Computation of Electric and Magnetic Field Strengths under Nigerian 330 KV Power Lines

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Abstract
High voltage overhead power transmission lines are statutorily assigned a right-of-way, but ignorance of the necessity for a right-of-way has encouraged the erection of buildings directly under high voltage overhead power transmission lines. Associated with every energized power line is an extremely low frequency (ELF) electromagnetic field, and it is the need to avoid possible biological effects of this field on humans that necessitates a right-of-way. By a combination of Biot-Savart law, image theory and the generalized Ampere law we present a theoretical estimate of the characteristic and magnitude of the electromagnetic field in the vicinity of energized high voltage overhead power transmission lines. The field is non-uniform close to the line and approximately uniform at the ground level. The magnitude of the field at the ground level exceeds the maximum permissible exposure level considered safe, and as such there may be a health risk associated with spending long hours within the vicinity of the line.
Keywords: *Electric and Magnetic field strengths, Power lines, right-of-way, Maximum permissible exposure levels, extremely low frequency*

1. Introduction

Presently, it is commonly accepted that the availability of electricity in a community facilitates development. This has increased the tempo and clamor to bring electricity to every door-step, and the attendant routing of overhead power transmission lines (OPTLs) to deliver the ever sought for electric energy in our society. There are various categories of overhead power transmission lines, today; those that serve our homes operate at about 230 volt and can be near our dwellings, on the other hand, the transmission lines which carry electric energy over very long distances from generating stations operate at very high voltages, in the kilovolt range, and are not expected to be near dwellings. High voltage overhead power transmission lines (HV-OPTLs) are statutorily assigned a right-of-way (ROW) within which there should be no dwelling. However, in most Nigerian urban communities, we do see houses directly under HV-OPTLs. Such occurrences reflect un-planned urbanization, neglect by the agency authorized to maintain the ROW, and ignorance of the necessity of a right-of-way for extra high voltage overhead power transmission lines.

Energized overhead power transmission lines (i.e. those OPTLs that are in service) support both a current and voltage simultaneously and, according to electromagnetic theory, associated with every current carrying conductor is an electromagnetic field. Concern for possible biological effects of the electromagnetic field from HV-OPTLs has grown considerably during in recent time (Esmailzadeh et. al, 2019). This interest is not occasioned by the incidence of dwellings within OPTLs ROW, but also due to the need to maintain the lines to avoid undesirable power outages. The primary technical objective of every electric energy provider is to satisfy its customer expectation by providing an economic, acceptable level of undisrupted quality service. It is therefore necessary to understand the environmental and health implications of HV-OPTLs with a view to providing safety guidelines against the effects of the electromagnetic field that they produce.

A description of the electromagnetic field emanating from an overhead power transmission line and an understanding of the interaction mechanism(s) between this field and humans is necessary to allay the fear of the public. The magnitude of this field depends on the current and voltage supported by the line. Also, the height of the line above the ground and the nature of the earth surface influence the field. An accurate determination of electromagnetic field coupling to the human body is a challenging problem in the electric power industry. This is because at power frequencies all organs of the human body act as conductors embedded

in a saline fluid. A body exposed to an electromagnetic field absorbs a fraction of the incident field. The magnitude of the absorbed field can be used to predict possible biological effects of the field in humans. Studies have shown that these fields result in electric shock, reduction in sperm count, increase in neurological disorder and increase in cardiovascular disorder in people within the immediate vicinity of HV–OPTLs (Perry et. al, 1981).
Here we present a theoretical estimate of the characteristics and magnitude of the electromagnetic field in the vicinity of an energized extra high voltage overhead power transmission line. The results are compared with published maximum permissible exposure (MPE) levels of some professional organizations and the Electricity Supply Regulations of Nigeria, enabling us-to make safety recommendations to electric energy providers in Nigeria.

