IEEE Access
Multidisciplinary | Rapid Review | Open Access Journal

Received 7 February 2024, accepted 7 March 2024, date of publication 18 March 2024, date of current version 22 March 2024.

Digital Object Identifier 10.1109/ACCESS.2024.3376417

RESEARCH ARTICLE

Mitigation of the Electric Field Under EHVTL in Limited Space Crowded With Human Activities

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This work was supported by the Department of Electrical Engineering and Automation, School of Electrical Engineering, Aalto University, Espoo, Finland.

ABSTRACT Workers in the activities under high-voltage lines are exposed to the influence of the electric field of these lines, which may cause, in some cases, death as a result of some serious accidents such as the collapse of the towers and the occurrence of line to ground faults. In some densely populated countries, people may live near the right-of-way (ROW) of extra high-voltage transmission lines (EHVTLs), which may cause, as a result of the high electric field, health problems, for this reason, some researchers have pointed out the possible relationship between exposure to electric and magnetic fields on the one hand and the appearance of some diseases, especially in children, on the other hand. The aim of this article is to suggest a way to reduce the electric field in the place where people are found by using metal grids at safe distances from the EHVTLs. In this article, the electric field is calculated in the event that these grids are isolated or grounded. A comparison between the electric field without the use of shielding grids and with using these grids when they are isolated and earthed is carried out. The effect of changing the location of the shielding grids on the electric field values is examined. It is illustrated from this study that the peak value of the electric field intensity is mitigated to be 16.66% of its value before shielding, which proved the method's effectiveness in lowering the intensity of the electric field. The effect of an isolated shielding grid is to shift the electric field curve to be more flat. The installation of the earthed grids beside and parallel to the lines has a significant influence on the mitigation of the electric field under the EHVTL.

INDEX TERMS Extra high-voltage transmission lines, electric field, earthed shielding grids, isolated shielding grids.

I. INTRODUCTION

Some of the people have to live or they have a permanent job near the extra high voltage power transmission lines (EHVTLs). The strong impact of the low-frequency electric fields around such these high-voltage lines may cause serious accidents causing death. Therefore, protection systems need to work as quickly as possible [1].

The associate editor coordinating the review of this manuscript and approving it for publication was Yi Ren.

Many people work in agriculture or even live permanently under or near high-voltage lines. The topic of HV transmission lines and human health is a controversial issue. While some publications have indicated that the low-frequency electric field may cause diseases in humans, especially children [2], others denied that [3].

The magnetic field under EHVTLs is also important for health issues. In 2002, the World Health Organization (WHO) and the International Agency for Research on Cancer (IARC) categorized low-frequency fields as being greater than 0.3 to

0.4 microtesla (μT), averaged over time as class 2B "possibly carcinogenic" [4].

Hence, it is very important to mitigate the high voltage transmission line fields to the acceptable limits to protect such these peoples. There are guidelines regarding the limits for the magnetic and the electric fields (these are different for technicians and non-technicians who are working in the vicinity of the EHVTLs). The electromagnetic fields under the transmission line can be measured with specific measurement techniques as reported by *EN* 61786-01:2014 [5], IEC 61786-2:2014 [6], and ANSI IEEE Std. 644:2019 [7] for every transmission system operators (TSOs) or distribution system operators (DSOs) and the values must be within the limits.

Some of the standards set safe limits for the electric field for residents or workers near the path of high voltage lines, such these are the Health and Human Services department (HHS) [8], National Institutes of Health (NIH) [9], National Institute of Environmental Health (NEIHS) [10], and ICNIRP [11]. The safety limits of the electric fields for power transmission lines with voltages from 230 to 69 kV oscillate between 6.48 kV/m and 0.96 kV/m, which are below the maximum limit of 10 kV/m recommended by the ICNIRP standard. Therefore, many technologies have been designed to reduce the effect of the electric and the magnetic fields in areas where humans and animals are present. It is worth noting here that the article focused on the electrical field because it deals with the effect of extra high-voltage transmission lines (500 kV).

There are already many traditional compensation methods of the mitigation of the electric fields near the HVTLs that may be used in areas where there are high human densities near the ultra-high voltage lines, or some people work near such lines. One of these techniques is to use active or passive shielding wires beneath the high voltage conductors as illustrated in [12], [13], and [14]. Reference [15] proposed the use of active and passive shield wires for the electric fields' mitigation under extra high voltage transmission lines. In [16], two methods of the electric and magnetic fields Mitigation are presented, one is to change center phase position and the other is by using more than shielding wire. In [17], [18], and [19], the reduction technology and safety assessment for ELF and EMF are presented. The impact of span configurations and the sag of the conductor on the EHVTL calculations under the overhead transmission lines are investigated by [20] and [21]. It is recommended in the installation of the extra high voltage 500 kV transmission line to increase the minimum conductor-ground height to be in the value of 11.7 m in order to limit the electric field to less than 10 kV/m within the safety level. Other techniques should be introduced for the mitigation of the electric field under EHVTL.

Charge Simulation Method (CSM) was previously used in the electric field calculations [22], [23], [24], unfortunately, the accuracy of this method depends on the number and location of the charges. For this reason, the finite element method (FEM), represented in COMSOL multi-physics program, is used in the present study.

