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Mitigation of the Electric and Magnetic Fields of 500-kV Overhead Transmission Lines

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ABSTRACT The electric and magnetic fields of overhead high voltage transmission lines are still a critical problem for new construction because of their biological effects on the human body. This issue has been a subject of scientific interest and public concern for the risk of the electric and magnetic fields on living organisms. Accordingly, the overhead transmission lines are considered a source of such this risk due to their high electric and magnetic fields in the populated areas. Because of the recent concerns that electric besides magnetic fields, generated by overhead transmission lines, electric power researchers have been trying to find effective methods for the mitigation of the electrical and magnetic fields to be in the range of acceptable limits. Researchers have been trying to find transmission line geometries that will reduce these electric and magnetic fields. Therefore, in this article two novel methods of reducing the electric and magnetic fields are discussed, one is to change the position of the center phase to optimize the delta configuration and the other is to use more than two shielding wires with calculating the currents in these wires. The obtained results of the two proposed methods are compared with the electric as well as magnetic fields, and the right-of-way values of the present conventional configuration. Additionally, this article presents a case study carried out on an Egyptian 500 kV high voltage overhead transmission line for the mitigation of magnetic and electric field intensities.

INDEX TERMS Mitigation of the electrical and magnetic fields, numerical methods, biological effects of electromagnetic, overhead power transmission lines.

I. INTRODUCTION

The use of electrical energy transmission lines in populated areas causes numerous issues, that's due to the high value of the electric besides magnetic fields on the ground level which affects the men, animals, and plants, and also because most of the people have been concerned about possibly of their carcinogenic influences [1]. Possible danger to humans and animals' health from living near electrical energy transmission lines has been worried by scientists throughout the past years [1]. Electric field effects from overhead lines are caused by the extremely high voltage while magnetic field effects are due to line loading and short circuit currents. Exposure to 50-Hz electric and magnetic fields created by overhead lines has been expected of increasing the risk to living organisms [2]. One of the main key elements that determine the selection of transmission line right of way (ROW) is that the high impact of electric and magnetic fields. Power line ROW, in general, can be defined as the safe path of the overhead transmission lines (OHTLs) so that humans are not exposed to influential values of electric and magnetic fields while maintaining the continuous flow of electrical energy. Such as, for 230 kV, 500 kV, and double-circuit 500-kV lines, the supervisory staff selected magnetic field levels of 150, 200, and 250 mG edge of ROW magnetic field, respectively [3]. In another way, the ROW is described as the distance from the center phase into a point where the electric field at one meter directly above the ground level is considered to be 1.5 kV/m [4].

The supervisory staff's regulations establish the width of ROW necessary for a certain line design, or, opposite, what lines can be built on a particular ROW [2]. The magnetic

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and electrical field values, as well as profiles around underneath overhead transmission lines, are known to be affected by the geometrical characteristics of these lines. Some of the researchers used a passive loop conductor to reduce the magnetic field. Moreover, the influence of active and passive shield wires on the magnetic field values below the lines as well as the electric field on the conductor's outer surface are underlined by reference [5]. Mitigation of magnetic field below overhead transmission line was done including the impacts of the sag between towers, as well as the sag variant with the temperature on the magnetic field calculations [6]. Safety assessment and lessening technology for extremely low frequency (ELF) of electromagnetic fields and guidelines for restricting exposure to time-varying electric and magnetic fields age were presented in references [7], [8]. A summary of the methods used in the mitigation of electric and/or magnetic fields was given in Table 1.

This article presents two methods for reducing the magnetic and electrical fields' values, one by changing the position of the center phase to optimize the delta configuration, which considers as an innovative method that has not been used before, and the other is by the use of more than one shielding wire. Investigation of the impact of the shielding wires' parameters namely, their numbers, their heights directly above the ground level, as well as the spacing between them on the electromagnetic fields of electrical energy transmission lines are done. The effects of the center phase position to optimize the delta configuration, both on the ROW and profiles of electric and magnetic fields at ground level have been investigated.

The Charge Simulation Method (CSM) is utilized for electric field computations [12], [13], the number and position of line charges are chosen to give the exact values of the electrical field under the transmission lines. The Biot-Savart law is used for magnetic field computations. The calculations of electromagnetic fields in case of changing the centerline position and in case of using shielding wires are compared with the using of the conventional 500 kV overhead transmission line configuration.

The study shows that the geometrical parameters of the three-phase configuration can be optimized to reduce the maximum ground electric and magnetic fields. Also, it is noticed that increasing the shielding wires by a number of more than two has little influence in reducing the electric and magnetic fields.

