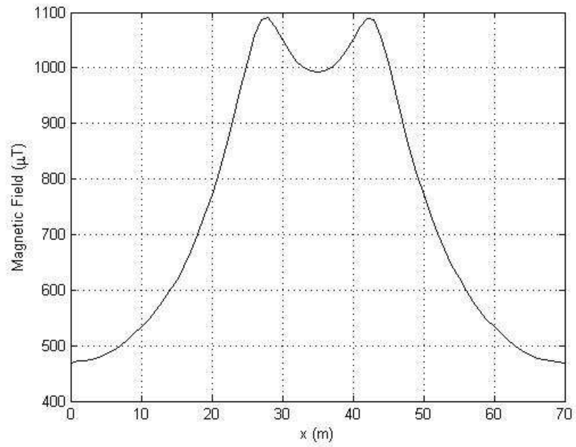

Fig.9Magnetic field distribution at 10 m above the ground for all type

From the simulation results, the six types of transmission lines transposition in case of long distance distribution, it will not affect changing electric field and magnetic field which surround the transmission line.

VI. Conclusion

This paper has studied electric and magnetic field distribution resulting from six types long distance distributing transposition. 500-kV, double-circuit, four-bundled power transmission lines of Electricity Generating Authority of Thailand (EGAT) were investigated. FEM developed by using MATLAB programming was employed. As a result, the impact from simulation of six types long distance distributing transposition will not effect changing of electric field and magnetic field which surround the transmission line.

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