In this article, a new technique has been proposed to reduce the effect of the low-frequency electric field on the workers or even residents in areas near the right of way (ROW) of the high-voltage transmission lines by using a metal grid that is installed under or beside the high voltage lines. This grid may be grounded or isolated, and safety factors have been taken into account when installing this grid. So that an electric arc does not occur between the transmission line and the earthed metal grid. By using the shielding grid, the electric field strength has been reduced from 1.6 kV/m to 0.85 kV/m at a level of 1.8 m above the ground which is the proposed level of the human head.

II. ELECTRIC FIELD CALCULATIONS

This article aims to give a proposed method for the mitigation of the electric field of EHVTL in the densely populated areas near to the 500 kV transmission line. Therefore, careful calculations of the produced electric fields have to be carried out. The electric field is calculated by the use of the Finite Element Method (FEM) which is based on the ANSYS software package with the aid of the COMSOL multi-physics program. Laplace's differential equation with taking into account the boundary conditions surrounding the transmission lines and the used metal grid has to be considered for the calculations of the electric field distribution under and beside the EHVTL. In this article, the 500 kV EHVTL and the shielding grid are simulated in the COMSOL multi-physics program with some of the assumptions taken into consideration in the calculations of the electric field. These assumptions are:

1) The extra high voltage transmission line (EHVTL) is assumed to be straight and has an infinitely length.

2) The phase currents of EHVTL are considered in balance conditions and their wave shapes are sinusoidal.

3) The mutual couplings concerning the phases are ignored.

4) The ground resistivity under the EHVTL is considered constant.

5) The phase bundles are treated according to their equivalent radius [25].

As it is known the Finite element method FEM depends on the concept of finding differential equations by applying Maxwell's equations [26], [27]. The Finite element program is used to solve Gaus' Law for the electric field employing the scalar electric potential (V) such as the dependent variable. The followin equations are the used:

$$\nabla.J = Q_{j,v} \tag{1}$$

$$J = \sigma E + j\omega D + J_e \tag{2}$$

$$E = -\nabla V \tag{3}$$

The FEM basically involves four steps as given in Figure 1:

i. The solution region is discretized into a finite number of elements.

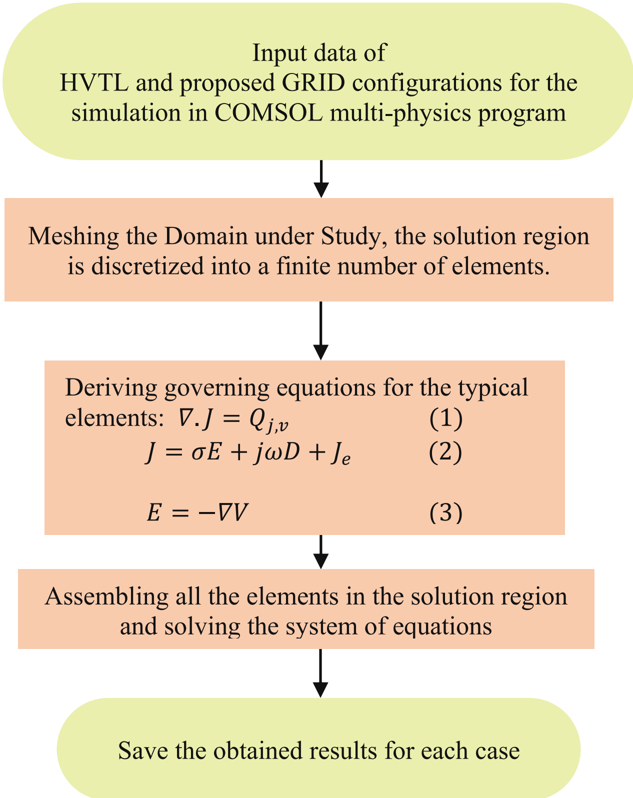

FIGURE 1. Flowchart of the proposed procedure.

ii. For typical elements, deriving the governing equations.
iii. Assembling all the elements in the solution region.
iv. Solving the obtained equations system.

To reduce the effect of the approximations done in this article on the electric field calculations and to improve the accuracy of the calculations in future research, the influences of the conductor sag and span configurations on the distribution of the electric field under overhead transmission lines are studied. Moreover, the actual values of the soil resistivity under the HVTLs must be taken into account, and the actual length of the lines must be considered.

To employ FEM [28], [29], [30], the field region is to be discretized into separate finite elements to collect a grid. All the conductors and the shielding grid are simulated in the 3D dimension inside a large box and grounded (potential =0) at the bottom of the box. All the box material is considered to be air with a unity relative permittivity except the conductors of the power lines and that used for the shielding grid. Inside each element, the electric field intensity is supposed to be constant. Furthermore, for an excellent approximation of the field distribution, a greater number of elements is necessary.

Because of its extreme flexibility, FEM may be used on even the most complex geometries. It can produce extremely precise results, albeit the degree of precision varies according to how many geometry-related elements are taken into account. A common tool for forecasting and modelling the physical behaviour of complex engineering systems is the FEM. In the case of an earthed grid, its surface potential is considered zero, while in the case of an isolated grid, its volume charge (q) is considered zero. The transmission line length is assumed to be infinity from both of the used grids.