II. ELECTRIC AND MAGNETIC FIELDS CALCULATION

Some assumptions are considered in the proposed methods of calculations, they are as the following:

1) The overhead transmission line is assumed to be infinitely long.

2) The overhead transmission line phase currents are assumed to be sinusoidal besides at balance condition. The mutual couplings between the transmission line phases are ignored.

TABLE 1. Methods used in the mitigation of electric and magnetic fields of power lines.

Method	Method description	Drawbacks
Line compaction [9]	Reduction in phase spacing	May introduce corona; may limit available techniques for live line maintenance
Reverse phase (transposition) [10]	Reversal of phases on double circuit line	Only applicable to double circuit lines
Delta or reverse delta configuration [10]	Conversion from a flat configuration to delta	May introduce corona
Split phases [10]	Splitting of phases to create additional phases to create significant field reduction.	Increases complexity of line structures
Shielding with loops [11]	Conductive loop placed under the line	Increases complexity of the transmission system

3) The electrical resistivity of the earth under the overhead transmission line is assumed to be constant.

A. ELECTRIC FIELD CALCULATION

In this article, the charge simulation and image methods are employed to compute the electric field in the surrounding area of the 500 kV transmission line. In the traditional CSM, fictitious charges are applied to estimate the field in the nearby region under study. The position, as well as the type of these charges, are determined although their magnitudes are unidentified. Further, infinite line charges are utilized to model the systems that have translational equilibrium; therefore, they are applied to simulate the electric field of the multiphase ac overhead transmission lines including the shielding wires. Regarding, the three-phase transmission structures, the applied voltages on the three-phase OHTLs are considered sinusoidal and can be placed in phasor or static form as:

$$V_1 = V_{rms}\angle 0^o \tag{1}$$

$$V_2 = V_{rms}\angle 120^o \tag{2}$$

$$V_3 = V_{rms}\angle 240^o \tag{3}$$

The potential of the shielding wires is considered as zero voltage. Enforcing these potentials as boundary restrictions at a set of contour points sitting on the surfaces of the OHTLs including compensating conductors leads to a linear system of equations in the complex unknown charges. These equations have the following structure:

$$\sum_{j=1}^{n} P_{ij}Q_i = V_i \quad i = 1, 2, \ldots, n \tag{4}$$

in which n represents the number of contour points and/or simulating charges, P_{ij} represents the potential coefficients [14], in addition, Q_j represents the unknown simulating charges. Further, Equation (4) can be placed into a matrix structure as:

$$[P][Q] = [V] \tag{5}$$

where;

- $[P]$ is defined as a square matrix containing the potential coefficients,
- $[Q]$ is defined as a complex vector of the unknown charges, and
- $[V]$ is defined as the vector of boundary conditions' voltages.

The line charges simulating the overhead transmission lines of the system under study are given by:

$$[Q] = [P]^{-1}[V] \tag{6}$$

For checking the simulation method accuracy, checkpoints, at locations other than those utilized for the contour points that are employed in the simulation procedure, are validated by using the static shape of the charges presented in equation (6). After fulfilling the solution-quality measures, the electric field strength, as well as potential at every point in the space, can be computed from analytical expressions as follows [14].

$$E_t = \sqrt{E_{vi}^2 + E_{hi}^2} \tag{7}$$

$$E_{hi} = \sum_{j=1}^{n} Q_j \cdot L_{ij} \tag{8}$$

$$E_{vi} = \sum_{j=1}^{n} Q_j \cdot K_{ij} \tag{9}$$

$$L_{ij} = (x_i - x_j)(1/A_{ij}^2 - 1/I_{ij}^2) \tag{10}$$

$$K_{ij} = (y_i - y_j)/A_{ij}^2 - (y_i + y_j)/I_{ij}^2 \tag{11}$$

$$V_i = \sum_{j=1}^{n} P_{ij} \cdot Q_j \tag{12}$$

$$I_{ij} = \sqrt{(x_i - x_j)^2 + (y_i - y_j)^2} \tag{13}$$

$$A_{ij} = \sqrt{(x_i - x_j)^2 + (y_i - y_j)^2} \tag{14}$$

in which;

- E_{hi}, E_{vi} are the component of an electric field at the specified i^{th} point in the horizontal plus vertical paths, respectively, (kV/m),
- L_{ij}, K_{ij} are the horizontal plus vertical electric field coefficients at specified i^{th} point, respectively,
- V_i is the potential at the specified i^{th} point, (V),
- x_i, y_i are the coordinates of the i^{th} boundary contour point, and
- x_j, y_j are the coordinates of the j^{th} line charge.

