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Biological risk assessment of high-voltage transmission lines on worker's health of electric society

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Abstract: A probable risk for different diseases has been reported due to exposure of peoples living in the vicinity of electrical substations and electrical workers. The aim of this paper is to examine and reduce the induced current density due to the power system field acting on human beings in the working environment, by using the spheroidal calculation model. The results obtained by means of computer programs developed by the author in the MATLAB environment are compared with the limit values given by the International Committee on Non-Ionizing Radiation Protection (ICNIRP) for demonstrating the degree of danger due to the induced current and have a certain guidance function for worker's health to ensure their safety.

Key words: biological risk, electromagnetic fields, extremely low frequency, induced current, overhead lines

1. Introduction

The increasing use of electrical energy worldwide (increased by 20 times in the US between 1940 and 1992) [1], has raised concerns about the possible negative effects of Electromagnetic Field (EMF) exposures on biological systems and in particular on human health [2].

In recent years, numerous research studies on the effects of exposure to electromagnetic fields generated by electric power transmission lines and mobile communication stations [3] have been published. These studies are characterized by the diversity of methods used for the characterization of these fields and the definition of the mechanisms of their coupling with biological tissues and electrical equipment.

The exposure of living beings to the electromagnetic fields generated by high voltage power lines on human health is an interesting and topical subject for researchers because of the harmful effects that can occur [4], such as: electric shocks, tissue burns and interference with medical implants [5, 6].

Some clinical correlations are very significant (increase of certain cancers in children). However, for other clinical hypotheses the relationship between EMF exposure and the occurrence of presumed diseases has not yet been proven. Nevertheless, the tendency of scientific researchers' opinions is to favor the "precautionary principle". This is an approach based on the principle that, in the absence of evidence of the safety of EMF, precaution should be the rule [7, 8].

In this debate, the literature analysis on the state of knowledge and controversy about the effects of low frequency EMF (50–60 Hz) on human health shows that the first effects of high voltage power lines were first found among the electricity workers, in 1972, by the Russian epidemiologists who noted: headache, fatigue, and sleep disorders [9] in exposed persons, then later in the United States, were notified: leukemia, brain tumors and melanomas.

A study among electrical workers reinforces the increase in myocardial infarction and arrhythmias under chronic exposure to extremely low frequency EMF [10]. Numerous experimental data support the genotoxicity of extremely low frequency EMF: they would cause DNA damage by oxidative stress, resulting in DNA repair and cell cycle abnormalities [11]. In addition, the "corona effect" is still mentioned to explain the risk of lung cancer: the ionization by the electric field of the high voltage line of polluting particles, such as carcinogenic aromatic hydrocarbons present as an aerosol in the air, would favor their bronchial deposition [12].

As a precautionary measure, various legislative institutions (European Parliament, etc.) and learned societies have established exposure limits for electromagnetic fields for the public and workers. Among these organizations: the ICNIRP, the OMS and the IEEE directive. These recommendations define a basic restriction on the density of electrical current induced in the body by the ELF (extremely low frequency) fields [13–15].

2. Models and methods

The biological phenomena generated by the electromagnetic fields depend on the interaction waves-living matter. According to the frequency range considered they can be induced current or overheating tissues.

Extremely-low frequency electromagnetic fields generate in the human body a biological risk, the assessment of which requires, firstly, the environment characterized by calculating the spatial distribution of the radiated electric and magnetic field, then the coupling study between the field and the human body.

2.1. The radiated electric and magnetic field model

The choice of the calculation method of the electric and magnetic field depends on the type of problem to be solved. The charge simulation method finds its natural application when calculating the field in the vicinity of transmission lines and substations. So, this is the method I will apply in this paper using the geometry shown in Fig. 1.

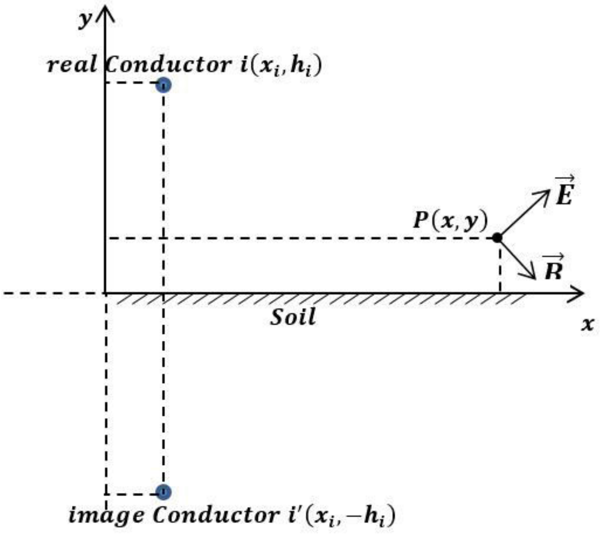

Fig. 1. Geometry used for calculation of electric and magnetic

The basic formula of this method indicates that the potential resulting from a set of fictitious charges of magnitude Q_i at any point in the surrounding space can be written as [16–18]:

$$E_x = \left(\frac{1}{2\pi\varepsilon_0}\right)\sum_{i=1}^{n} Q_i \left[\frac{x - x_i}{(x - x_i)^2 + (y - h_i)^2} - \frac{x - x_i}{(x - x_i)^2 + (y + h_i)^2}\right], \tag{1}$$

$$E_y = \left(\frac{1}{2\pi\varepsilon_0}\right)\sum_{i=1}^{n} Q_i \left[\frac{y - h_i}{(x - x_i)^2 + (y - h_i)^2} - \frac{y + h_i}{(x - x_i)^2 + (y + h_i)^2}\right], \tag{2}$$

$$B_x = \left(-\frac{\mu_0}{2\pi}\right)\sum_{i=1}^{n} I_i \left[\frac{y - h_i}{(x - x_i)^2 + (y - h_i)^2} - \frac{y + h_i}{(x - x_i)^2 + (y + h_i)^2}\right], \tag{3}$$

$$B_y = \left(\frac{\mu_0}{2\pi}\right)\sum_{i=1}^{n} I_i \left[\frac{x - x_i}{(x - x_i)^2 + (y - h_i)^2} - \frac{x - x_i}{(x - x_i)^2 + (y + h_i)^2}\right], \tag{4}$$

where:

B_x, and B_y are, respectively, the horizontal and vertical component of the magnetic field.
E_x, and E_y are, respectively, the horizontal and vertical component of the electric field.
ε_0, μ_0 are, respectively, air permittivity and permeability.
(x, y), (x_i, y_i) are, respectively, the coordinates of the observation point $\boldsymbol{P}$ and the conductor i.
I_i is the line current.
Q_i is the fictitious charge carried by each conductor given by:

$$[Q] = [\boldsymbol{P}]^{-1}[\boldsymbol{V}], \tag{5}$$

where $[\boldsymbol{V}]$ is the vector of a voltage line.

[$\boldsymbol{P}$] is the potential coefficient matrix, where

$$P_{ii} = \frac{1}{2\pi\varepsilon_0}\ln\left(\frac{2h_i}{r_i}\right), \qquad P_{ij} = \frac{1}{2\pi\varepsilon_0}\ln\left(\frac{D_{ij}}{d_{ij}}\right).$$

r_i is the conductor radius.
h_i is the conductor heigh.
d_{ij} is the distance between the i^{th} conductor and the j^{th} conductor.
D_{ij} is the distance between the i^{th} conductor and the image of the j^{th} conductor.

2.2. Model of induced phenomena

The induced phenomena studied in this paper are created from a coupling of the field radiated by a power overhead line and a human body immersed in this field. There are two basic mechanisms of coupling [19]:

2.2.1. Coupling with low frequency electric field

Due to the interaction of electric fields with the human tissue, electric currents are induced. If the internal electric field in the tissue is E, the current density, J, can be determined as follows:

$$J = \sigma E. \tag{6}$$

$\sigma$is the electrical conductivity of the biological tissue.

A prolate spheroid model of a human in an electric field is presented in Fig. 2 [20].

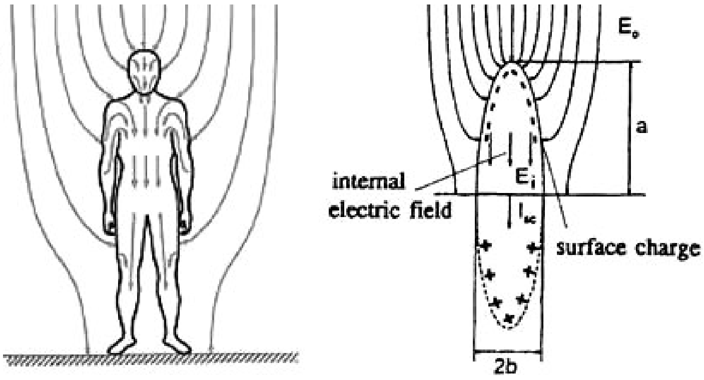

Fig. 2. Human body and it's prolate spheroid immersed in an electric field generated by overhead line [20]

The peak value of the internal induced field E_i due to the external electrical field E_0 is described as follows (E_0 is the electric field radiated by transmission line):

$$E_i = j\left(\frac{2\pi f\varepsilon_0}{\sigma(N/4\pi)}\right)E_0\,. \tag{7}$$

f is the frequency.
$N/4\pi$ is the bipolarity factor for a prolate spheroid.