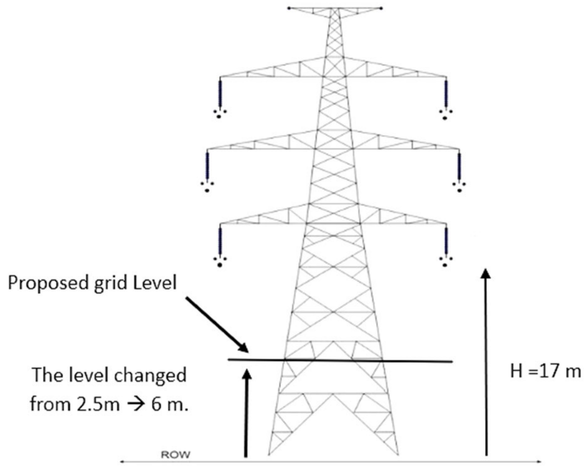

FIGURE 2. 500 kV double circuits EHVTL, 3 bundles per phase.

III. TRANSMISSION LINE AND GRID CONFIGURATION

A. THE USED DATA OF THE EXTRA HIGH VOLTAGE LINE

The 500 kV double circuit – 3 bundles per phase used in this study is illustrated in Figure 2 [31], [32], [33].

The 500 kV double-circuit line proposed for this study has its geometry imposed by normal suspension towers, corresponding to data given in Table 1. The three phases are made from Aluminum conductors. Each phase is comprised of 3 bundles of radius equal to 15.3 mm with spacing of 47 cm in between. Two ground wires are used from the same materials with a radius of 15.3 mm. The areas of interest to achieve an electric field shielding are beneath and beside the transmission line conductors at the maximum sag between any two towers at which the human activities are carried out.

B. GRID CONFIGURATION

A metal grid of rectangular shape, in which the number of conductors can be changed, whether in the direction of length or width, can be used with its connection by one or more rods to the ground, or it can be isolated from the ground. The grids are employed in the process of reducing the electric field. Figure 3 gives a sample of the proposed metallic grid configuration.

This grid can be installed below or beside the high-voltage line at appropriate distances so that corona or air ionization to a large extent does not occur between the grid and the high voltage transmission lines that leads to the occurrence of flashover. Based on the worker's activity, the shielding grid will be installed beneath or beside the power line. The grid dimensions depend on the area of the human activities.

It should be noted here that, in the simulation carried out in this article by the use of FEM, the mutual coupling between the phases of the two circuits and also the earth wires with the proposed grid are considered.

TABLE 1. 500 kV double circuit – 3 bundles per phase.

Item	Value
MVA	575
Line voltage (r.m.s) in kV	500
Length in km	124
Positive & negative sequence impedance per phase in ohms	3.307+j 14.053
Zero sequence impedance per phase, ohm	10.75+j45.67
No. of circuits per tower	2
No. of conductors per phase	3
No. of ground wires	2
Diameter of a single conductor, mm	30.6
Spacing between conductors in the bundle in cm	47
Distance between Phase A and phase B, m	9.7
Distance between Phase B and phase C, m	9.7
Distance between Phase C and ground wires, m	4.85
Span in meter	400
The distance between the lower phase and the ground level, m	17

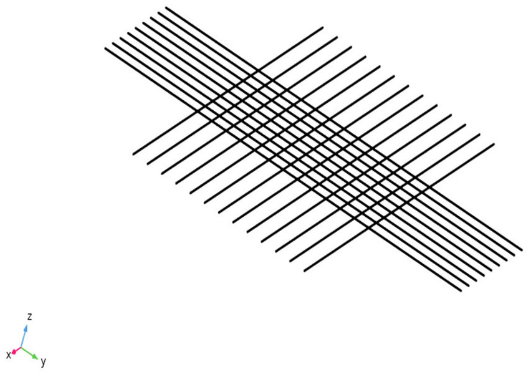

FIGURE 3. Sample of the grid configuration.

The advantage of using this method is that the grid can be installed between two or more towers, secured with steel ties at the required height from the ground, or by using metal arms that have a length of the required distance and are attached to the towers using nails and metal rings in the case of installing the network next to the lines. The grid can be dismantled after completing the activities below the lines and then reused again in other areas. It is also worth noting that the cost of the proposed grid is low and does not exceed a few hundred dollars, as the frame can be made of steel while the rest of the grid can be made of aluminum wires [34], [35].

IV. RESULTS OF THE PROPOSED METHOD

A. ELECTRIC FIELD CALCULATIONS WITHOUT AND WITH EARTHED SHIELDING GRID INSTALLED UNDER THE HIGH-VOLTAGE LINES

The electric field under the 500 kV line is calculated at the human head level which is taken as 1.8 meters. Figure 4

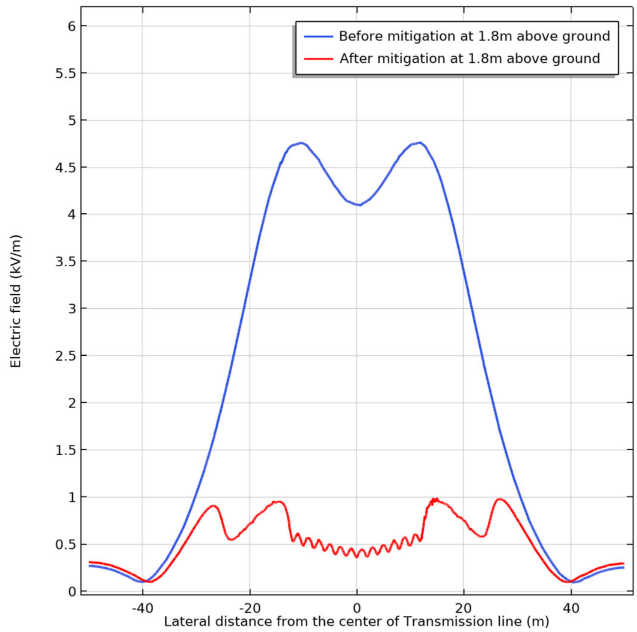

FIGURE 4. The electric field intensity at 1.8 m level without and with earthed shielding grid.

