Line Configuration Analysis of an Overhead Ground Wire the Effect of Electric Fields Distribution around the HV Power Transmission Line Using Finite Element Method

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Abstract: - This paper has proposed a mathematical model of electric fields caused by high voltage (HV) conductors of electric power transmission systems by using a set of second-order partial differential equations (PDE). This study has considered line configuration of an overhead ground wire (OHGW) the effect on electric fields emitted around a 500-kV power transmission line. Comparison among seven test cases configuration, varying height of OHGW, varying distance between two-line of OHGW and varying size of OHGW, has been illustrated. Computer-based simulation utilizing the two-dimensional finite element method (FEM) in the time harmonic mode, instructed in MATLAB programming environment with graphical representation for electric field strength has been investigated. From all test cases, the calculation line of 1.0 m above the ground level is set to investigate the electric fields acting on a human.

Key-Words: - Overhead Ground Wire (OHGW), Line Configuration, Electric Field, Finite Element Method (FEM), Transmission Line

1 Introduction

An overhead ground wire (OHGW) is one of key components in electrical power transmission systems. It is a small metal conductor run between the tops of overhead power transmission towers. At each tower, the OHGW is connected to ground through the tower metal frame. It exhibits the protection of high voltage conductors from lightning strokes. Beside the lightning protection, the OHGW also influences electric field distribution around the power transmission lines caused by the high voltage conductors. This paper presents line configuration of an OHGW the effect on electric fields emitted around a 500-kV power transmission line. 500-kV extra high-voltage (EHV) transmission lines of Electricity Generating Authority of Thailand (EGAT) have been increasingly installed due to electrical demand growth in Thailand. The first 500-kV power lines is a double-circuit configuration linked between Maemoh Power Plant, Lumpang province and Thatako Substation, Nakhon Sawan province. Another 500-kV power link is a single-circuit power transmission line connecting between Thatako Substation and Nongchok Substation, Bangkok. In this research, single circuit 500-kV power transmission line is selected for implementation.

Finite Element Method (FEM) is one among popular numerical methods that is able to handle problem complexity in various forms. At present, the FEM has been widely applied in most engineering fields. Even for problems of electric field distribution, the FEM is able to estimate solutions of Maxwell's equations governing the 500-kV power transmission systems. With defining a line of calculation and assuming very thin power lines, two-dimensional problems of electric field analysis governed by empirical mathematical expressions can be applied. To provide a potential tool of simulation, the FEM is flexible and suitable to estimate electric field distribution. Although the conventional methods are simpler than the use of the FEM, they are limited for the system of simple geometry. In practice, several metallic structures can be found underneath the power transmission line, e.g. steel tower trusts, communication lines nearby, metallic fends or other lower voltage transmission lines. Employing the FEM can includes these effects by choosing material dielectric constant for each additional structure domain. With this feature, the FEM is one of potential numerical simulation tools for analyzing electric field problems of combined material regions. Unfortunately, there is no report of exploiting the FEM for electric field analysis of electric power transmission systems. To utilize the advantages of the FEM for handling the electric field problems, FEM model development and problem formulation need to be defined in electric field problems of EHV power transmission systems.

From literature, most research works involving the OHGW mainly devote to put emphasis on reducing the effects of lightning strokes on overhead transmission lines [1-3]. In this paper presents line configuration of an OHGW the effect on electric fields emitted around a single circuit 500-kV power transmission line that has been installed in Thailand. It is currently the highest operating voltage level in this country. Comparison among seven test cases configuration, varying height of OHGW, varying distance between two-line of OHGW and varying size of OHGW, has been illustrated. The computer simulation based on the FEM in the time harmonic mode with appropriate graphical representation of electric fields is conducted. All the programming instructions are coded in MATLAB program environment.

2 Electric Field Modeling for a Power Transmission Line

A mathematical model of electric fields (**E**) radiating around a transmission line is usually expressed in the wave equation (Helmholtz's equation) as Eq.(1) [4-5] 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.

This paper has considered the system governing by using the time harmonic mode and representing the electric field in complex form, $\mathbf{E} = Ee^{j\omega t}$ [6], 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.

From Eq.(1), by substituting the complex electric field, Eq.(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

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

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 in Eq.(2) and Eq.(3) [7-9].

3 FEM for the power transmission line

3.1 Discretization

This research is to focus on a power transmission system of Electric Generating Authority of Thailand (EGAT), especially single-circuit, 500-kV power transmission line. The circuit is 4-bundled conductors, horizontal arrangement as illustrated by Fig. 1. The height of the lowest conductors at midspan (maximum sag allowance) is 13.00 m above the ground level [10].

