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Modelling and Simulation of Electric Fields in the Vicinity of High Voltage Transmission Line

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ABSTRACT

The purpose of this work is to evaluate the electric fields emission in the vicinity of the overhead high voltage transmission lines, owing to rising concerns from people living close to overhead power lines. One of the reasons for the study is the fact that electromagnetic field emissions caused by the overhead power lines could influence the health of surrounding inhabitants. This paper presents an example of the quasi-static electric field calculation occurring under the high-voltage transmission lines of voltage level 330 kV and 161 kV, taking into consideration, real catenary curve shapes of the conductors. The obtained results were compared with exposure limits specified by safety guidelines and regulations. Furthermore, in order to obtain more accurate calculation of the electric field in the vicinity of overhead transmission lines, an application based on Coulomb equation has been used with a combination of the method of image charges dependence of electric field from the positions of the conductor, the observer and its symmetric image. This complex approach gives in combination with finite element method tool for calculation of the electric field intensity. Gmsh and GetDP open source software packages have been used for the simulation of the electric field created near the transmission lines, located in the Republic of Benin. The results of the study revealed that, there were some areas near the overhead high voltage line where the electric field strength exceeded 5 kV/m and 10 kV/m. A comparison of the study results with exposure limits specified by safety guidelines and regulations shows that there is no critical concern for the people living near the transmission lines. Rather, the exposure level seems dangerous for workers and individuals working closely to the line for a long duration. Consequently, the findings of this paper are useful in specifying

appropriate clearance distance and duration to be maintained while working on life line as an amendment to existing standards in electromagnetic protection.

Keywords—HV transmission line, Electric Field, Magnetic Field, Electromagnetic Field, Human Health, Electromagnetic compatibility.

INTRODUCTION

Electrical energy is transmitted from power plant, where it is generated, along overhead high voltage transmission lines (OHVTLs) or underground cables to substations and finally to energy consumers. A typical overhead line consists of towers or pylons from which the live conductors are suspended by sets of insulators. In the Republic of Benin, to ensure a smooth transmission of electricity to consumers, a wide area grid has been deployed. The national grid comprises a high voltage transmission system that uses the following voltages: 161 kV and 330 kV. As a direct consequence, magnetic and electric fields are induced in the vicinity of power line and in the neighbouring environment. All OHVTLs produce extremely low frequency (ELF) electric and magnetic fields. The magnetic field are caused by electric current flows and the electric field are caused by sinusoidally-oscillating charges located on the conducting wires of the transmission line [1]. Several studies have reported these fields can induce electrical currents within the human body.

The effect of long term or chronic exposure to electric fields was studied in several countries [2]-[3]. Several studies have reported that children living near high voltage transmission lines had a higher probability of suffering cancer and leukemia [4] - [5]. However, limited studies report on the adverse effects of these fields on to adults who live near high voltage transmission and distribution lines [5]. According to [6], higher cancer incidences were not observed for adults living near high voltage transmission lines.

In order to check the compliance with the exposure limits established by health regulations, such as those published by the International Commission on Non- Ionizing Radiation Protection (ICNIRP) [7] - [8] and by the IEEE Standard [9]. These ELF fields need to be properly assessed. The Republic of Benin limits for emissions of electromagnetic fields draw on the guidelines set by ICNIRP. The prescribed limits are to be four (4) times lower in areas that are more sensitive such as: living areas, schools and hospitals.

To reduce the aforementioned electric field emissions, different solutions have been attempted in the past. Some included: interchanging of phase sequences of line conductors; usage of very tall towers; optimal arrangements and placement of phase conductor determined by rigorous design principles [10].

Optimization processes have also been applied severally in the estimation of electric and magnetic fields [11]-[12]. When electric field calculation is used in an optimization procedure, the computational effort required for the electric field calculation has an extremely important role. Overhead power line conductor sagging inside the span can be described by the catenary curve which could require even higher computational efforts for accurate estimation of the electric field [13]-[14]. The electric field produced by electric power lines is usually calculated analytically with the use of the Coulomb law. In [15] the electric field produced by power lines of big length in comparison with the distances between the conductors and the distances between the conductors and the ground, was analysed by analytical model. The analytical method is very useful for the determination of the way the electric field decays as the distance increases. Furthermore, through this approach, it is not difficult to design a power line that produces a fast-decaying electric field. Unfortunately, most analytical models are not accurate when assessed close to the line and lack real terrain model inclusion possibility or real catenary curve shape of the conductor.

This paper presents an example of the quasi-static electric field calculation occurring under the high-voltage transmission lines of voltage level 330 kV and 161 kV, taking account of real catenary curve shapes of conductors. The obtained values are compared with exposure limits specified by safety guidelines and regulations. In order to obtain more accurate calculation of the electric field in the vicinity of overhead transmission lines, an application based on Coulomb equation has been used. This application was deployed in combination with the method of image charges dependence of electric field from the position of the conductor, the position of the observer and its symmetric. In addition, a finite element tool was used for the calculation of the electric field intensity. Gmsh and GetDP [16]-[17] open-source software packages have been used for the simulation of electric field created in the vicinity of transmission lines.