B. MAGNETIC FIELD CALCULATION

The common practice, in the calculation of magnetic fields underneath OHTLs, is to assume that the overhead transmission lines are straight away horizontal wires of infinite length. By applying the Biot-Savart law, the magnetic field intensity H at a specified point $P(x_i, y_i)$ has only an azimuthal component, which can be calculated by equation (15) [2]–[4];

$$H = \frac{I}{2\pi d}\vec{a}_\phi \tag{15}$$

where:

- I is known as the flowing current in the conductor in root-mean-square (RMS) value of Ampere;
- d is known as the distance from the conductor to a specified point P in meters;
- $\vec{a}_\phi$ is known as the unit vector in the azimuthal, ϕ, direction.

Mostly, because the power transmission line has several conductors (more than 1), the overall summation of the magnetic fields by each line current must be computed at a specified point P repeatedly. Further, Fig. 1 depicts the magnetic field intensity components created by a three-conductor system carrying currents, and in the z-direction (perpendicular to the page and get out).

For AC overhead high voltage transmission lines, the line currents are sinusoidal varying with time at the specified power frequency. Accordingly, the induced magnetic field in the surrounding area of the power transmission lines as well differs at the power frequency and phase algebra can be utilized to combine numerous components, so that yield the amplitude of the mandatory magnetic field (horizontal in addition to vertical vectors).

For a three-phase system with one conductor per phase, current I can be written as follows:

$$[I] = I_{rms}\angle 0^o, I_{rms}\angle 120^o, I_{rms}\angle 240^o] \tag{16}$$

One can take into consideration the magnetic field part affected by the image currents. Hence, the complex depth α of each conductor image current can be originated as presented in [15].

$$\alpha = \sqrt{2}\delta e^{-j\pi/4} \tag{17}$$

where;

δ is identified as the skin depth of the earth, which can be calculated by equation (18) [15].

$$\delta = 503\sqrt{\rho/f} \tag{18}$$

- ρ is defined as the earth resistivity, and
- f is defined as the source current frequency in Hz.

The magnetic field intensity at a specified point $P(x_i, y_i)$ induced from the passing current I_i and its image is computed as follows:

$$\vec{H}_{ij} = H_{xij}\vec{a}_x + H_{yij}\vec{a}_y \tag{19}$$

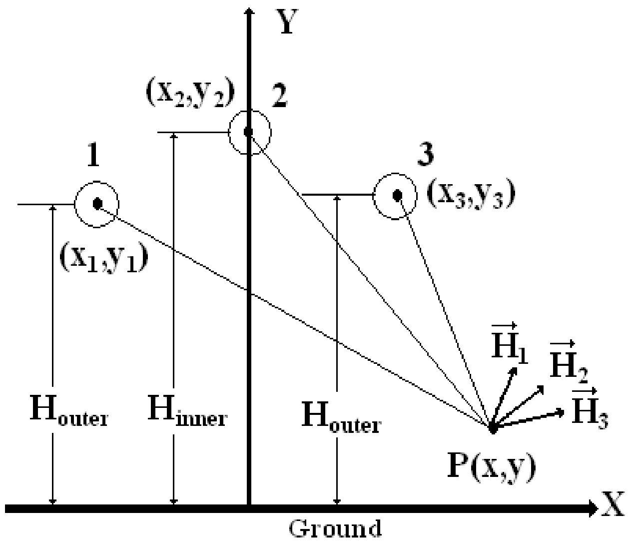

FIGURE 1. Magnetic field intensity components for 3 conductor system carrying currents.

$$H_{xij} = \frac{-I_j}{2\pi}\left[\frac{y_i - y_j}{r_{ij}^2} - \frac{y_i + y_j + \alpha}{r'^{2}_{ij}}\right] \tag{20}$$

$$H_{yij} = \frac{I_j}{2\pi}\left[\frac{x_i - x_j}{r_{ij}^2} - \frac{x - x_j}{r'^{2}_{ij}}\right] \tag{21}$$

where;

$\vec{a}_x$ represents the unit vector in the x-direction,
$\vec{a}_y$ represents the unit vector in the y-direction, and;

$$r_{ij} = \sqrt{(x_i - x_j)^2 + (y_i - y_j)^2} \tag{22}$$

$$r'_{in} = \sqrt{(x_i - x_j)^2 + (y_i + y_j + \alpha)^2} \tag{23}$$

The total summation of magnetic field intensity in the both x-and y-directions (i.e., horizontal and vertical components, respectively) are:

$$H_{xt} = \sum_{j=1}^{3} H_{xij} \tag{24}$$

$$H_{yt} = \sum_{j=1}^{3} H_{yij} \tag{25}$$

Finally, the magnitude of the resultant magnetic field intensity H_t is:

$$H_t = \sqrt{H_{xt}^2 + H_{yt}^2} \tag{26}$$

Equations (20) and (21) are applicable in case of the distance away from the field point into the conductor is lesser than $\lambda/20$ where λ is considered the free-space wavelength ($\lambda = c/f$ meters, where $c = 3 \times 10^8$ m/sec is the speed of the light). Furthermore, they are reasonable for any point above or near the ground outside the surface.