2. Simple Physical Model

We estimated the extremely low frequency (ELF) electromagnetic field due to HV-OPTLs by using a combination of Biot-Savart law and the generalized Ampere law. This was simpler than using Maxwell equations and is permissible at 50 Hz operating frequency. Assuming a uniform current on the source wire, we calculated the magnetic vector potential from which the transverse electromagnetic field is obtained. We used this simple approach because the vertical electric strength is orders-of-magnitude greater than the axial electric strength that may be obtained by other methods.
We model a set of long parallel OPTLs using a single line carrying a known alternating current, with an earth return, at a perpendicular height *(h)* above a flat homogeneous and perfectly conducting earth. The relatively small value of wire radius *(a)* and line height, compared to the free space wavelength (6000 km) allow us to use the thin-wire approximation. Also, we assumed that the current is a traveling wave directed along the wire length *(z).* Assuming a traveling wave implies that the line is terminated with a matched load. Usually, the actual field is a function of the load because of a mismatch between line and load, and the effect of multiple lines can be accommodated using a multiplication factor, since the medium is linear and the superposition principle applies.
Solving for the electromagnetic field due to the combination of a single overhead power transmission line and earth return was simplified when we invoked image theory, and replace the plane conducting earth with an image of the line at a distance *(h)* below the surface, Fig 1. For a point in air separated from the line by a distance *(r)* less than the wavelength, Biot-Savart law gives the magnetic vector potential due to a current element ***dl*** as

$$dA = \frac{\mu_o i dl}{4\pi r}, \qquad (1)$$

where i is the current and μ_0 is the permittivity of free space. For the geometry of Figure l, the magnetic vector potential becomes

$$\boldsymbol{A_z = \frac{\mu_0 i}{2\pi} In\left(\frac{R_1}{R_2}\right), A_x = 0, A_y = 0} \qquad (2)$$

where R_1 is the distance from the field point to the line and R_2 is the distance from the field point to the image. Since in air

$$\mu_0 \boldsymbol{H} = curl\ \boldsymbol{A} \qquad (3)$$

we have that

$$H_x = -\frac{i}{2\pi}\left[\frac{y-h}{R_1^2} - \frac{y+h}{R_2^2}\right],\ H_y = \frac{i}{2\pi}\left[\frac{x}{R_1^2} - \frac{x}{R_2^2}\right],\ H_z = 0. \qquad (4)$$

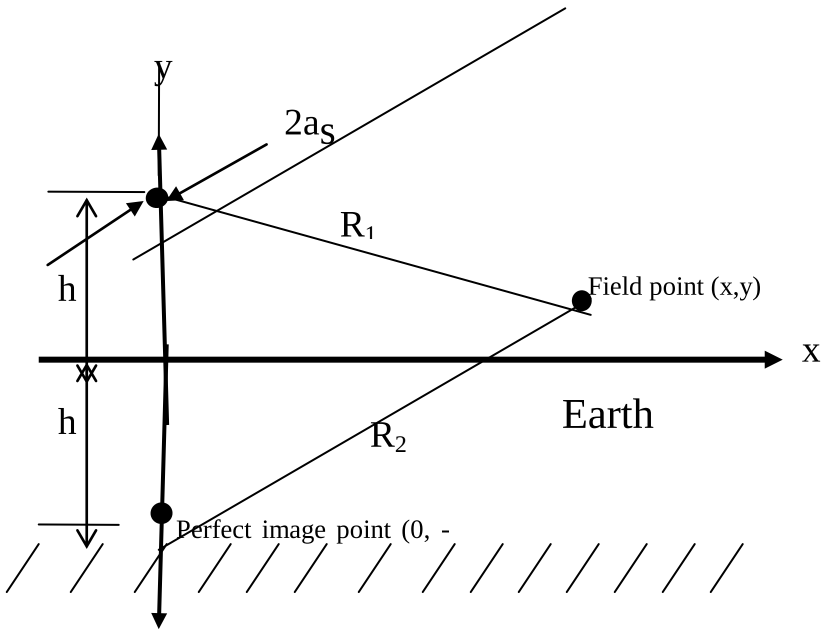

Fig1: Wire above earth

For a current with exp($j\omega t$) time dependence, the associated electric strength at the field point is determined using the generalized Ampere law and noting that at the field point in the air the free conduction current density is zero. Thus,