CATENARY SHAPE OF CONDUCTORS

Each phase conductor in a span of overhead transmission line is attached in two points and take the shape of a catenary. The shape of a catenary depends on the conductor weight per unit length, w, the horizontal component of tension, H, and the span length, S. The catenary can be considered as symmetric, if conductors at each end have the same height above a flat surface, or asymmetric otherwise. Figure 1 shows conductor sag and span length for a general asymmetric catenary shape [18]-[19].

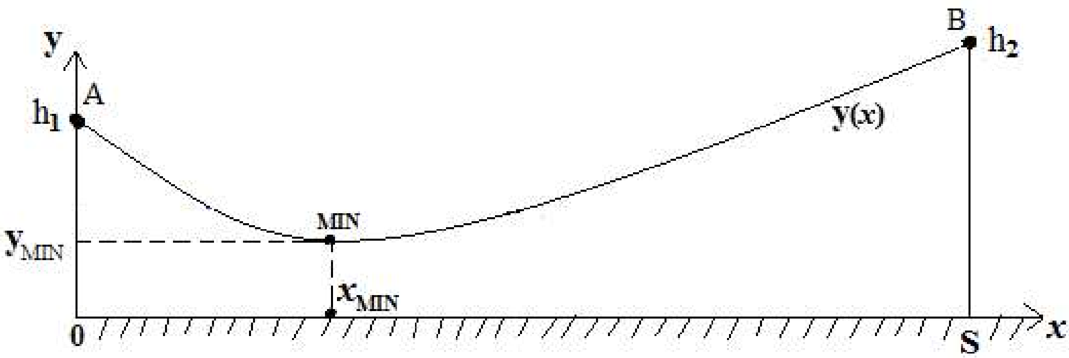


Figure 1: Example of asymmetric catenary

The basic equation of the graph in the interval [0, S], illustrated in Figure 1 is as follows:

$$y(x) = c.\cosh\left(\frac{x-x_{MIN}}{c}\right) - c + y_{MIN} \qquad x \in [0, S] \qquad (1)$$

Where the point A(0; h1) is the left–hand side support point , the point B(S; h2) is the right–hand side support point, MIN (xMIN; yMIN) is the catenary's lowest point, S is span length, and $c = \frac{H}{w}$ is a constant defining the shape of the catenary.

GEOMETRICAL CHARACTERISATION OF THE TRANSMISSION LINES

The specifications of the transmission lines were obtained from the Transmission Division of Republic of Benin's Energy Service Provider. Figure 2 shows the actual characteristics of the overhead power lines. Figure 3 shows the tower dimensions, the space arrangement and heights of the conductors of the power line in relation to the X, Y, Z axes system, leading to a power line with six phase conductors and one guard conductor. The line conductors are not straight, but they are sagged by their weight. The curve that is drawn by each conductor in a span between two sequential suspension points is known as the catenary. In order to simplify the calculations and the analysis of the electric field produced by the line, the model of an assembly of horizontal conductors parallel to the axis can be used [20]. This model is precise for the calculation of the electric fields if, as usual, the conductor sag is small in comparison to the span [21].

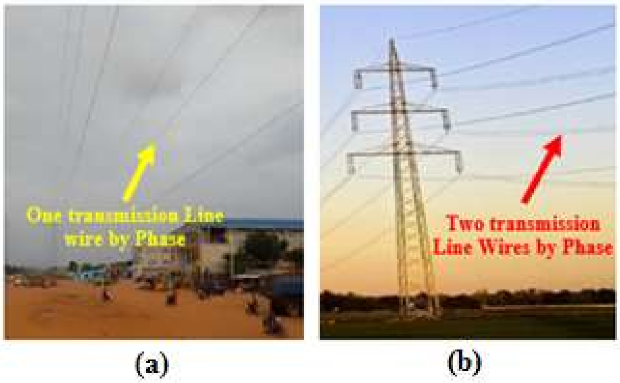


Figure 2: Characteristics of conductors of the overhead power line for 161kV (a) and 330 kV (b)

Table 1 indicates the details of the voltage level and current capacity used for the transmission lines in Benin Republic.