The current in the shielding wires can be calculated by using the multi-conductor transmission lines (MTL) technique, in which [16]:

$$\begin{bmatrix} \Delta V_p \\ \Delta V_G \end{bmatrix} = \begin{bmatrix} Z_{pp} & Z_{pG} \\ Z_{Gp} & Z_{GG} \end{bmatrix} \begin{bmatrix} I_p \\ I_G \end{bmatrix} \tag{27}$$

where; ΔV_p and ΔV_G are two vectors preset the drop along with the three phases and shielding wires respectively, I_p and I_G are three phases and shielding wires vectors currents respectively ($I_p = I$ in equation (16)), and Z_{ij} is the per-unit series impedance (where i and j equal p or G). Z_{ij} can be calculated as follow:

$$Z' = j\omega L + Z_E + Z_{skin} \tag{28}$$

The external-inductance matrix is considering a frequency-independent real symmetric matrix with specified entries:

$$L_{ii} = \frac{\mu_o}{2\pi} \ln \frac{2y_i}{r_i} \tag{29.a}$$

$$L_{ij} = \frac{\mu_o}{4\pi} \ln \frac{(y_i + y_j)^2 + (x_i + x_j)^2}{(y_i - y_j)^2 + (x_i + x_j)^2} \tag{29.b}$$

Here r_j symbolizes conductor radius, y_j as well as x_j represent the vertical and horizontal coordinates of the specified j^{th} conductor, respectively.

The Z_E represents the matrix of earth impedance correction and it is considered as a frequency-dependent complex matrix their entries can be obtained by using Carson's theory and/or by the approach of Dubanton complex ground plane [17]–[21]. Where the entries of Z_E are calculated by:

$$(Z_E)_{jj} = j\omega \frac{\mu_o}{2\pi} \ln\left(1 + \frac{\alpha}{y_j}\right) \tag{30.a}$$

$$(Z_E)_{ij} = j\omega \frac{\mu_o}{4\pi} \ln\left(\frac{(y_i + y_j + 2\alpha)^2 + (x_i - x_j)^2}{(y_i - y_j)^2 + (x_i - x_j)^2}\right) \tag{30.b}$$

Here α, is considered the complex depth, given in equation (17). The matrix of Z_{skin} represents a frequency-dependent complex diagonal matrix with their entries that can be calculated by applying the skin-effect theory meant for cylindrical conductors [19]. For the instant of low-frequency situations, it becomes:

$$(Z_{skin})_{jj} = (R_{dc})_j + j\omega \frac{\mu_o}{8\pi} \tag{31}$$

in which $(R_{dc})_j$ indicates the dc resistance with per-unit-length of a specified j^{th} conductor.

As the shielding wires are connected to earth (i.e., tower resistances are ignored), that outcome in: $\Delta V_G = 0$ then from equation (27), the induced shielding wires current can be calculated from the three-phase currents I_p and Z_{ij} matrix as follow;

$$I_G = \frac{-1}{Z_{GG}}(Z_{Gp} I_p) \tag{32}$$

The accuracy of a specific prediction of the electromagnetic fields under overhead transmission lines mainly depends on the reliability of the model into the actual situation [18], []19]. There are two categories of deviations from the actual situation. In the first case, the values of the model's parameters

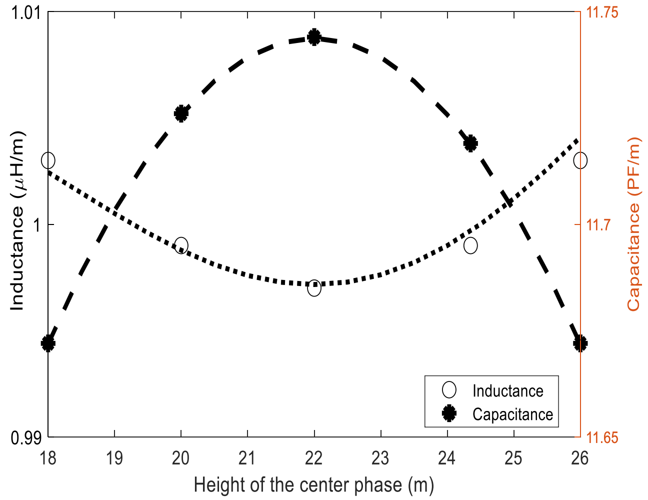

FIGURE 2. Variation in inductance and capacitance with the change in the middle phase position.