$$\text{curl}\ \boldsymbol{H} = \varepsilon_0 \frac{\partial E}{\partial t}, \qquad (5)$$

from which we obtain

$$E_x = \frac{1}{j2\pi\omega\varepsilon_0}\left[\frac{x}{R_1^2} - \frac{x}{R_2^2}\right]\frac{\partial i}{\partial z},\ E_y = \frac{1}{j2\pi\omega\varepsilon_0}\left[\frac{y-h}{R_1^2} - \frac{y+h}{R_2^2}\right]\frac{\partial i}{\partial z},\ E_z = 0. \qquad (6)$$

Since the actual z-dependence of the current is unknown, the expressions in (6) may be written in items of the line voltage. Using Gauss law, we define a potential difference between ground and a field point above as

$$V = -\int_0^{h-a} E_y(0, y)\,dy. \qquad (7)$$

In the limit $h >> a$, the integral (7) can be solved to obtain

$$\frac{V}{In(2h/a)} = \frac{1}{j2\pi\omega\varepsilon_0}\frac{\partial i}{\partial z}. \qquad (8)$$

Using equation (8) in (6) to eliminate the z-derivative of the current gives

$$E_x = \frac{V}{In(2h/a)}\left[\frac{x}{R_1^2} + \frac{x}{R_2^2}\right], E_y = \frac{V}{In(2h/a)}\left[\frac{y-h}{R_1^2} - \frac{y+h}{R_2^2}\right], E_z = 0. \qquad (9)$$

Thus, the transverse electromagnetic field in air due to an energized overhead power transmission line is described by the electric strength (9) and the magnetic strength (4). Observe that this field consists of two perpendicular polarizations, both transverse to the line axis. At points directly under the line (x = 0) the field is vertically (E_y, H_x) polarized. We observe that the expressions in (4) and (9) are not appropriate if the wire is very close to the earth surface, such that h is of the same order-of-magnitude as a.

3. Results and Discussions

Values of the electromagnetic field in the near vicinity of a 330 KV 900 A OPTL of wire radius 0.01 m at a height 12 m above ground are calculated using (4) and (9). On a *z*- plane we calculate the magnitude of the rectangular components of the field for observation points at a height *(y)* ranging from 0 to 11 m, over a horizontal distance *(x)* from the line ranging from 0 to 20 m. The results are given in Fig 2 and 3, respectively for the vertical (E_y) and horizontal (E_x) components of the electric strength, and in Fig 4 and 5 for the vertical (H_y) and horizontal (H_x) components, respectively, of the magnetic strength.