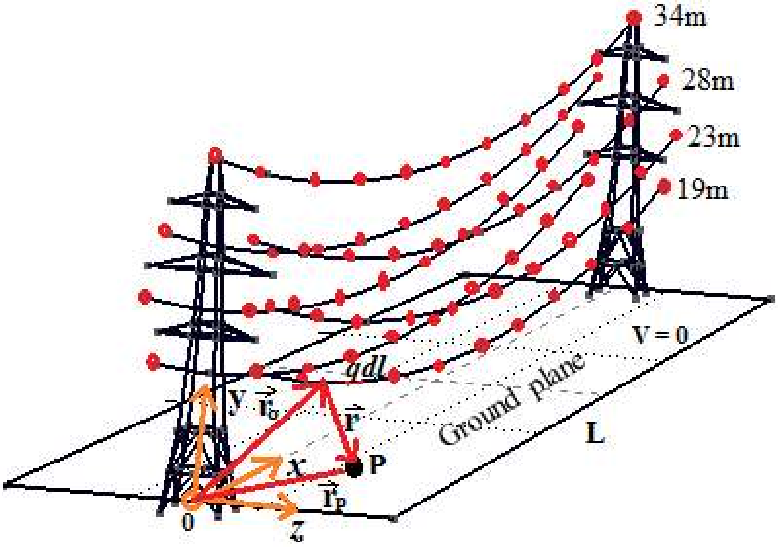


Figure 3: Positions of vectors $\vec{r}, \vec{r}_0$ and $\vec{r}_p$ in relation to the observer P

In Figure 3, P represents any desired point of calculation in space of $\vec{E}$; $\vec{\mathbf{r}}$ is the vector points from element of conductor dl to P; $\vec{r}_p$ represents the vector point from origin of coordinate system to P and $\vec{r}_0$ represents the vector point from origin of coordinate system to element of conductor dl ; q represents the charge in phase conductor; dl is the length along the path taken by the current.

Table 1 : Details of the transmission lines parameters in Benin Republic

Voltage level (kV)	161 kV	330 kV
Current each conductor(A)	485 A	1700

ELECTRIC FIELD CALCULATION

For an overhead power line with complex shapes of conductors as a catenary, it is necessary to use a numerical method to calculate the magnetic field. The application of this method to every conductor shape implies a change from analytic form consisting of unit derivations to numerical form consisting of unit differences. This approach is applicable to both electric and magnetic fields components.

The electric field produced by the power line at any point in space can be represented using vectors and phasors. An electric field vector is characterized by three spatial components as illustrated in equation (2) [22] - [23]:

$$\vec{E} = [E_x; E_y; E_z] \tag{2}$$

Each phasor represents the quantity with a sinusoidal time variation described by a magnitude and a phase angle φ_x.

$$E_x(t) = E_x e^{j\varphi x} e^{j\omega t} \tag{3}$$

Three orthogonal components of vector may be phasors with different magnitude and phase angles. These components are called phase–vector [24] as in equation 4.

$$\hat{\vec{E}} = [\hat{E}_x; \hat{E}_y; \hat{E}_z] \tag{4}$$

Electric fields caused by the overhead high voltage lines are low-frequency fields and can be approximated by quasi-static fields and for calculation of $\hat{\vec{E}}$, the followings are required [25]-[26]:

- The geometry of the system, the position of phase conductors and ground wires in 3D space and dimensions of the conductors,
- geometry of the ground,
- potentials on conducting elements (phase conductors, and ground),
- position of the observer.

The calculation of the $\hat{\vec{E}}$ is based on summation of the contribution of finitely small elements of each phase conductor into single point of observer P. Calculation can be described by the following steps:

- differentiation of conductors into elements of finite length,
- calculation of charge across conductor length for each element (calculation is based on Maxwell potential coefficients computations using the method of images),

- evaluation of $\hat{\vec{E}}$ at a single point of observer as a result of summing the contribution to the field from every element in Figure 1.

The equation for intensity of electric field under power transmission line consisting of k conductors in shape of catenary at point of observer P derived from Coulomb's Law is defined as follows [27]:

$$\vec{E} = \int_{\Gamma} \overrightarrow{dE} = \frac{1}{4\pi\mathcal{E}_0}\int_{\Gamma} \frac{qdl}{r^3}\vec{r} \tag{5}$$

Where **q** is charge element of line, dl is element of the line, Γ is conductors curve shape (catenary), $\vec{\boldsymbol{r}}$ is vector point from element of conductor dl to the observer points P in Fig. 3.
The vector $\vec{\boldsymbol{r}}$ can be written as:

$$\vec{r} = \left(\overrightarrow{r_p} - \overrightarrow{r_0}\right) \tag{6}$$

With the definition of vector $\vec{r}$, equation (5) can be rewritten as follows:

$$\vec{E} = \int_{\Gamma} \overrightarrow{dE} = \frac{1}{4\pi\mathcal{E}_0}\int_{\Gamma} \frac{qdl\cdot\left(\overrightarrow{r_p} - \overrightarrow{r_0}\right)}{\left|\overrightarrow{r_p} - \overrightarrow{r_0}\right|^3} \tag{7}$$

It is not possible to determine $\vec{E}$ in a dielectric environment, where conductors hang above a conductive plate with equation 7. The electric field in this model is created not only by charges in conductors but also by charges created due to electrostatic induction in the ground plane (Earth). The charge distribution and density in this earth is uneven. Solving this problem is done by the method of image charges. The method creates a new symmetrical conductor according to the boundary plane to each real conductor [28] - [29]. The mirror conductors have the opposite charge to the real ones as shown in Figure 4.