TABLE 2. Influences of the center phase heights on magnetic & electric fields and right-of-way.

Center phase heights (m)	E_{max} (kV/m) above one meter from the ground surface	ROW (m)	$E_{surf.\ Outer}$ (kV/m) On conductor surface	$E_{surf.\ Center}$ (kV/m) On conductor surface	H_{max} (A/m) Above one meter from the ground surface
18	6.216	37.29	419.254	460.526	30.852
20	4.831	36.97	422.619	457.55	27.439
22	4.855	36.69	424.804	454.325	25.392
24.35	4.9	36.44	425.742	448.863	24.004
26	4.938	36.3	425.455	443.679	23.432

may not be accurate. The amplitude of balanced currents, current asymmetry (phase and amplitude) incorporating shield wire currents, and earth resistivity are examples of these characteristics [21]–[28]. In this paper, the currents are assumed to be balanced in the three phases.

The second category consists of physical properties of the actual situation, which are not counted in the simplified model [29]–[32]. The most important of these are wires, pipes, towers, and non-homogeneous earth resistivity [33]–[38]. Some of these situations can be modeled in the above-mentioned magnetic field equations; others are more difficult to be represented.

As stated before, the aim of this article is to investigate two methods for mitigation of the electric and magnetic fields produced by 500-kV overhead lines, one is by the change of the position of the center phase of the delta configuration and the other is by using more than two shielding wires.

III. RESULTS AND DISCUSSIONS

A. CHANGING THE POSITION OF THE CENTER PHASE TO FORM DELTA CONFIGURATION

The effect of the change in the position of the middle phase conductor on the electrical characteristics of the line leads to changes in the phase inductance and capacitance. This is illustrated in Fig. 2. As it is noticed the phase inductance

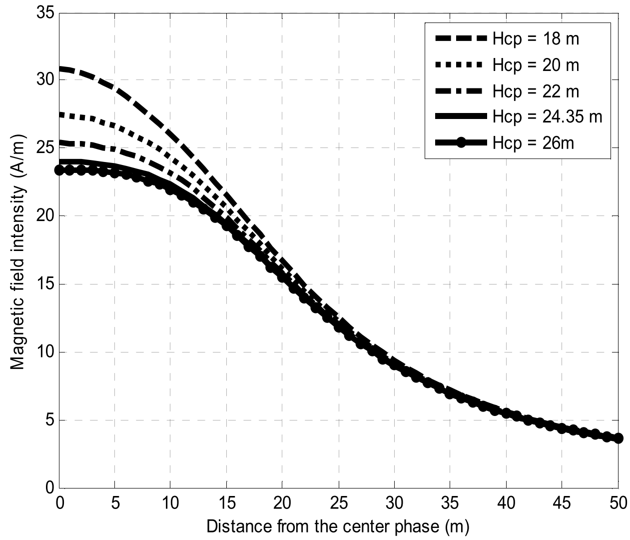

FIGURE 3. Effect of the centre phase height on the calculated magnetic field intensity of the 500 kV line.

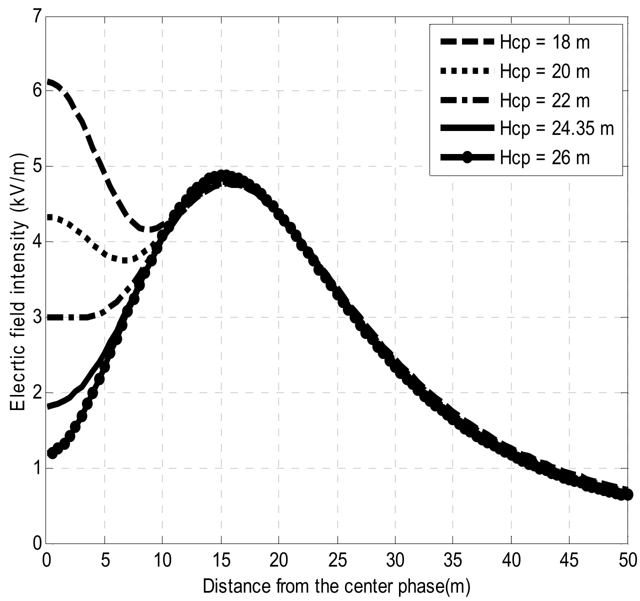

FIGURE 4. Effect of the centre phase height on the calculated electric field intensity.

is decreased, while at the same time the phase capacitance is increased. The variation in the line phase inductance and capacitance with the change in the middle phase position is considered in the electric and magnetic fields calculations.