gives the electric field intensity without and with the shielding grid. The grid is earthed from one point by the use of one or more grounding electrodes. The shielding grid is located at 3 m above the ground level. Its dimensions are 100 × 100 meters, and each mesh has dimensions of 2m2m. As it is illustrated in Figure 4, the peak value of the electric field intensity is mitigated from 4.8 kV/m to be about 0.8 kV/m. This means that the earthed shielding grid reduced the electric field intensity to be 16.66% of its value before shielding, which proved its effectiveness in reducing the intensity of the electric field.

The impact of the grid height above the ground level on the electric field intensity at the human head level is illustrated in Figure 5. As it is noticed from this figure that, increasing the height of the shielding grid leads to a remarkable decrease in the electric field intensity affecting human behavior under these lines. This, of course, is due to the shielding grid's proximity to the high-voltage lines. It is noted that increasing the height of the shielding grid from 2.5 meters to 6 meters has reduced the electric field strength from 1.6 kV/m to 0.85 kV/m at a level of 1.8 m above the ground which is the proposed level of the human head.

B. ELECTRIC FIELD CALCULATIONS BETWEEN THE EARTHED SHIELDING GRID AND THE TRANSMISSION LINES

To ensure that no corona or air ionization occurs leading to flashover between the earthed grid and the high voltage lines, the electric field was calculated between the high voltage lines and the grounded shielding grid when it was at a height

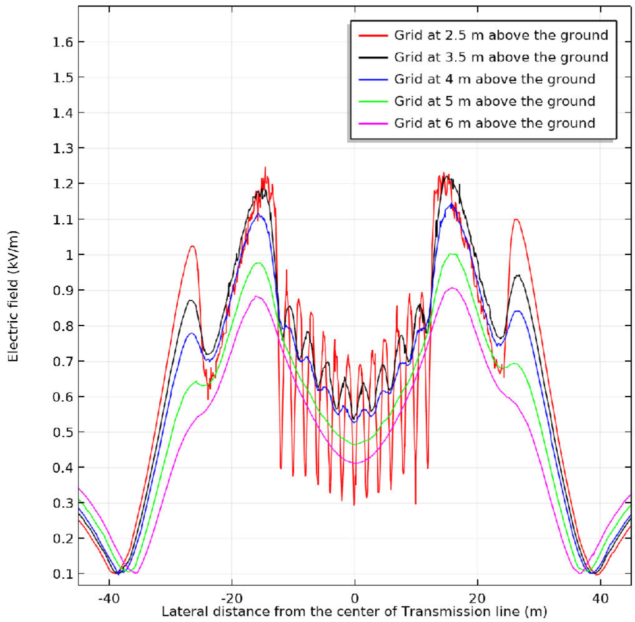

FIGURE 5. **The effect of the shielding grid height from the ground level on the electric field intensity at level 1.8 m above the ground.**

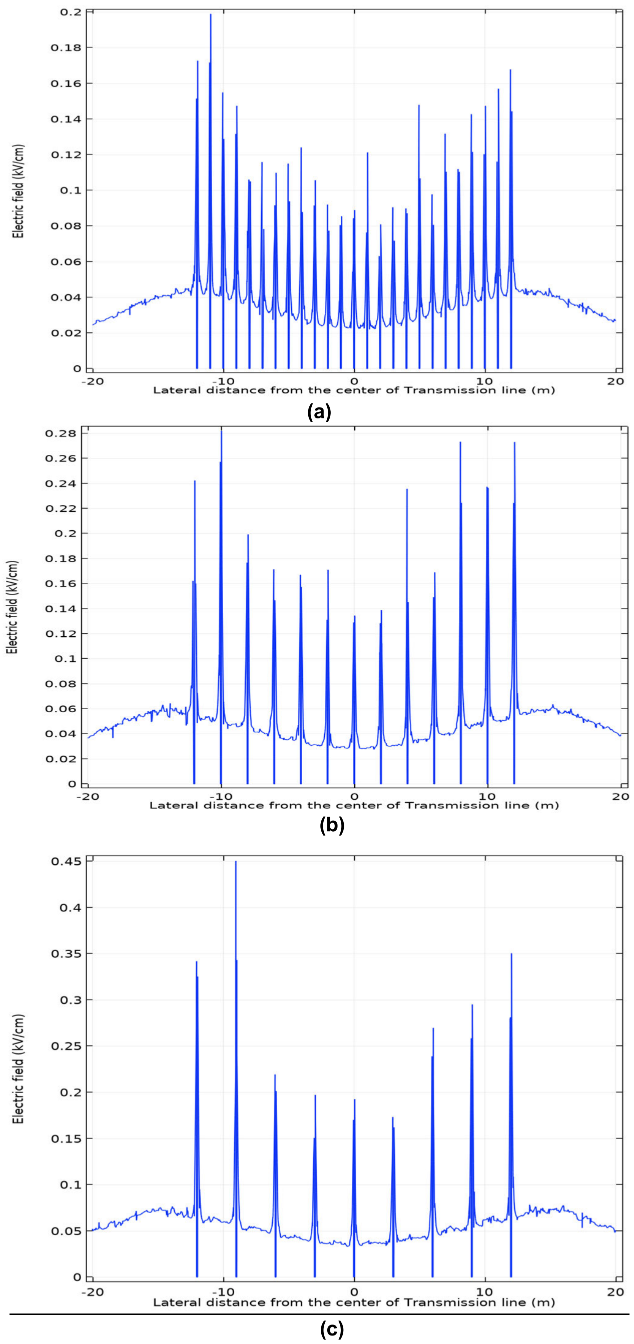

FIGURE 6. **The Electric field intensity at the grid level of 6 m above the ground using different grid mesh sizes: (a) grid mesh sizes of 1 × 1 m (safe), (b) grid mesh sizes of 2 × 2 m (safe), and (c) grid mesh sizes of 3 × 3 m (safe).**