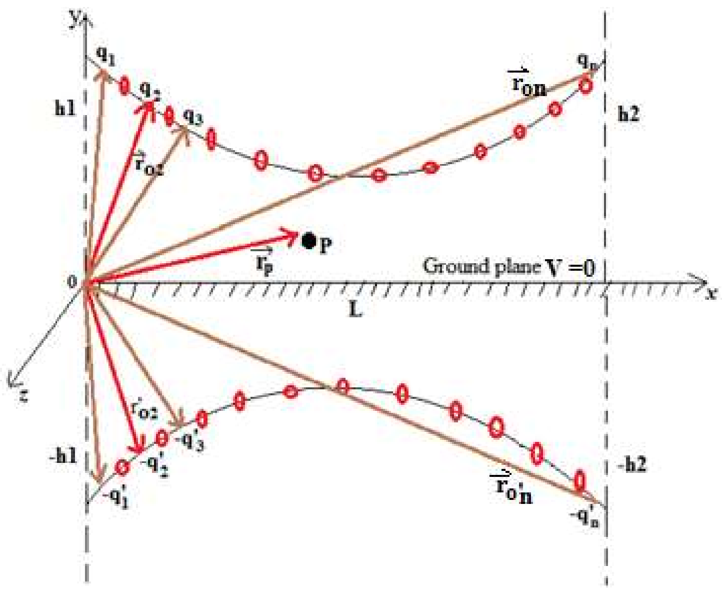


Figure 4: Method of mirror charges and visualization of calculation of electric field intensity

The total electric field vector $\vec{E}$ at point P equals the superposition of electric fields created by each conductor, $\vec{E}_k$ and its mirror $\vec{E}_{k'}$ as shown in Figure 4, where k is the index of conductor and apostrophe as upper index indicates mirror object in the ground. In our case (k = 6) as illustrated in Fig. 4

$$d\vec{E}_{k,k'} = \frac{1}{4\pi\varepsilon_0}\frac{+qd\vec{l}.\ (\vec{r}_p-\vec{r}_{0k})}{\left|(\vec{r}_p-\vec{r}_{0k})^3\right|} + \frac{1}{4\pi\varepsilon_0}\frac{-qd\vec{l}.\ (\vec{r}_p-\vec{r}_{0k'})}{\left|(\vec{r}_p-\vec{r}_{0k'})^3\right|} \tag{8}$$

The linear charges density can be calculated by solving simultaneous equations which relate the line charges with the potentials on the conductors. These equations were

$$\begin{aligned} V_1 &= P_{11}q_1 + P_{12}q_2 + \cdots + P_{1k}q_k \\ V_2 &= P_{21}q_1 + P_{22}q_2 + \cdots + P_{2k}q_k \\ &\vdots \\ V_1 &= P_{k1}q_1 + P_{k2}q_2 + \cdots + P_{kk}q_k \end{aligned} \tag{9}$$

The matrix form is given as follows:

$$[V_k] = [P_{kk}]\cdot[q_k] \tag{10}$$

where

- k = number of conductors
- Vk = potential of conductor k to ground plane
- P = potential coefficient
- qk = line charge per unit length on conductor k

As shown in figure 5, the values of the potential coefficients were as follows:

$$P_{kk} = \frac{1}{2\pi\varepsilon_0} ln\left(\frac{2h_k}{r_k}\right) \tag{11}$$

$$P_{kj} = \frac{1}{2\pi\varepsilon_0} ln\left(\frac{S_{kj'}}{S_{kj}}\right) \tag{12}$$

where

h_k = height of conductor k above ground
ε_0 = permittivity of free space
r_k = radius of conductor k
S_{kj} = distance between conductors k and j
$S_{kj'}$ = distance between conductor k and the image of conductor j
Pkk = self-potential coefficient of the conductor k
Pkj = mutual potential coefficient of the conductors k and j

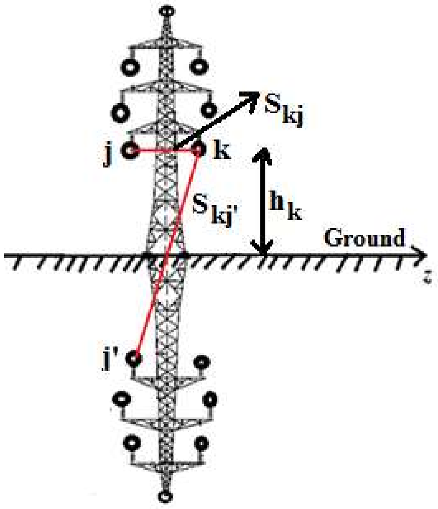


Figure 5: Location and distance among conductors (real and symmetric) for the calculation of P_{kj}

Since the values of the potential and the potential coefficients were known, the values of the line charges were calculated by solving equation 10. Once these values were obtained, the electric field at any desired point have also been deduced by summing the contributions due to the individual element line charges (real and image) of each conductor.