To calculate the electric and magnetic field intensities at specified points one meter above the ground level for a 500 kV OHTLs, the data in appendix (A) are employed, besides the phase bundles are treated in terms of their corresponding radius [14]. The data given in Appendix A has been obtained regarding the El-Kuirmate-Cairo 500 kV power line, which is a part of the Egyptian overhead transmission line network [36]–[38].

Figures 3 and 4 show the variations of magnetic and electric fields intensities with the variation of the delta configuration center phase height. In this case, two ground wires

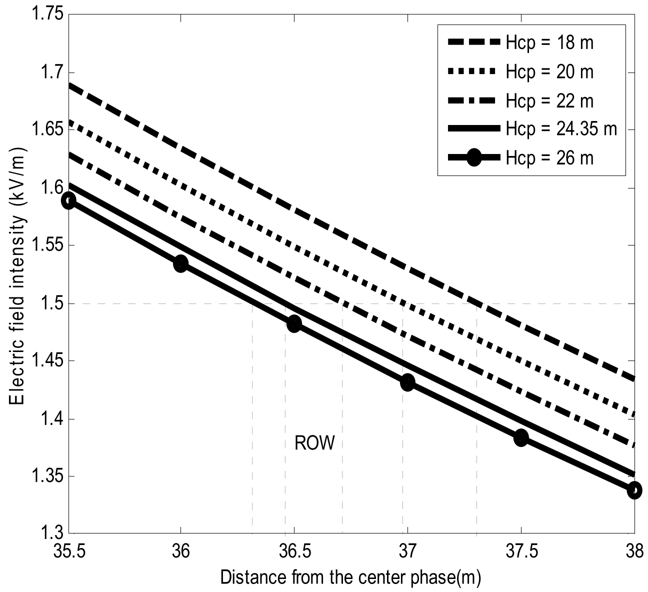

FIGURE 5. Variation of ROW with the centre phase height.

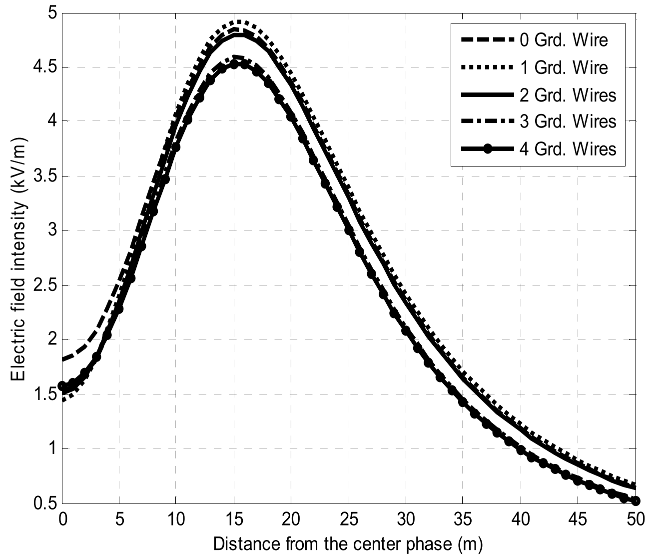

FIGURE 6. Effect of the shielding wires number on the calculated electric field intensity.

TABLE 3. Effect of the ground wires numbers on magnetic & electric fields and right-of-way.

No. of Ground Wires	0	1	2	3	4
E_{max} (kV/m) above one meter from the ground surface	4.84	4.943	4.878	4.58	4.5274
ROW (m)	36.46	36.71	36.24	34.57	34.3
$E_{Surf.Outer}$ (kV/m) On conductor surface	425.93	422.588	425.088	435.3	437.6
$E_{Surf.Center}$ (kV/m) On conductor surface	449.37	463.313	458.871	470.71	462.16
H_{max} (A/m) above one meter from the ground surface	24.0	23.3	23.07	22.31	23.68
Induced ground currents (A)	-	127.8	102.1 129.5	159.9 135.6 184.7	154.6 111.4 111.2 177.8

were positioned at the center of the tower, at height equals 30 m, and separation distance between them equals 7.5 m. Table 2 gives the influences of the center phase heights on both of magnetic and electric fields and ROW also. From Fig. 3 and Table 2 it is noted that, as it is expected, the maximum magnetic field decreases with the increase of the center phase height.