of 3 meters from the ground level. While the electric field was calculated at a half meter higher than the shielding grid level.

It is found that the value of the maximum electric field intensity reached to 7 kV/m, which is far from the required values for air breakdown. As it is known at atmospheric pressure, the breakdown strength of air is 21.1 kV/cm. However, installing the earthed shielding grid at a height of 3 meters is considered as a safe installation for both the shielding grid and the persons under the lines as illustrated in Figures 4 and 5, respectively.

It is clear that the earthed grid provides a high degree of field reduction at the area in which the human activity is done, and optimum reduction is achieved by small mesh dimensions.

The worst case is observed when the shielding grid is installed at a level near to the power lines. So, the grid level of 6 m is chosen to check if a corona formation occurs or not. The calculations are done using grid mesh dimensions of 1 × 1 m, 2 × 2 m, and 3 × 3 m. The results are given in Figures 6 (a), (b), and (c), respectively. It is found that the electric field does not exceed 0.2 kV/cm (safe) for 1 × 1 m grid mesh dimensions, 0.3 kV/cm (safe) for 2 × 2 m, and 0.45 kV/cm (safe) for mesh dimensions 3 × 3 m.

C. ELECTRIC FIELD CALCULATIONS WITHOUT AND WITH ISOLATED SHIELDING GRID

To investigate the effect of the isolated shielding grid on the electric field intensity calculations are carried out with and without the isolated grid. Each mesh dimensions of the grid are changed to be 1m1m, 2m2m, and 3m3m. The results are as given in Figure 7. It is observed that a slight decrease is carried out in the peaks of the electric field intensity, i.e., the electric field intensity became flat.

It is also noticed that the mesh dimensions have no effect on the electric field intensity values. Finally, it can be concluded that the isolated grid has no effect on the mitigation of the electric field under the high-voltage power lines even with the change of the mesh dimensions.

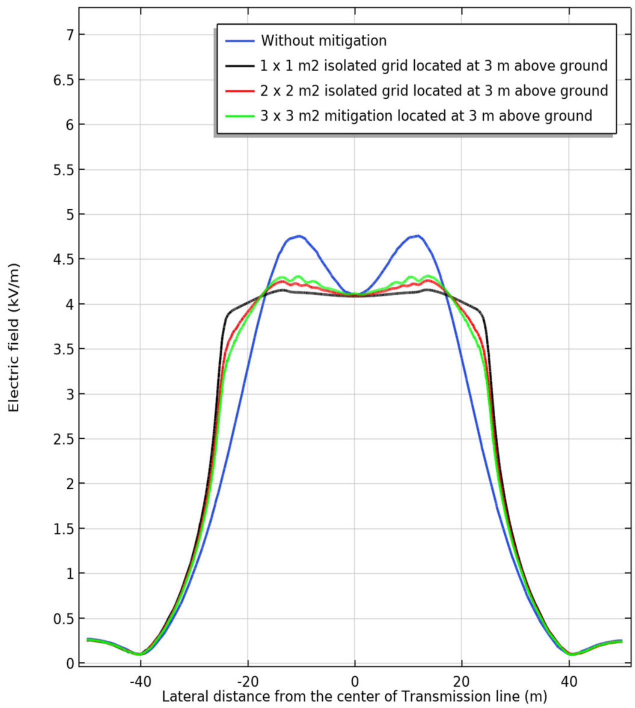

FIGURE 7. Electric field with isolated grid using different mesh dimensions.

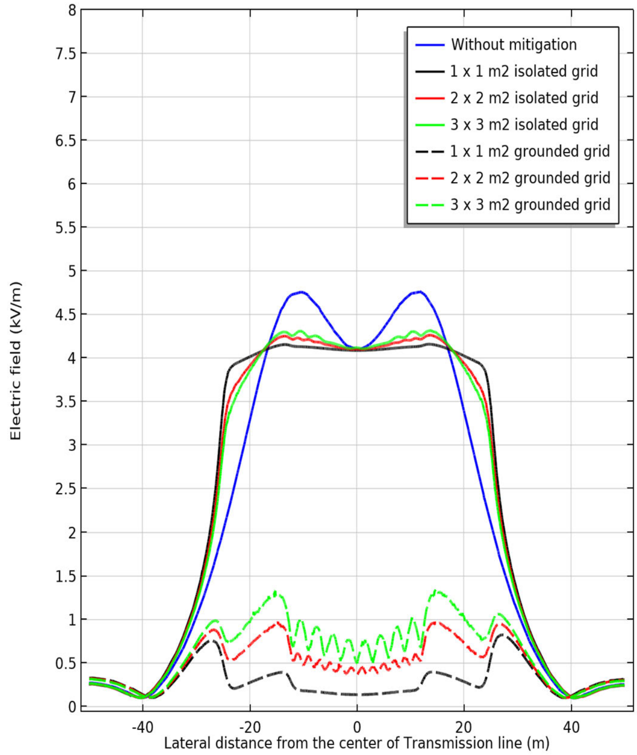

FIGURE 8. Comparison between the isolated and earthed grids with different mesh dimensions.