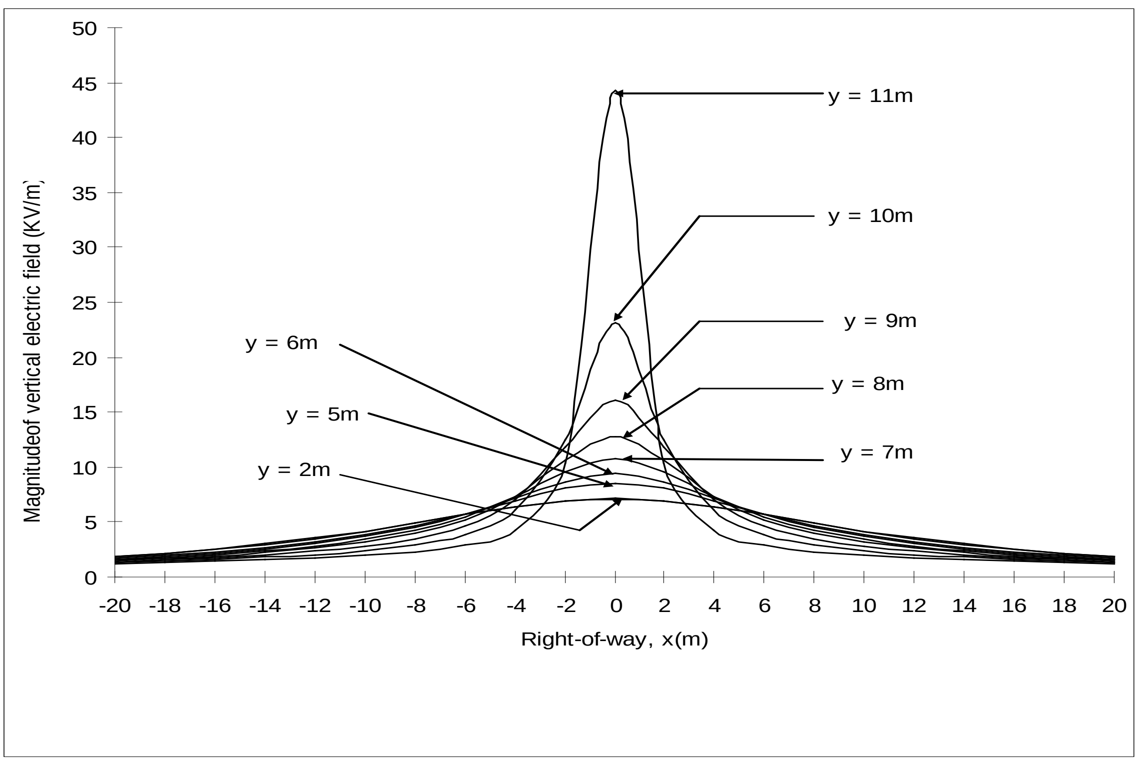

Fig 2. Magnitude of Vertical Magnitude Strength

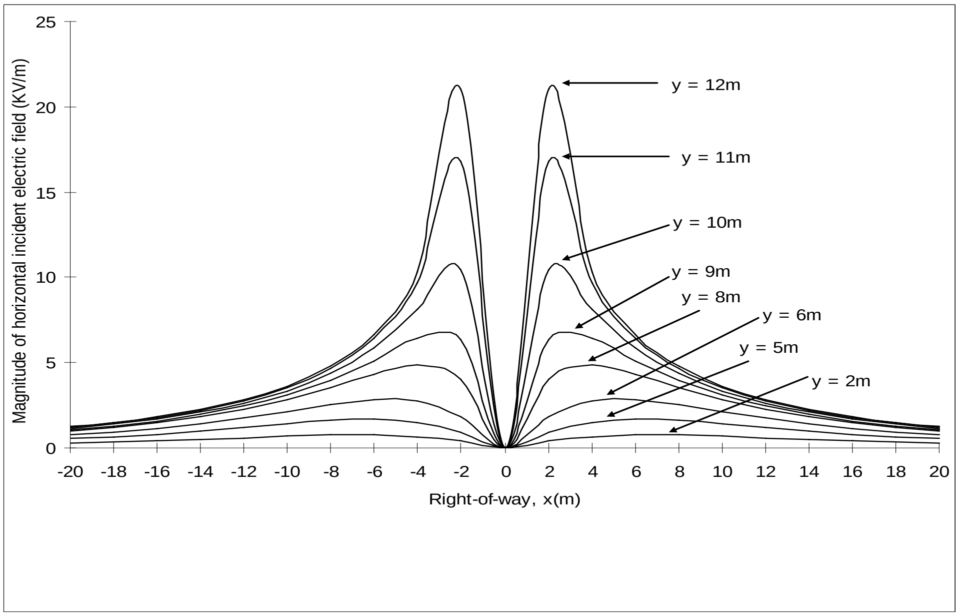

Fig 3. Magnitude of Vertical Electric Strength

These plots illustrate that the electromagnetic field in the vicinity of an energized extra high voltage overhead power transmission line is a non-uniform field. Secondly, the field attains its maximum value at points directly under the line, and the magnitude tapers to a minimum as we move away from the line along the horizontal (right-of-way). Thirdly, observe that E_y and H_x have the same spatial variation, and so are E_x and H_y, as expected from Maxwell equations. Also, the peak value of the pair E_x and Hy occurs at a point displaced from the line by about 3 m along the horizontal. In addition, we observe that close to the ground the electromagnetic field is approximately uniform. Thus, objects on the ground may be assumed to be in- a uniform_field, but linemen who service an energized line above are certainly in a non-uniform field, with a steep gradient along the vertical direction.

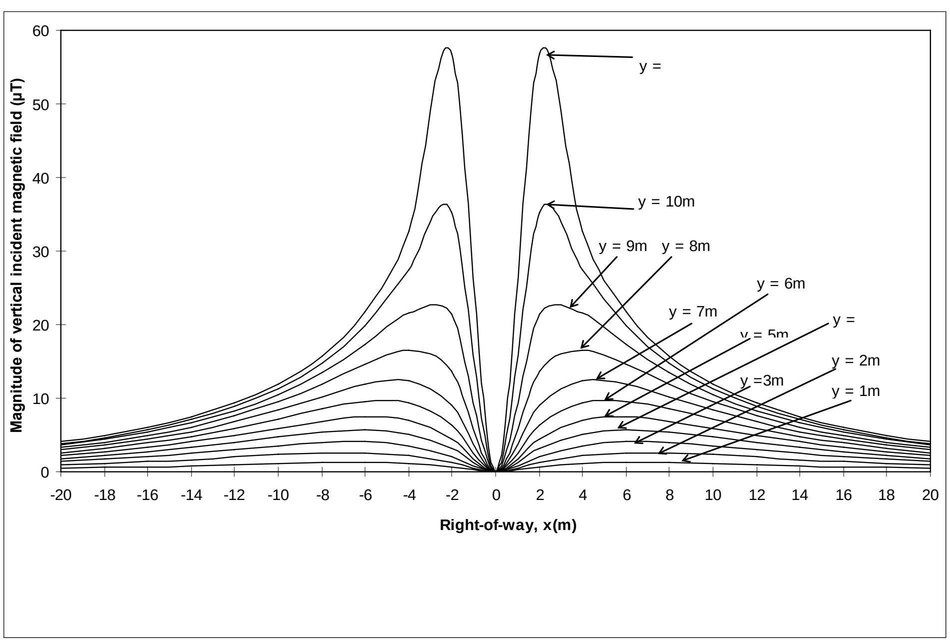

Fig 4. Magnitude of Horizontal Electric Strength