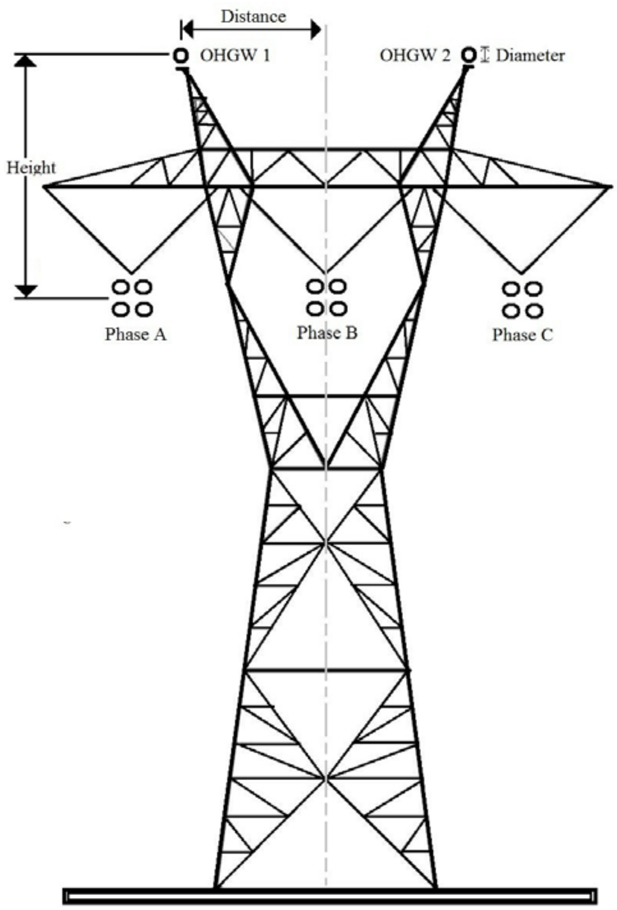

Fig.1 Single circuit 500 kV transmission system

The working region for modelling electric fields using FEM is defined by Fig. 2, which is decretized by using linear triangular elements. Fig. 3 is just a zoom-in version of Fig. 2 to show how triangular meshes around the conductors are generated.

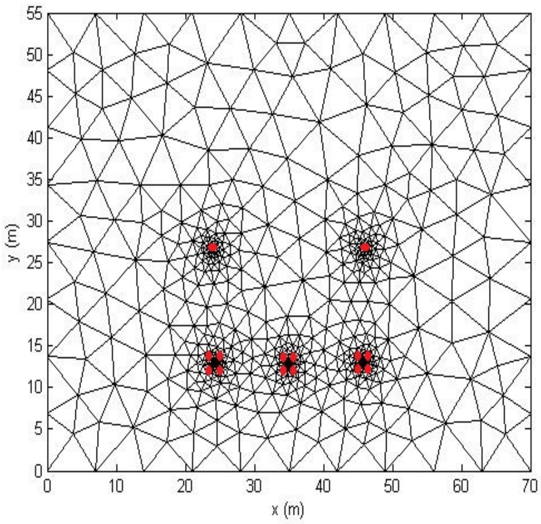

Fig.2 Discretization of a test system

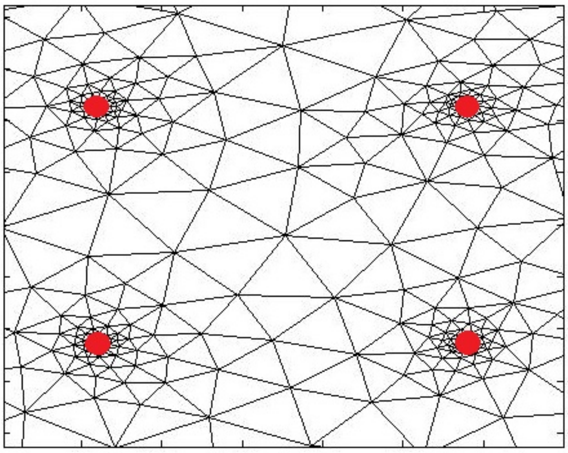

Fig.3 Grid around the conductors

In this paper presents line configuration of an OHGW the effect on electric fields emitted around a power transmission line. This research is categorized by seven test cases configuration which comparison among varying height of OHGW from conductors, varying distance between two-line of OHGW and varying size or diameter of OHGW as shown in Fig. 1. The standard case is entrusted at case 1, which phase conductors used are 795 MCM (diameter = 0.02772 m) while OHGW are 3/8 inch (diameter = 0.009114 m). The detail of the seven test cases configuration is tabulated in Table 1. By case 2 and case 3 compares about distance between two-line of OHGW with case 1 (standard case), case 4 and case 5 compares about height of OHGW from conductors with case 1, case 6 and case 7 compares about diameter of OHGW with case 1. The seven test cases are illustrated diagrammatically by Fig. 4 - Fig. 10, respectively.