Figure 8 illustrates a comparison between the impact of the isolated and the earthed grids on the electric field intensity under the overhead transmission lines with different mesh dimensions. The following observations have been confirmed in Figure 8:

i) The isolated shielding grid did not reduce the intensity of the electric field under the extra high-voltage lines, regardless of the mesh dimensions of the grid. The effect of the shielding grid in this case is to shift the electric field curve to be more flat.

ii) There was a significant decrease in the electric field intensity using the earthed grids. It is noted that this decrease increases with the use of grids with small mesh dimensions.

iii) The use of earthed grids gives safe values for the intensity of the electric field for human activity and is consistent with international standards ICNIRP [11].

Figure 9 gives the maps of the electric field density under the zone covered by the earthed shielding grids at 1.8 m above the ground level (human length). Different grid size meshes are used 1×1 m, 2×2 m, and 3×3 m. It is clear that the field in the desired zone under the shielding grid is highly reduced especially with grids having small mesh dimensions.

D. CAPACITIVE CURRENT BETWEEN THE TRANSMISSION LINE AND THE EARTHED SHIELDING GRIDS

The capacitive current between the transmission line conductors and the earthed shielding grids is given in Figure 10. This current flows from the grid towards the earth through the conductor connecting the grid with the grounding electrode.

As shown in the figure, the relationship between the installation level of the grounded shielding grid and the capacitive current between the transmission line conductors and the earthed shielding grids is linear, and the closer the shielding grid to the high-voltage lines, leads to the increase of the capacitive current. It was also noted that reducing the mesh dimensions leads to an increase in the capacitive current.

E. ELECTRIC FIELD CALCULATIONS WITH EARTHED SHIELDING GRID INSTALLED ON THE SIDE OF HIGH VOLTAGE

Human activities may require that the grounding grid be installed beside the high-voltage line and not under it as illustrated in Figure 11. Moreover, Figure 12 illustrates the normal electric field surrounding the transmission line conductors.

As it is seen from this figure, the intensity of the electric field on the surface of the transmission line conductor exceeds 30 (kV/m), while between the each conductor and the other, the value of the electric field intensity is around 20 (kV/m), and this value decreases to 18 (kV/m) between the lower conductor and the grounded grid. These values confirm that flashover does not occur between the grounded grid and the conductors carrying the high voltage.

The earthed grid was installed beside and parallel to the lines at heights of 9 m and 12 m respectively. Figure 13 shows the effect of the earthed shielding grid on the distribution of the electric field near the lines.

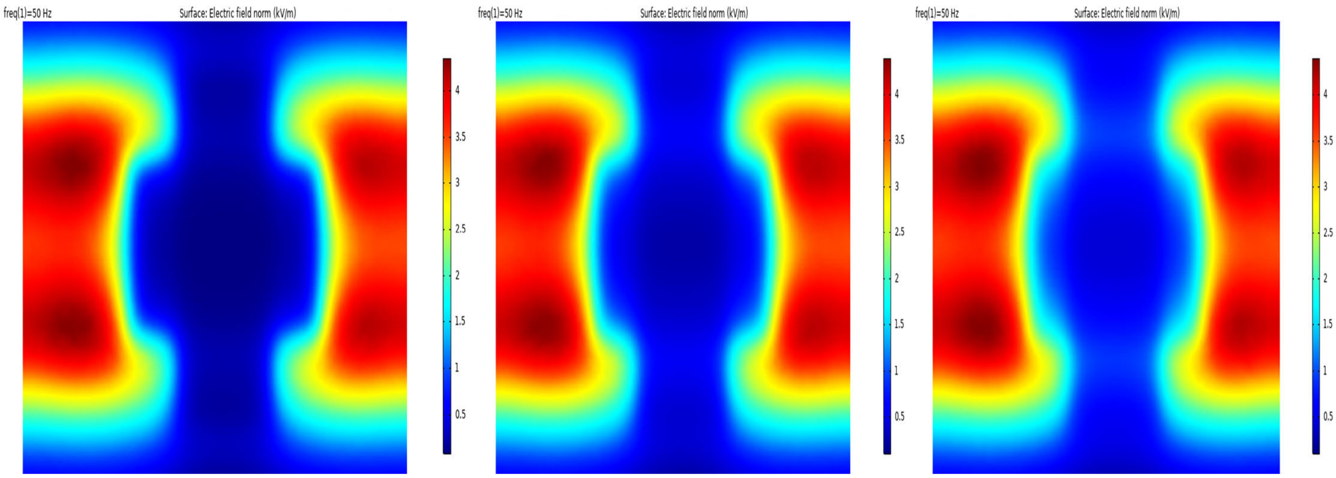

FIGURE 9. Maps of the electric field density under the zone covered by the earthed shielding grids: (a) grid mesh of 1 × 1 m dimensions, (b) grid mesh of 2 × 2 m dimensions, and (c) grid mesh of 3 × 3 m dimensions.