Furthermore, a harmonic oscillating voltage $\widehat{U}$ is added to finalise the calculation of $\hat{\vec{E}}$ The linear charge density also changes based on the harmonics and thus equation10 can be rewritten as follows:

$$[\hat{\mathrm{q}}_{\mathrm{k}}] = [\mathrm{P}]^{-1}[\hat{\mathrm{U}}_{\mathrm{k}}] \quad (13)$$

Finally, the equation for determining the field $\hat{\vec{E}}$ under overhead lines consisting of k conductors with voltage $\widehat{U}_k$ in shape of catenary, split into n segments with length dl and at the observation point P, is deduced as follows:

$$\hat{\vec{E}} = \frac{1}{4\pi\varepsilon_0}\sum_{k=1}^{k}\left[\sum_{n=1}^{n}\left[\frac{\hat{q}_{kn}\,d\vec{l}\,(\vec{r}_p - \vec{r}_{0_{kn}})}{\left|(\vec{r}_p - \vec{r}_{0_{kn}})\right|^3} + \frac{-\hat{q}_{k_n}d\vec{l}\,(\vec{r}_p - \vec{r}_{0'_{kn}})}{\left|(\vec{r}_p - \vec{r}_{0'_{kn}})\right|^3}\right]\right] \quad (14)$$

Where the vectors $\vec{r}_{0_{kn}}$ and $\vec{r}_{0'_{kn}}$ determine the conductor element position and its image according to the coordinate system as shown in Figure 4. Subsequently, considering the 3D space coordinates x,y,z the components of $\hat{\vec{E}}$ are described as follows:

$$\widehat{\overrightarrow{E_x}} = \widehat{\overrightarrow{E_{xr}}} + \widehat{\overrightarrow{E_{x\imath}}} \quad (15)$$

$$\widehat{\overrightarrow{E_y}} = \widehat{\overrightarrow{E_{yr}}} + \widehat{\overrightarrow{E_{y\imath}}} \quad (16)$$

$$\widehat{\overrightarrow{E_z}} = \widehat{\overrightarrow{E_{zr}}} + \widehat{\overrightarrow{E_{z\imath}}} \quad (17)$$

The vector $\hat{\vec{E}}$ is therefore rewritten as

$$\hat{\vec{E}} = \hat{E}_x\mathbf{\hat{e}}_x + \hat{E}_y\mathbf{\hat{e}}_y + \hat{E}_z\mathbf{\hat{e}}_z \quad (18)$$

$$\hat{\vec{E}} = E_{xr}\mathbf{\hat{e}}_x + E_{yr}\mathbf{\hat{e}}_y + E_{zr}\mathbf{\hat{e}}_z + jE_{xi}\mathbf{\hat{e}}_x + jE_{yi}\mathbf{\hat{e}}_y + jE_{zi}\mathbf{\hat{e}}_z \quad (19)$$

where $\hat{\mathbf{e}}_x$, $\hat{\mathbf{e}}_y$ and $\hat{\mathbf{e}}_z$ are the unit vectors on x, y and z axis, respectively, and the vectors $\vec{E}_r = E_{xr}\hat{\mathbf{e}}_x + E_{yr}\hat{\mathbf{e}}_y + E_{zr}\hat{\mathbf{e}}_z$ and $\vec{E}_i = E_{xi}\hat{\mathbf{e}}_x + E_{yi}\hat{\mathbf{e}}_y + E_{zi}\hat{\mathbf{e}}_z$ are the real and imaginary part of $\hat{\vec{E}}$, which corresponds to the real and the imaginary part $U_{k,r}$ and $U_{k,i}$, respectively, of the voltage $\underline{U}_k = U_{k,r} + jU_{k,i}$.

For the calculation of electric field, equation (14) has been used and solved with GetDP tool. The magnitude of the electric field is usually characterized by its resultant rms value, which is equal to

$$E = \sqrt{\left(E_x^2 + E_y^2 + E_z^2\right)} = \sqrt{\left(E_r^2 + E_i^2\right)} \tag{20}$$

$$E = \sqrt{(E_{xr}^2 + E_{yr}^2 + E_{zr}^2 + E_{xi}^2 + E_{yi}^2 + E_{zi}^2} \tag{21}$$

The electric field E is generally used to determine the magnitude of the magnetic field in order to compare it with exposure limits.

Boundary Conditions

For practical reasons and for quasi-electrostatic problem, Dirichlet conditions have been assumed. Dirichlet conditions are electric potentials on earth, pylons, guard and phase conductors.

Electric potential **V** on earth, pylons, guard conductors: V = 0
Electric potential **V** on phase conductors are given as follows:

$$\hat{V}_{1a} = V, \hat{V}_{1b} = Ve^{-i2\pi/3}, \hat{V}_{1c} = Ve^{-i4\pi/3} \tag{22}$$

$$\hat{V}_{2a} = Ve^{-i4\pi/3}, \hat{V}_{2b} = Ve^{-i2\pi/3}, \hat{V}_{2c} = V \tag{23}$$

All calculations are based on known theorems and laws of EMF. The different parts of the overhead high voltage line such as the pylon, the phase and guard conductors' positions, are modelled using the open-source mesh generator Gmsh [14]. This is a 3D finite elements grid generator with build-in CAD system. The electric field calculation is performed using the multi-physics finite element solver GetDP [15]. Gmsh and GetDP are integrated in the graphical environment. Finally, MATLAB software was used to process the data and plot the graphs.