Table 1 Detail of the seven test cases configuration

Case	Height (m)	Distance (m)	Diameter (m)
1	13.6	10.65	0.009114
2	13.6	13.00	0.009114
3	13.6	9.00	0.009114
4	10.0	10.65	0.009114
5	17.0	10.65	0.009114
6	13.6	10.65	0.027720
7	13.6	10.65	0.007500

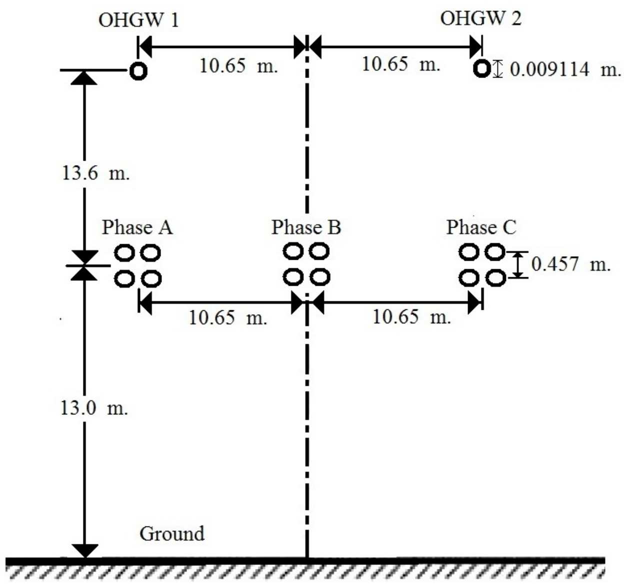

Fig.4 The dimension of case 1

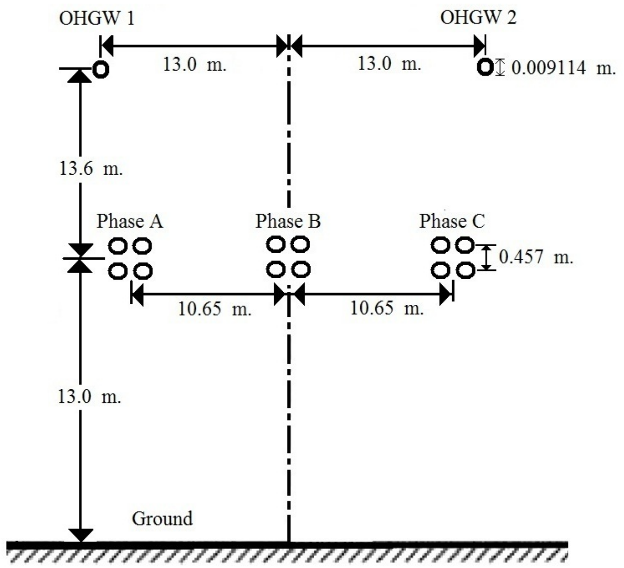

Fig.5 The dimension of case 2

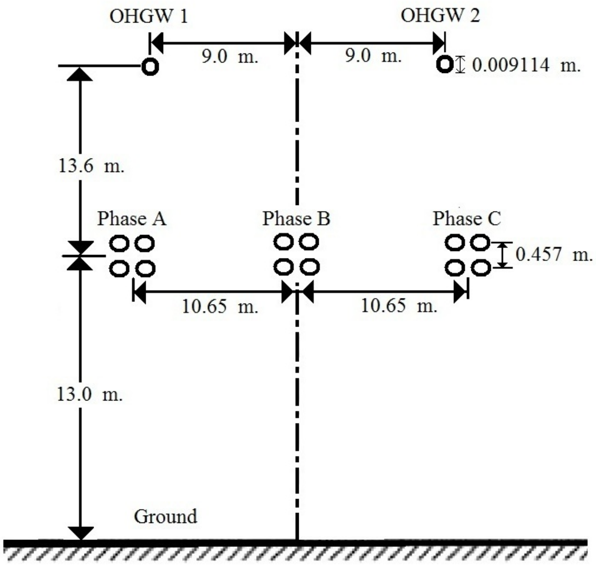

Fig.6 The dimension of case 3

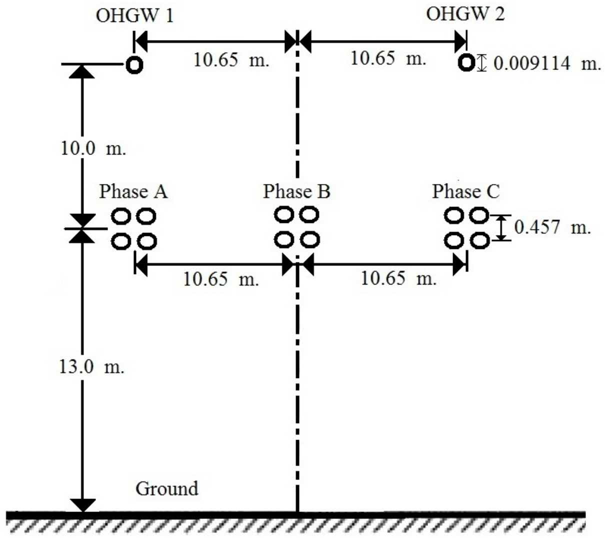

Fig.7 The dimension of case 4

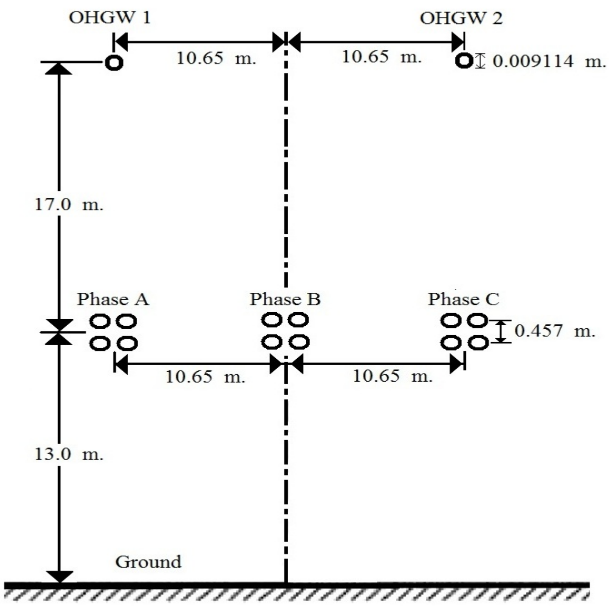

Fig.8 The dimension of case 5

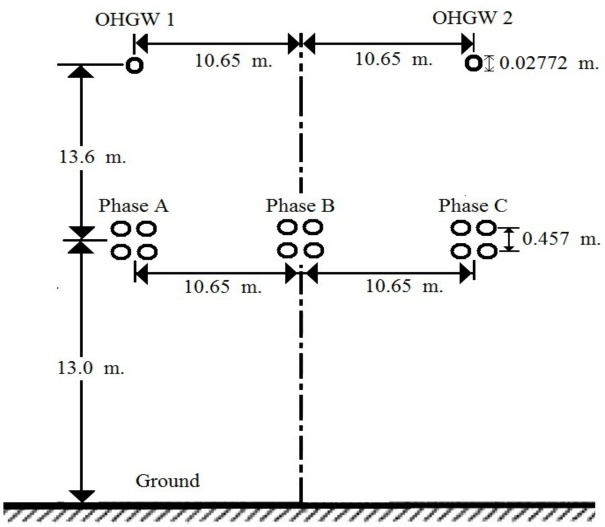

Fig.9 The dimension of case 6

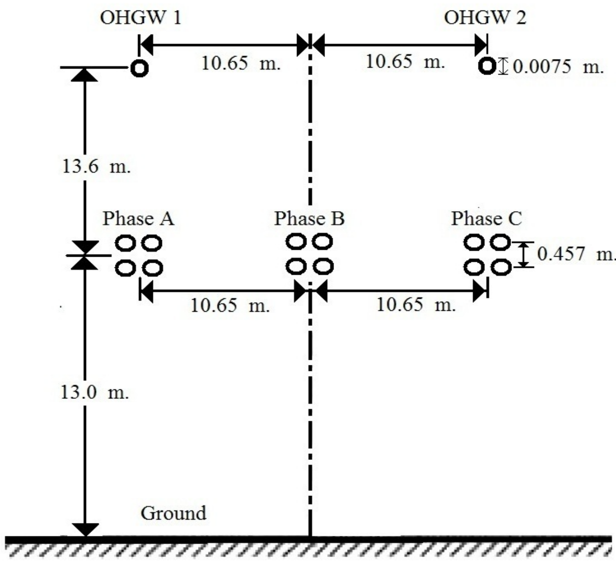

Fig.10 The dimension of case 7

3.2 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. The shape function for two-dimensional (2D) finite element method used in this research is the application of 3-node triangular element (two-dimensional linear element) [11-12]. According to the method, the electric field is expressed as follows.

$$E(x,y) = E_i N_i + E_j N_j + E_k N_k \tag{3}$$

…, 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,

$$\begin{aligned} a_i &= x_j y_k - x_k y_j, & b_i &= y_j - y_k, & c_i &= x_k - x_j \\ a_j &= x_k y_i - x_i y_k, & b_j &= y_k - y_i, & c_j &= x_i - x_k \\ a_k &= x_i y_j - x_j y_i, & b_k &= y_i - y_j, & c_k &= x_j - x_i. \end{aligned}$$

The method of the weighted residue with Galerkin approach is then applied to the differential equation, Eq.(2), 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

$$[M + K]\{E\} = 0 \tag{4}$$

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

$$K = \frac{1}{\mu}\int_\Omega \left(\frac{\partial N_n}{\partial x}\frac{\partial N_m}{\partial x} + \frac{\partial N_n}{\partial y}\frac{\partial N_m}{\partial y}\right) d\Omega = \frac{1}{4\mu\Delta_e}\begin{bmatrix} b_i b_i + c_i c_i & b_i b_j + c_i c_j & b_i b_k + c_i c_k \\ & b_j b_j + c_j c_j & b_j b_k + c_j c_k \\ Sym & & b_k b_k + c_k c_k \end{bmatrix}$$

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.

3.3 Boundary Conditions and Simulation Parameters

The boundary conditions applied here are that to set zero electric fields at the ground level and the OHGW. For the boundary conditions at outer perimeters of 12-single circuit power lines has applied with the research of [10], [13]. This simulation uses the system frequency of 50 Hz. The conductors used for test are 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 4π×10^{-7} H/m, and the free space permittivity (ε_0) is 8.854×10^{-12} F/m [14].