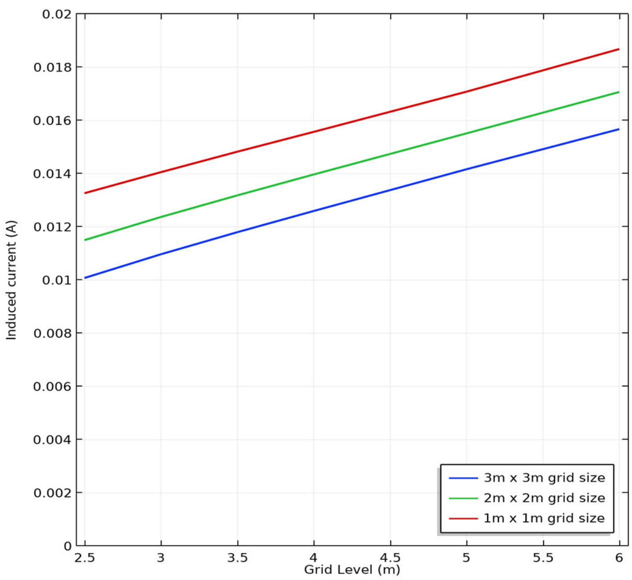

FIGURE 10. The capacitive current between the transmission line conductors and the installed earthed shielding grids.

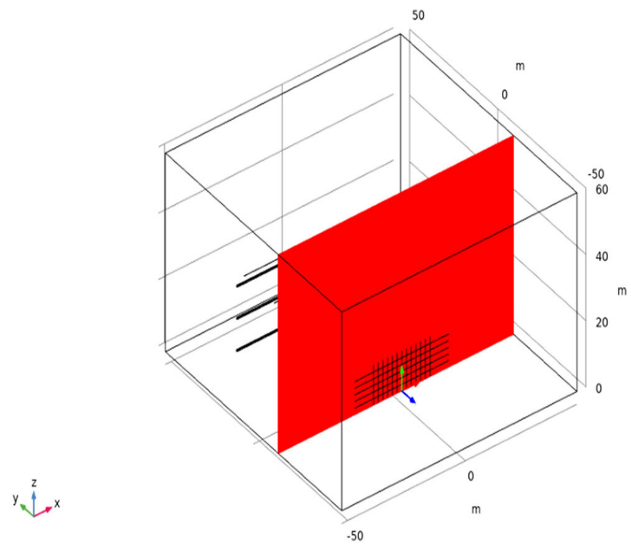

FIGURE 11. Simulation of the grounding grid installed beside the high-voltage line.

From this figure, it is noticed that by comparing the electric field density curves without and with using grounded grids beside the high voltage lines and at a safe distance from them, the presence of the grounded grid has caused an effective reduction of the electric field up to the end of the grid's width. Then it is noticed an increase again in the electric field density and after that, a decrease is observed with increasing the distance from the lines. It is also noted that there is a noticeable effect in reducing the electric field with the increase of the height of the earthed shielding grid.

The influence of grid mesh dimensions on the electric field density is illustrated in Figure 14. It is clear in this figure that the effect of the grid dimensions on the distribution of the electric field can be ignored, as the effect does not exceed 2% at most.

V. DISCUSSION

Several methods are used for the mitigation of low-frequency electric and magnetic fields under overhead transmission lines. One of these is the reversal of line phases on a double-circuit line, which is applicable only to a double-circuit system [13]. Another method is the conversion of the transmission lines from flat to delta configuration [13], but unfortunately, this method may introduce corona [13]. Reference [12] proposed a reduction in phase spacing which may introduce corona. Two methods were proposed by reference [16] to reduce the electric and magnetic fields produced by HVTLs, one of them is the change of the center phase position for the optimization of the delta configuration and the other is the use of more than two shielding wires. The

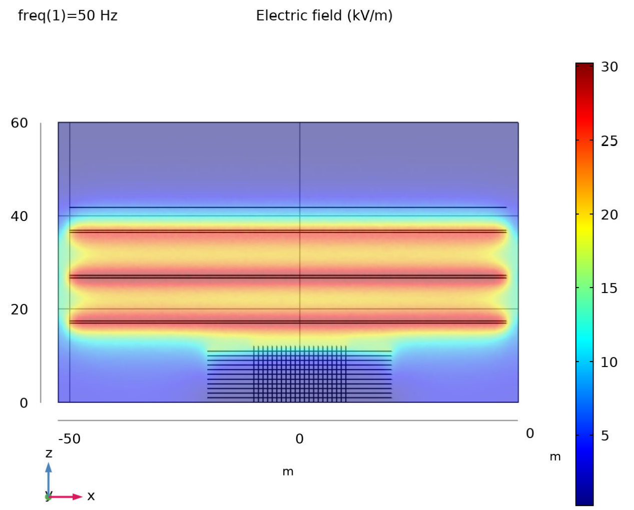

FIGURE 12. The normal electric field in kV/m.