The maximum magnetic field is decreased from 30.852 (A/m) to 23.432 (A/m) with the increase of the center phase height from 18 m to 26 m. From Fig. 4, it is noticed that the maximum electric field intensity and its position are changed with the change of the center phase height. The maximum value of the electric field under the center phase reached (1.2 kV/m) when the center phase height was 26 m (higher than the outer phases by 4 m), while it was (6.13 kV/m) when the center phase height was 18 m (lower than the outer phases by 4 m). From 20 m to 26 m valuable differences in electric field intensity values are noticed until the change of the center phase is done by about 8 meters (from 18 to 26 meters). Table 2, also shows the effect of the center phase height variation on the maximum electric and magnetic fields, ROW taking the safety limit of electric field (1.5 kV/m) [4] and outer and inner phases' surface gradient.

The maximum electric field decreases with the increase in the center phase height until distance (12 m) starting from the center phase as exposed in Fig. 3 in which the delta is changed to a flat configuration. Beyond this value, the maximum electric field intensity is slightly increasing at a distance of 15 m from the center phase with the increase of the center phase height.

As shown in Fig. 5 both of ROW and center phase surface gradient decrease with the increase in the center phase height, and finally the outer phases' surface gradient decreases with the increase in the center phase height as given in Table 2.

Finally, it is concluded that the maximum value of the electric field under the center phase is reduced to 19.57% of its value, the magnetic field intensity is reached to 76% of its value, and 3% reduction in the ROW of the overhead transmission lines is observed when the center phase height was 26 m rather than 18 m. As it is observed in Fig. 3, Fig. 4, and Table 2, the use of inverted delta configuration instead of flat formation or traditional delta can reduce the electric and magnetic fields on the ground level. The outer phases' surface gradient decreases with the increase in the center phase height as given in Table 2.

B. USING MORE THAN SHIELDING WIRE

Figures 6 and 7 show the effect of the shielding wires' number on the calculated electric and magnetic fields, respectively. In this case, the original delta configuration was considered. The shielding wires were positioned at the center of the tower, at a height equal to 30 m, and there was a distance of 7.5 m between each adjacent two shielding wires.

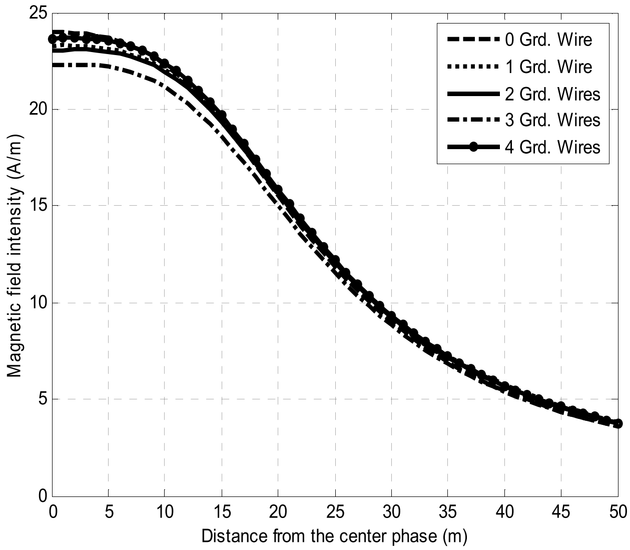

FIGURE 7. Effect of the shielding wires number on the calculated magnetic field intensity.

Table 3 illustrates the effect of the shielding wires' number on the maximum electric and magnetic fields, ROW, and outer and inner phases' surface gradient; also, this table presents the values of the induced currents in each shielding wire. Earth or shielding wires costs contain manufacturing and delivery of the shield wire to site and installation cost. According to Transmission Cost Estimation Guide MTEP19, the earth wire cost is 1,313 \$ per each foot [39]. Increasing the earth wire number leads to an increase in the costs of installing the earth wires system.

From these results, it is noticed that and also from the economic point of view, the choice of two shielding wires is the best situation, where the maximum electric field, the ROW, and the center phase surface gradient have smaller values than those when the number of shielding wires equals one, three or even four, on the other hand, both the maximum magnetic field and the outer phase surface gradient decrease with the increase of the number of shielding wires, the choice of four shielding wires reduces the electric field by 8.1% than using two-wire shielding. On the other side, the magnetic field increases in the case of four shielding wires by 1.68% than using two shielding wires. The ROW decreases by about 2.6% when four shielding wires are used rather than the two wires. It is noticed also that the values of induced currents in (A) are unequal as given in Table 3. This is happened because of the phase differences between the currents carried by the phase conductors and the change in the space between shielding wires and phase conductors.