For this numerical illustration, at a distance 1 m directly below the line, the electromagnetic field has an electric strength about 44.2 kV/m and a magnetic strength about 150 µT. Observe that even at 11 m below the line (i.e., 1 m above ground) the electric strength is about 7.1 kV/m and the magnetic strength is about 24.0 µT. Thus, a person standing on the ground directly under the line is exposed to an electromagnetic field with electric strength about 7.0 KV/m and magnetic strength about 24.0 µT. The Institute of Electrical and Electronics Engineers in 2002 (Institute of Electrical and Electronics Engineers, 2002) recommended that the maximum permissible exposure level for the general public should be 5.0 kV/m and 904 µT, respectively, for the electric strength and magnetic strength, while the International Commission on Non-Ionizing Radiation Protection in 1998 recommended 4.2 kV/m and 83 µT (Kavet, 2003). These values assume a power line operating at 60 Hz. Observe that the calculated electric strength of about 7.0 KV/m exceeds the maximum permissible exposure level recommended for the general public.

A simple way to reduce the field strength from an OPTL at the ground is by increasing the height of the power line. Incidentally, the Electricity Supply Regulations of Nigeria recommends that at 330 KV the power line should be at a height not less than 7 m. We observe that these regulations were issued by the Federal Ministry of Mines and Power in 1979 (Federal Ministry of Mines and Power, 1979), and we could not find any revision.