RESULTS AND DISCUSSION

The proposed numerical method is applied for the determination of the electric field in the vicinity of power line. In Part A of this section, the electric field simulation has been carried out for the 132kV /260 A overhead power lines proposed by [30] as shown in Figure 6. Part B covers simulation results for 161kV/485A and 330kV/1700A overhead power located in the Republic of Benin.

a. 132 kV/260 A Transmission Line

Figure 6 show the geometry of the overhead power line proposed by [30]

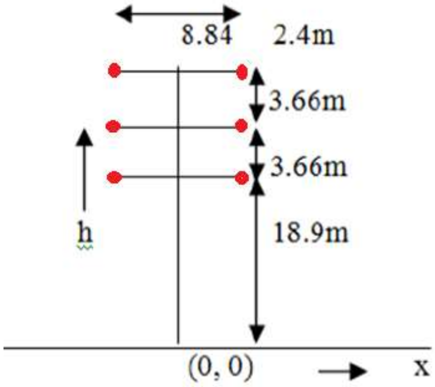
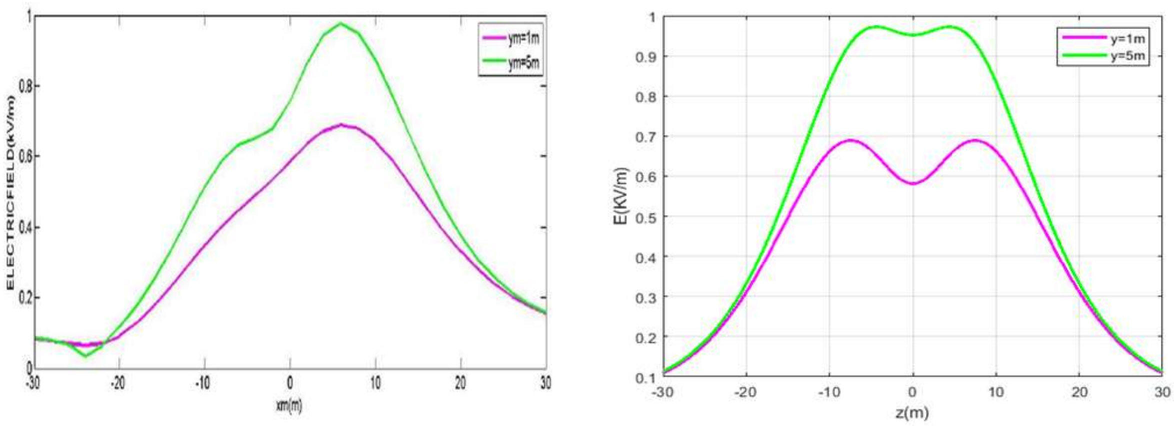


Figure 6: 132kV/260A power overhead power line, proposed by [30]

Figure 7a and figure 7b show the electric field variation obtained in [30] at height of 1 m and 5 m above the ground level respectively. The same peaks were observed on the electric field values using the method adopted in [30]. The observed peaks of electric field values are 0.7kV/m (h=1m) and 0.98kV/m (h=5m). The simulation of the proposed model led to the generation an electric field distribution graph, very similar and also symmetrical compared to that of [30].



a. Model based on [30] (analytical model) **b. Our proposed model (numerical method)**

Figure 7: Variation of electric field for 132kV/260A, at 1m and 5m height from ground level

b. 161 kV and 330kV Transmission Lines

The phase conductors of the transmission line, which represent the sources, are oriented along the x-axis in the Cartesian coordinate system (x, y, z) as shown in Figure 3. The calculation of the electric field was carried out in the horizontal x-z plane and vertical y-z plane. Gmsh and GetDP open-source software packages have been used for analysis and MATLAB software for the processing of data and plotting of graphs.

Figures 8 and 9 show the shapes of the electric field distribution in the x-z plane and y-z plane for the 161kV/485A and for 330kV/1700A overhead transmission lines. In the x-z plane the electric field is calculated below the overhead transmission lines at a height of 1.5 m above the earth. In the y-z plane, electric field strength increases and takes a maximum value near the phase conductors. The maximum electric field strength is 74kV/m for 161kV/485A and 152 kV/m for 330kV/1700A overhead transmission lines.