4 Results and Discussion

The FEM-based simulation conducted in this paper is coded with MATLAB programming for calculation of magnetic field dispersion. To utilize a graphical feature of MATLAB, the contour of magnetic field distribution through the cross-sectional area of the working domain. Fig. 11 - Fig. 17 illustrate the result of electric field distribution for the seven test cases configuration, respectively.

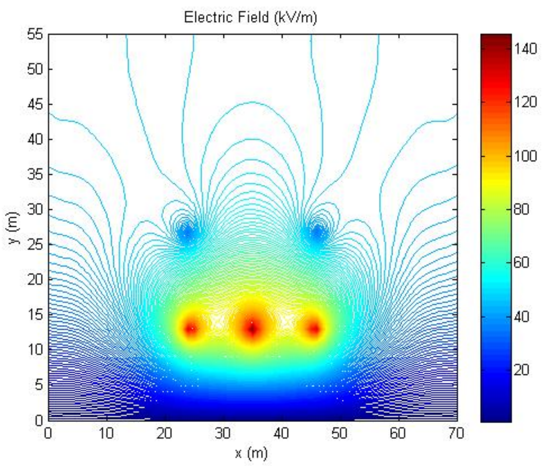

Fig.11 Electric field distribution of case 1

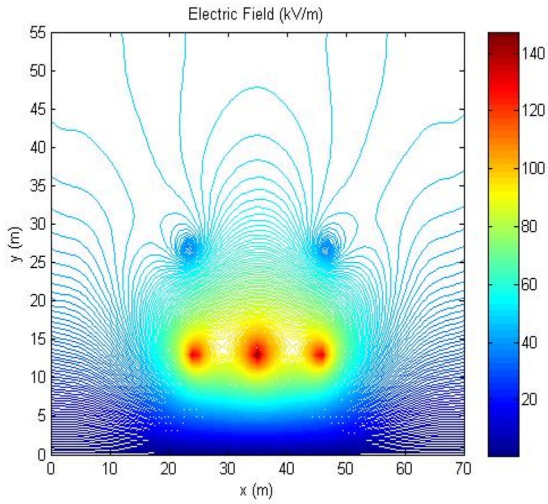

Fig.12 Electric field distribution of case 2

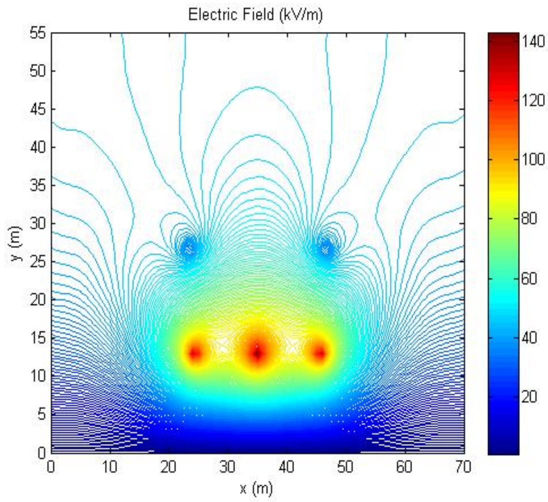

Fig.13 Electric field distribution of case 3

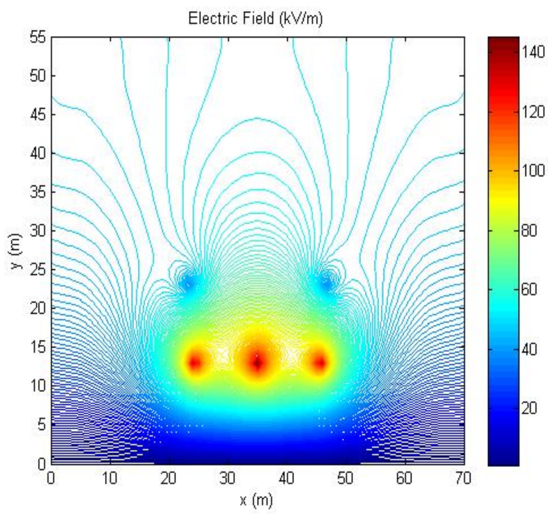

Fig.14 Electric field distribution of case 4

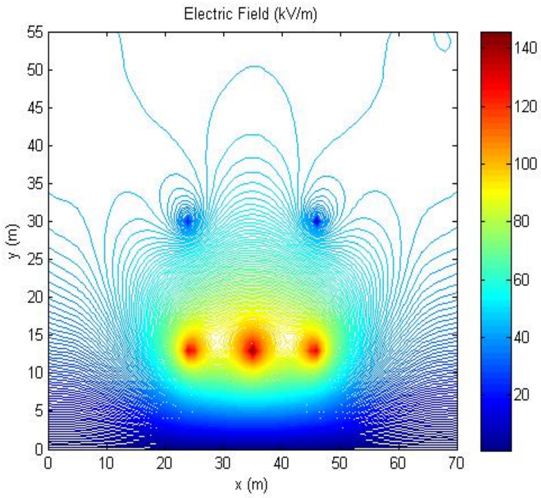

Fig.15 Electric field distribution of case 5

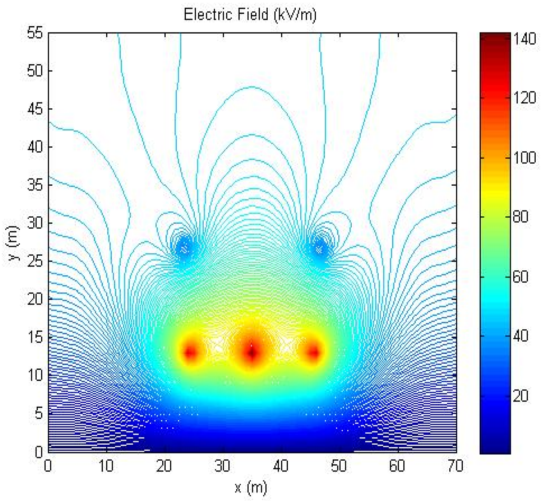

Fig.16 Electric field distribution of case 6

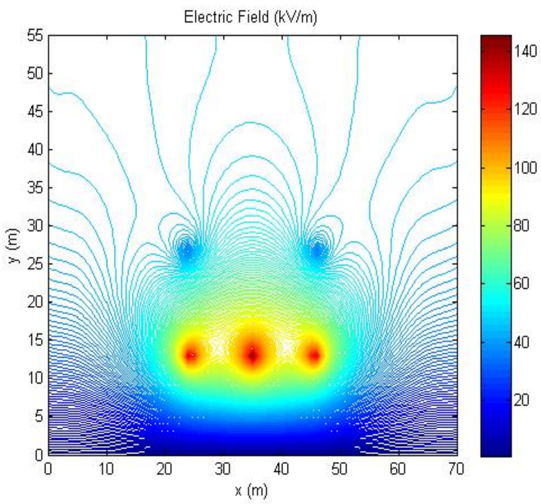

Fig.17 Electric field distribution of case 7

The illustration of electric field contour is given by a working area of the 70×55 m^2 rectangle as shown in Fig. 2. The electric field distributions simulated are determined by balanced conductor potentials of a power transmission lines. To describe possible effects of electric field on human or other living things underneath the power line, the line of calculation, 1.0 m above the ground (y = 1 m) is defined. Fig. 18 - Fig. 24 plotted the result of electric field at the height of 1 m above the ground for the seven test cases configuration, respectively. And the comparative result of electric field for all cases is shown in Fig. 25. It notices that all graphs have peak near the center position.

Table 2 showed the result of comparison in electric field distribution through distance x when consider the seven test cases configuration that is over from the ground level 1 m that people pass by. An average of electric field through distance x for all cases when consider the height of transmission line at midspan is less than electric field level that hazard to human. It is regulated by International Commission of Non Ionizing Radiation Protection [15], which the level of electric field safe to human for occupation whole working day must not over 10 kV/m. From those results, the average electric field magnitude is reduced when comparison between case 1 (standard case) with case 4 (best case, because lowest average electric field) by (5.09-4.93)/5.09 = 3.14%, resulting from focusing the closer height of OHGW from conductors. From the detail of all test cases configuration, case 2 and case 3 that compares about distance between two-line of OHGW with case 1, resulting from choosing the closer distance, the average electric field is reduced. Case 4 and case 5 that compares about height of OHGW, resulting from choosing the closer height, the average electric field is reduced. And case 6 and case 7 that compares about diameter of OHGW, resulting from choosing the bigger size, the average electric field is reduced.

Table 3 showed comparative results among average electric field for all the cases. It is considered that at the same height, the case 4 distributes more small electric field than the all test cases configuration.