Linemen who work on energized power lines are exposed to a non-uniform electromagnetic field with electric strength above 44.2 kV/m and magnetic strength above *150* µ*T*. The International Commission on Non-Ionizing Radiation Protection (ICNIRP, 2004) recommends a maximum permissible exposure level of 8.3 kV/m and 420 µT for this category of persons. This implies that those in this occupation require protective clothing or gadgets, and electric energy providers should not because of cost allow workers in unsafe work environments.

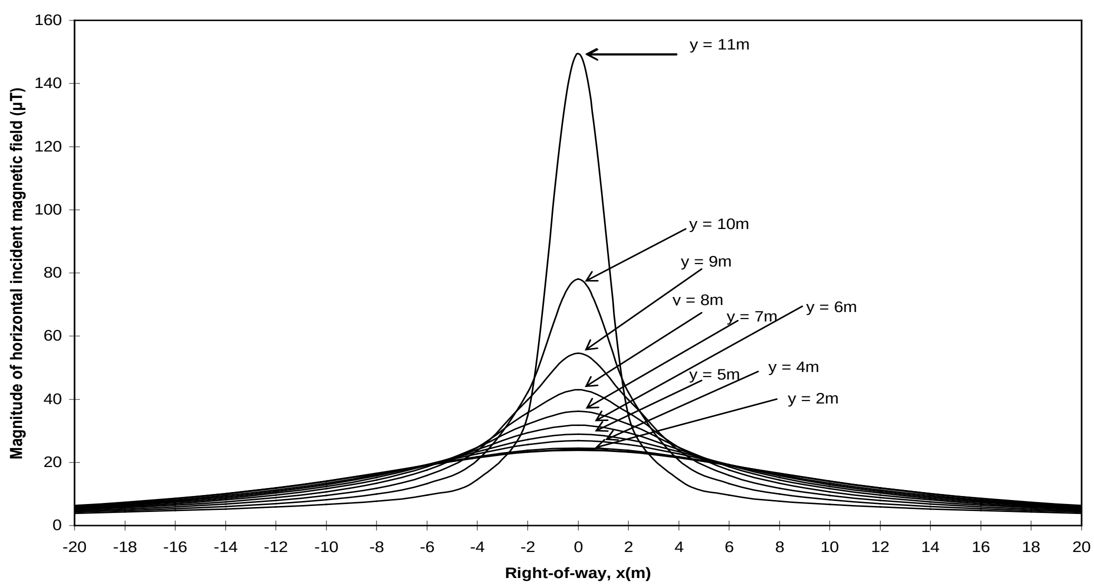

Fig 5. Magnitude of Horizontal Magnitude Strength

4. Conclusions

We were able to show the rationale for providing a right-of-way for high voltage overhead power transmission lines, based on the electromagnetic field in the vicinity of energized HV-OPTLs. The magnitude of this field exceeds the maximum permissible exposure levels that are recommended for human safety by relevant professional organizations: Since our primary concern is to show that the electromagnetic field magnitude exceeds the maximum permissible exposure level, we have used a rather simple model which allows us to estimate the dominant components of this field (transverse to the wire line). The field is almost uniform at the ground level but non-uniform close to the power line.

There seems to be a need to review the Electricity Supply Regulations of Nigeria, with special reference to tower heights used by local electric energy providers. The regulation should also make the use of protective clothing by linemen mandatory. It may become necessary to enforce compliance with overhead power transmission lines right-of-way among the populace. Individuals who live in buildings within the OPTLs ROW are ignorantly exposing their lives to danger, since the electromagnetic field at the ground exceeds the maximum permissible exposure level. While planning the construction of new HV-OPTLs provision should be made for the relocation of all existing buildings within the proposed HV-OPTLs ROW, and those buildings should be demolished before energizing the lines.

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