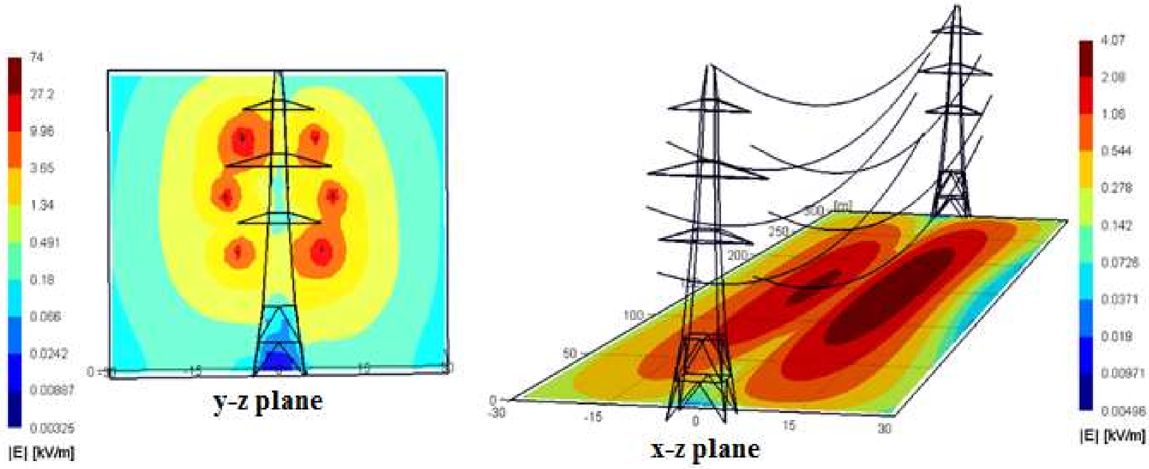


Figure 8. Electric field vector distribution in the x-z plane at 1.5 m above ground level and y-z plane for the 161kV/485A transmission line, carried out with Gmsh software

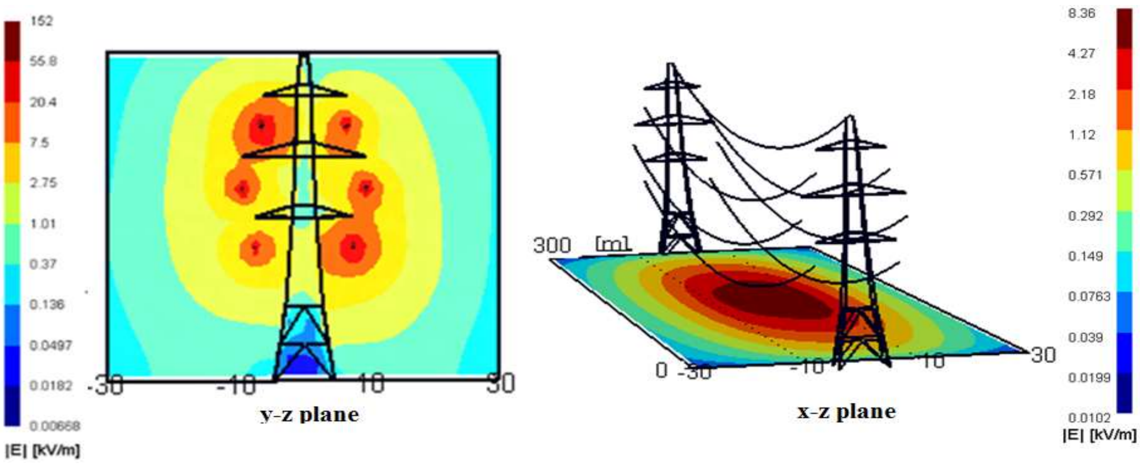
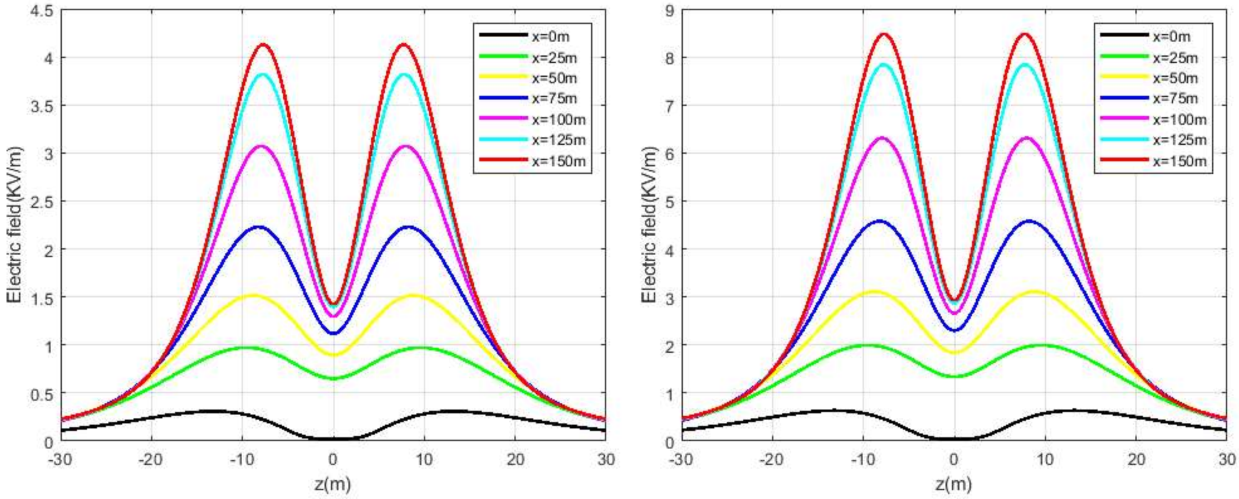