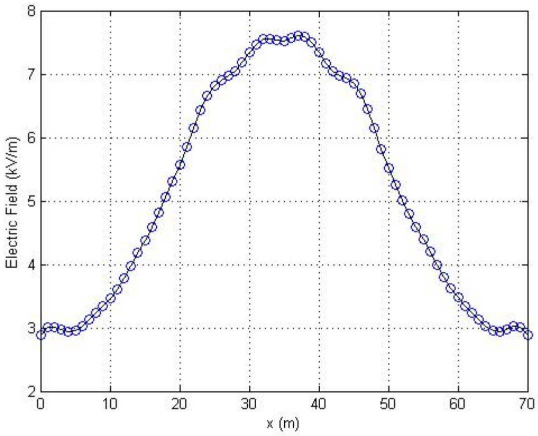

Fig.18 Electric field at high 1 m of case 1

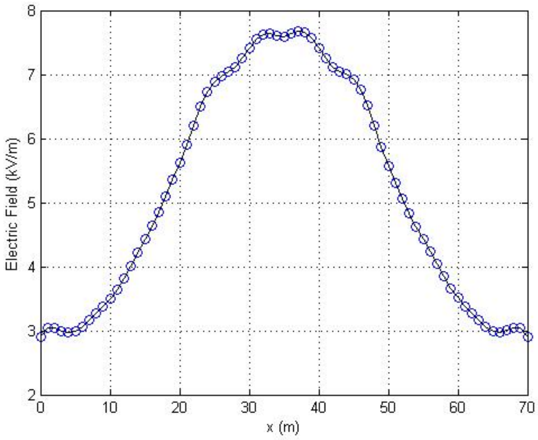

Fig.19 Electric field at high 1 m of case 2

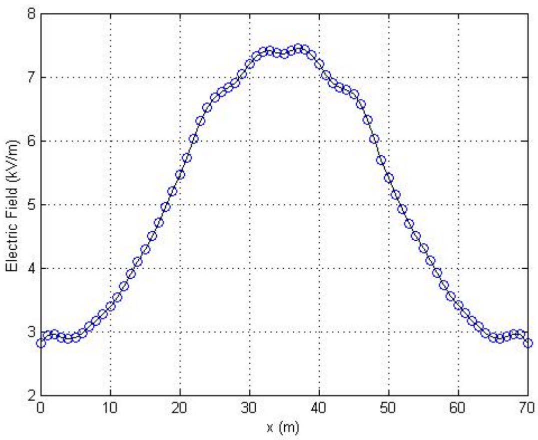

Fig.20 Electric field at high 1 m of case 3

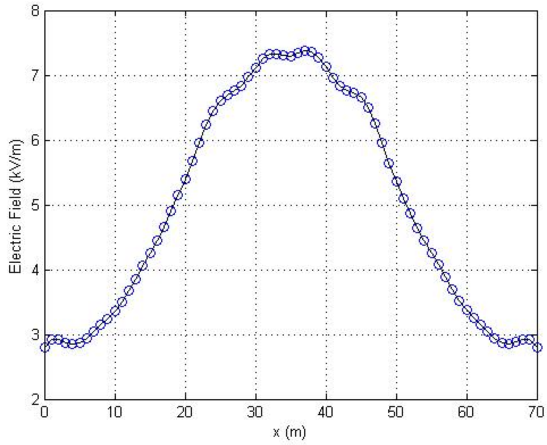

Fig.21 Electric field at high 1 m of case 4

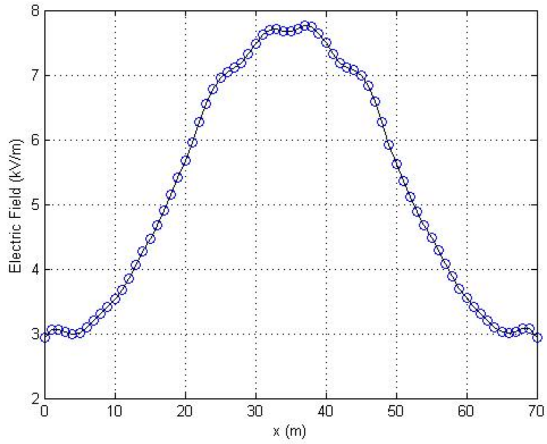

Fig.22 Electric field at high 1 m of case 5

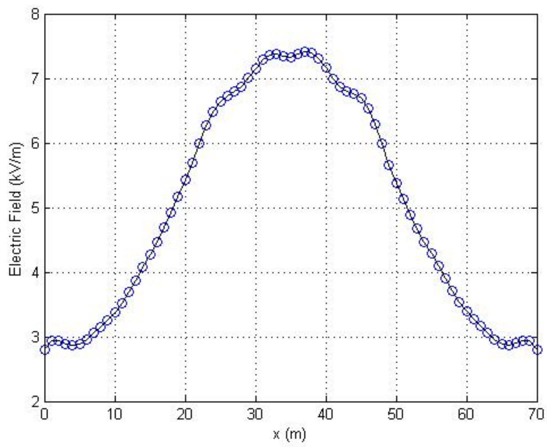

Fig.23 Electric field at high 1 m of case 6

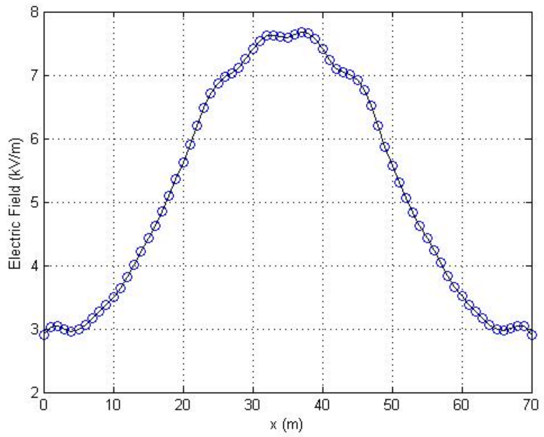

Fig.24 Electric field at high 1 m of case 7

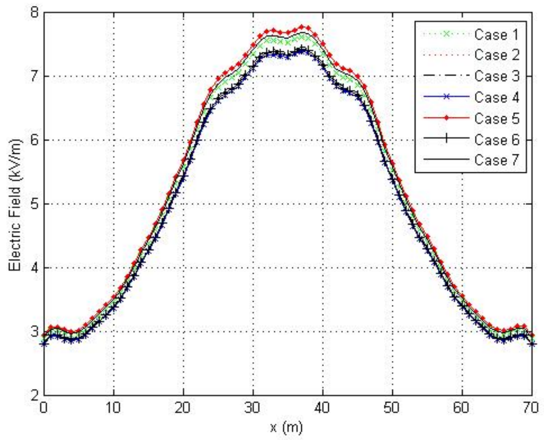

Fig.25 The comparison of electric field at high 1 m

5 Conclusion

This paper has studied line configuration of an overhead ground wire (OHGW) the effect on electric fields emitted around a power transmission line. Single-circuit, 500-kV transmission lines of Electricity Generating Authority of Thailand (EGAT), which is recently the highest voltage level in Thailand, is investigated. Comparison among seven test cases configuration, varying height of OHGW, varying distance between two-line of OHGW and varying size of OHGW, has been illustrated. The computer simulation is performed by using finite element method instructed in MATLAB programming codes. The results for all cases revealed that the electric fields, 500-kV transmission lines at a level of 1 m above the ground that are assumed to be the level of human working, do not excess the maximum allowance when compiled with the ICNIRP standard. As a result, it can conclude that the closer height of OHGW from conductors has the ability to reduce the electric field intensity.

Table 2 Comparing of electric field dispersion at high 1 m

x	The Electric Field (kV/m)						
(m)	Case1	Case2	Case3	Case4	Case5	Case6	Case7
2	3.01	3.04	2.95	2.92	3.07	2.93	3.02