Tables 4 and 5 indicate the effect of the distance between the two shielding wires and their height, respectively on the maximum electric and magnetic fields, ROW, and outer and inner phases' surface gradient. It is observed that with the increase in the spacing between the two shielding wires; the maximum electric field decreases by about 3.3%, 5%, and 9% when the spacing between the two shielding conductors was 7 m, 9 m, and 15 m, respectively comparing with one meter spacing. Where the optimal separation distance between the two shield wires equals 13 m. Also, it is noticed that the ROW and the center phase surface gradient decrease, and the outer phase surface gradient increases.

The maximum magnetic field decreases by about 0.6%, 0.58%, and 0.11%, which are not valuable reductions, when the spacing between the shielding conductors was 7 m, 9 m, and 15 m, respectively compared with one meter spacing. Also, it is observed that; with the increase in the heights of the two shielding wires the maximum electric and magnetic fields, the ROW and the center phase surface gradient increase; and the outer phase surface gradient decreases.

TABLE 4. Effect of the distance between the two ground wires on magnetic & electric fields and right-of-way.

Distance between the two ground wires (m)	E_{max} (kV/m) above one meter from the ground surface	ROW (m)	$E_{Surf.Outer}$ (kV/m) On conductor surface	$E_{Surf.Center}$ (kV/m) On conductor surface	H_{max} (A/m) above one meter from the ground surface
1	4.939	37.12	418.960	482.029	23.216
3	4.918	37	419.704	480.237	23.114
5	4.857	36.66	422.503	471.930	23.082
7	4.776	36.18	426.543	463.069	23.081
9	4.686	35.58	431.213	455.884	23.094
11	4.601	34.9	435.690	450.897	23.117
13	4.532	34.24	438.919	447.991	23.079
15	4.489	33.68	440.168	446.715	23.189

TABLE 5. Effect of the two ground wires' height on magnetic and electric fields and right-of-way.

Height of the two ground wires (m)	E_{max} (kV/m) above one meter from the ground	ROW (m)	$E_{Surf.Outer}$ (kV/m) On conductor surface	$E_{Surf.Center}$ (kV/m) On conductor surface	H_{max} (A/m) above one meter from the ground surface
26	4.1284	32.5	466.5034	440.3731	23.004
27	4.2715	33.1	455.3972	443.0351	23.039
28	4.3803	33.5	447.9607	445.1156	23.076
29	4.4650	33.9	442.7275	446.7383	23.113
30	4.5319	34.24	438.9186	447.9908	23.079

IV. CONCLUSION

The article gives modified algorithms to investigate the effect of the number of the shielding wires and the center phase position on the values of the electric and the magnetic fields, ROW, values of the induced current in the shielding wires conductors, and center and outer phase potential gradient. This article contains a case study carried out on an Egyptian 500 kV OHTL. Magnetic and electric fields' intensities at points one meter above the ground level are calculated. The obtained results of the two proposed methods are compared with the present electric and magnetic fields values of the conventional model. The calculations show that the number of the shielding wires and the center phase position which form inverted delta configuration instead of flat formation or normal delta can reduce the electric and magnetic fields on the ground level, but the electric surface gradient on the phase conductors slightly increases.

It is concluded that the maximum values of the electric field and the magnetic field intensity under the center phase of the OHTL are reduced to 19.57% and 76% of their initial values respectively, 3% reduction in the ROW of the overhead transmission line is observed when the center phase height was 26 m rather than 18 m. It is noticed, also that with the increase in the spacing between the two shielding wires; the maximum electric field decreases by about 3.3%, 5%, and 9% when the spacing between the shielding conductors is 7 m, 9 m, and 15 m, respectively comparing with one meter spacing. The ROW and the center phase surface gradient decrease and the outer phase surface gradient increases. The maximum magnetic field decreases by about 0.6%, 0.58%, and 0.11%, which are not valuable reductions when the spacing between the shielding conductors was 7 m, 9 m, and 15 m, respectively.

APPENDIX A

The calculations are done under three phases, single circuit, 500 kV TL, the following data of Egyptian 500 kV Kuirmate-Cairo power line are used [36]–[38] are used.

- The line-to-line voltage level: 500 kV (RMS)
- Rated power: 575 MVA
- Number of sub-conductors per phase: 3
- Diameter of a sub-conductor: 30.6 mm
- Spacing between sub-conductor in the bundle: 45 cm
- Minimum clearance to the ground: 9 m
- Height of the outer phases' conductors: 22 m
- Height of the center phase conductor: 24.35 m
- Diameter of compensating conductor: 11.2 mm
- Distance between adjacent two phases: 13.2 m
- Impedance per phase (positive and negative sequence): 3.307+ j 14.053 Ω
- Impedance per phase (Zero sequence): 10.75+j45.67 Ω
- Span: 400 m
- Line length: 124 km

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