Figure 9. Electric field vector distribution in the x-z plane at 1.5 m above the earth and y-z plane for the 330kV/1700A transmission line, Carry out by Gmsh

Figure 10a and 10b show the lateral electric field profile in the x-z plane above ground level as a function of distance for the 161kV/485A and the 330kV/1700A overhead transmission lines respectively. The magnitude is about4.07 kV/m for the 161kV/485A transmission line and 8.36 kV/m for the 330kV/1700A transmission line. The maximum value of the electric field, found in the middle of the x span, is justified by the fact that in the middle of the span, the weight of the phase conductors are big and therefore closer to the ground and subsequently closer to the point of data collection. Meanwhile the values diminish as the distance from the conductors increases.

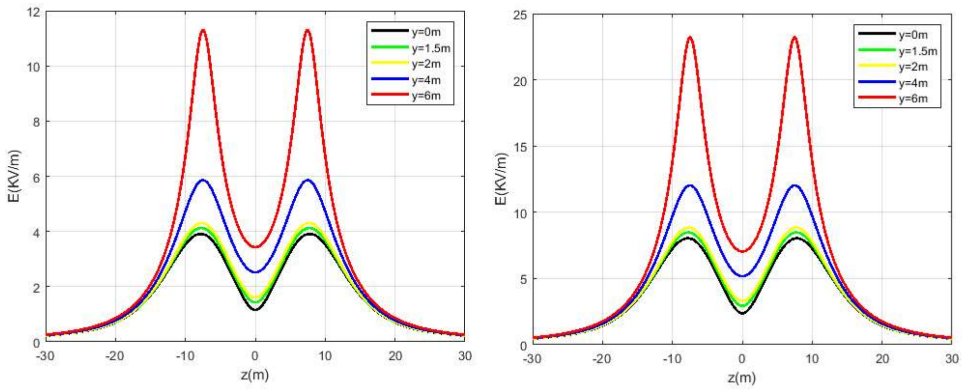
Referring to Table 2, for the 161kV/485A transmission line, the maximum values of the electric field is less than the maximum allowed exposure values. Thus, for the 330kV/1700A transmission line, the maximum value of the electric field is above the maximum allowed exposure values for the general public given by the standard specifications in Table 2. When moving away from the z-axis with a distance z = ±30 m, the values of the electric field are completely low and insignificant. Consequently, a decrease is observed according to the distance.



a. Profile for 161kV/485A transmission line b. Profile for 330kV/1700A transmission line
Figure 10 Electric field (kV/m) profile distribution in the x-z plane for 161kV and 330kV transmission lines.

In Figure 10a and 10b, the electric field is plotted, at the middle of the span field at the coordinates x = 150 m, up to some distance from ground surface and it is repeated for various heights from the ground surface at respective heights of 1.5m, 2m, 4m, 6m above the ground surface for the 161kV/485A and 330kV/1700A transmission lines.

Here, the values of the electric field strength increases while the height increases and reach the maximum values near the phase conductors with Emax = 11.3kV/m for 161kV/485A and Emax = 23 kV/m for 161kV/485A transmission lines. When moving away from the z-axis with a distance z = ±30 m, the values of the electric field are completely low and insignificant. Consequently, a decrease is observed according to the distance.



a. Profile for 161kV/485A transmission line b. Profile for 330kV/1700A transmission line
Figure 11 Lateral electric field (kV) profile calculated at mid-span length for different height above the earth for 161kV and 330kV transmission lines

Table 2. Exposure limits to low frequency electric and magnetic fields (50 Hz) ICNIRP (1998)

Power lines (50Hz)		
Limits per day	Electric field	Magnetic field
Professional exposure limits 8h/j	10kV/m	500 µT
Residential exposure limits 24h/24h	5kV/m	100 µT

CONCLUSION

In summary, this study adopted a numerical method of calculating the electric field vector in the vicinity of any arbitrary power line. The applied model considered the representation of the electric field phasors. In order to obtain more accurate calculation of the electric field in the vicinity of overhead transmission lines, an application based on Coulomb equation with a combination of the method of image charges dependence of electric field from the position of the conductor, the observer point and its mirror image, was adopted. The model gave accurate and valid output irrespective of the distance. Simulation results revealed there are some areas in the vicinity of the overhead high voltage transmission lines where the electric field intensity has exceeded the maximum allowed exposure limits for the general public or workers, according to standard specifications. However, the electric field decreases based on distance from source to the point of observation. Ultimately, this paper clarifies the myth or misunderstanding about level of exposure to electric and magnetic field close to overhead transmission lines. The findings could help document properly and efficiently, the health hazards associated with these exposures.

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