4	2.94	2.97	2.88	2.85	3.00	2.86	2.98
6	3.03	3.06	2.97	2.94	3.09	2.96	3.08
8	3.24	3.27	3.17	3.14	3.30	3.16	3.22
10	3.47	3.50	3.40	3.36	3.53	3.38	3.37
12	3.78	3.82	3.71	3.67	3.86	3.69	3.67
14	4.18	4.22	4.10	4.05	4.26	4.08	4.14
16	4.59	4.63	4.49	4.45	4.68	4.47	4.64
18	5.05	5.10	4.95	4.90	5.15	4.93	5.12
20	5.57	5.63	5.46	5.40	5.68	5.43	5.59
22	6.15	6.21	6.02	5.96	6.27	5.99	6.18
24	6.65	6.72	6.52	6.45	6.79	6.49	6.77
26	6.91	6.98	6.77	6.70	7.05	6.73	7.04
28	7.04	7.11	6.90	6.83	7.18	6.87	7.13
30	7.34	7.41	7.19	7.12	7.49	7.16	7.44
32	7.55	7.62	7.39	7.32	7.70	7.36	7.65
34	7.53	7.61	7.38	7.31	7.68	7.34	7.58
36	7.56	7.64	7.41	7.34	7.71	7.37	7.60
38	7.59	7.66	7.44	7.36	7.74	7.40	7.72
40	7.35	7.42	7.20	7.13	7.49	7.16	7.52
42	7.04	7.11	6.90	6.83	7.18	6.86	7.13
44	6.94	7.01	6.80	6.73	7.08	6.77	7.01
46	6.70	6.77	6.57	6.50	6.83	6.53	6.78
48	6.14	6.20	6.02	5.96	6.26	5.99	6.19
50	5.52	5.57	5.41	5.35	5.63	5.38	5.58
52	5.01	5.06	4.91	4.86	5.11	4.89	5.12
54	4.58	4.63	4.49	4.45	4.68	4.47	4.65
56	4.20	4.24	4.11	4.07	4.28	4.09	4.19
58	3.80	3.84	3.73	3.69	3.88	3.71	3.73
60	3.48	3.51	3.41	3.37	3.55	3.39	3.42
62	3.24	3.27	3.17	3.14	3.30	3.16	3.24
64	3.03	3.06	2.97	2.94	3.09	2.96	3.08
66	2.94	2.97	2.88	2.86	3.00	2.87	2.97
68	3.02	3.05	2.96	2.93	3.08	2.94	3.01
70	2.88	2.91	2.82	2.79	2.94	2.81	2.90
Avg	**5.09**	**5.14**	**4.98**	**4.93**	**5.19**	**4.96**	**5.13**

Table 3 Comparing of average of electric field at each height

y	The Electric Field (kV/m)						
(m)	Case1	Case2	Case3	Case4	Case5	Case6	Case7
1	5.09	5.14	4.98	4.93	5.19	4.96	5.13
2	10.18	10.28	9.97	9.87	10.38	9.92	10.23
5	25.56	25.82	25.05	24.79	26.07	24.92	25.51
10	50.78	51.29	49.76	49.26	51.80	49.51	50.78
15	63.24	63.87	61.97	61.34	64.50	61.66	63.25
20	56.55	57.12	55.42	54.86	57.68	55.14	56.69
25	49.67	50.17	48.67	48.18	50.66	48.43	49.97
30	47.40	47.87	46.45	45.97	48.34	46.21	47.77

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