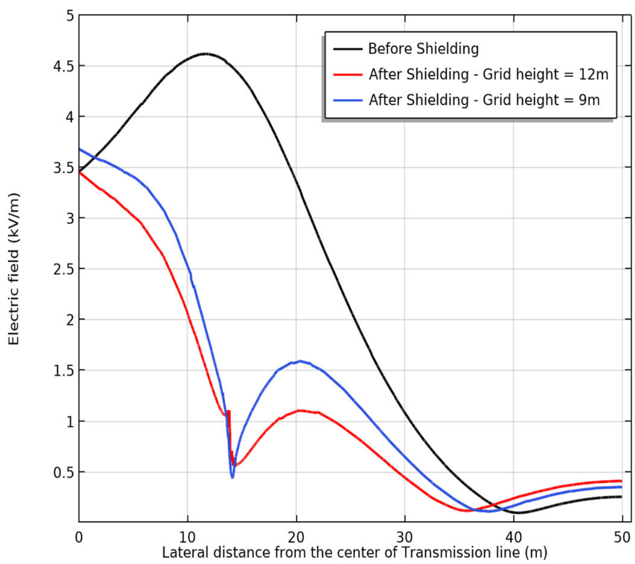

FIGURE 13. The Impact of the earthed shielding grid height beside and parallel to the lines on the distribution of the electric field near the lines (2m x 2m grid dimensions case).

change of delta configuration reduces the electric field by 19.57% and the use of four shielding wires reduces the electric field by 8.1% compared with the proposed method, the earthed shielding grid, reduced the electric field intensity to be 16.66% of its value before shielding, which proved the method effectiveness in reducing the intensity of the electric field.

This method is characterized by the fact that it can be used as an umbrella in an area crowded with human activity, and it can be fixed by galvanized steel strips between two towers at the required height. Its cost is much lower than the structure of a single tower, and it can be dismantled and reused in another place between two towers.

To reduce the effect of the approximations done in this article on the electric field calculations and to improve the accuracy of the calculations in future research, the influence of the conductor sag and span configurations on the distribution of electric field under overhead transmission lines is studied. Further, the actual values of the soil resistivity under the EHVTLs must be taken into account, and the actual lines of the lines must be calculated.

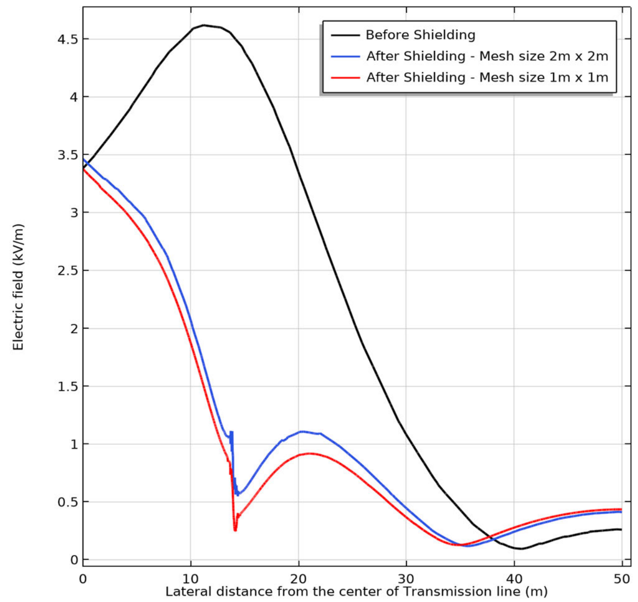

FIGURE 14. The effect of the mesh dimensions on both the distribution and reduction of the electric field.

TABLE 2. Comparison of present method calculations with charge simulation method and measured values without using the proposed grid.

Distance from the center of the transmission circuits, meter	0	10	15	20	45
E_{max} (kV/m) using the present calculations	4.2	4.5	4.7	3.5	0.3
E_{max} (kV/m) using the charge simulation method [16]	4. 25	4.4	4.9	4.2	0.5
E_{max} (kV/m) measured	4.2	4.6	4.8	3.5	0.2

Frankonia EFS-LASER Electric Field Probe has been used for measuring the electric field intensity under the 500 kV transmission line extended in Upper Egypt and its specifications are given in Table 1. The probe is accurate to measure the field strength from 0.1 V/m up to 10 kV/m. The field strength measurements are done according to IEC/EN 61000-4-3. The measured values are given in Table 2. The measurements were taken without installing the proposed grid, as its installation on high-voltage lines requires approvals that have not been obtained yet.

From Table 2, it is noticed that there is agreement between the measured and calculated values using charge simulation and the present calculated values.

VI. CONCLUSION

The paper proposed a new technique for the mitigation of the electric field under EHVTL in a limited space crowded with human activities. The method is based on using earthed metallic grids under the overhead transmission lines.

As illustrated from this study, in some cases the peak value of the electric field intensity is mitigated from 4.8 kV/m to be about 0.8 kV/m. This means that the earthed shielding grid reduced the electric field intensity to be 16.66% of its value before shielding, which proved the method's effectiveness in lowering the intensity of the electric field.

The isolated shielding grid did not reduce the intensity of the electric field under the extra high-voltage lines, regardless of the mesh sizes of the grid. The effect of the shielding grid in this case is to shift the electric field curve to be more flat.

The installation of the earthed grids beside and parallel to the lines at heights of 9 m and 12 m respectively has a significant effect on the mitigation of the electric field under the EHVTL. By using the shielding grid, the electric field strength has been reduced from 1.6 kV/m to 0.85 kV/m at a level of 1.8 m above the ground which is the proposed level of the human head.

One of the advantages of this method compared to other methods is that the proposed grid can be easily installed between two or more towers using steel ties. It can also be dismantled and reused when necessary, and it does not conflict with any other method of electric field mitigation.

ACKNOWLEDGMENT

This work was supported by the Department of Electrical Engineering and Automation, School of Electrical Engineering, Aalto University, Espoo, Finland.

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