In the case of a human body, appropriate values for the depolarization factor are, for an isolated ellipsoid 0.035, and for a grounded ellipsoid 0.02.

By using Equation (6), the internal current density can be obtained,

$$J_E = \sigma E_i \,. \tag{8}$$

2.2.2. Coupling with low frequency magnetic field

A prolate spheroid model of a human in a magnetic field is presented in Fig. 3 [20].

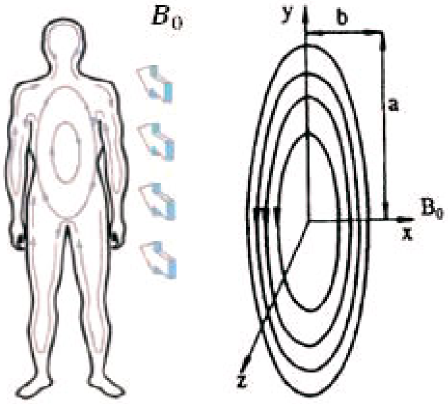

Fig. 3. Human body and its prolate spheroid immersed in an electric field generated by overhead line [20]

The external magnetic field B_0 (radiated by transmission line) will induce the internal electric field E_B in the human body, according to Faraday's law, which is given as:

$$E_B = -\frac{\partial B_0}{\partial t}\frac{r}{2} = -j\omega B_0 \frac{r}{2} = -j\pi f r B_0 \,. \tag{9}$$

E_B is in a plane perpendicular to B_0 and is oriented tangentially to circles of radius r.

It can be noted that the value of the current density induced by the magnetic field depends on the larger loop, so it is maximum at the prolate spheroid surface (the largest loop) corresponding to "$r = b$" (max radius of the spheroid). Using Equation (6), the internal current density is obtained:

$$J_B = j\pi f b \sigma B_0 \,. \tag{10}$$

A rough estimate of the total induced current density can be calculated by summing the two current densities (J_E) and (J_B).

$$J_T = J_E + J_B \,. \tag{11}$$

2.2.3. Electromagnetic properties of organs

In reality the human body is not homogeneous because its electrical properties (conductivity and permittivity) vary from one organ to another (according to their water content) as shown in Table 1; these properties also depend on the frequency.

Table 1. Electrical properties of certain human (1.75 m height) tissues at 50 Hz [21]

Tissues	**Conductivity [S/m]**	**Relative permittivity**	**Organ height [m]**
Stomach	0.521	1.6372e−6	1.06
Muscle	0.23329	1.7719e+7	
Kidneys	0.089239	1.0115e+7	0.9
Liver	0.0367	1.8317e+6	1.06
Heart	0.0827	8.6646e+6	1.25
Brain	0.0533	5.2898e+6	1.68
Bone	0.0504	8867.8	
Lungs	0.0684	5.7589e+6	1.25

2.2.4. Mitigation of induced phenomenon

Workers' insulation clothing is a way of protecting against electromagnetic radiation. There are also other ways to ensure their safety through: distance from the radiation source, modification of design parameters (height of lines, distance between phases), or the insertion of the parallel auxiliary conductors located between the power line and the ground and connected at their ends forming a closed loop [16–18].

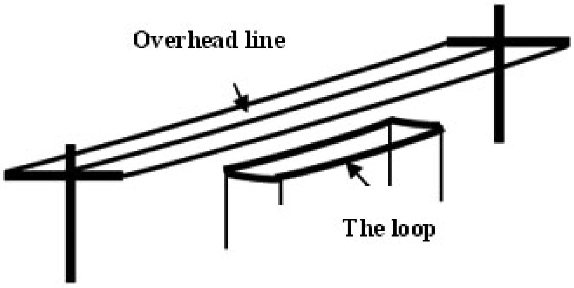

Fig. 4. Geometry of overhead line with a loop

Its principle is that the induced currents I_i in the loop generate a field opposite to that radiated by the line:

$$I_i = \frac{V_i}{Z}\,. \tag{12}$$

Z is the loop impedance.

V_i is the induced voltage in the loop which is derived from the Faraday law.

$$V_i = -\frac{\mathrm{d}\Phi}{\mathrm{d}t} = -j\omega\Phi. \tag{13}$$

Φ is the magnetic flux generated by the three phases of the line.

ω is the pulsation.

$$\Rightarrow\ I_i = -j\frac{\omega}{Z}\Phi\,. \tag{14}$$

The total field B_T is the superposition of the two fields, it is therefore the reduction.

$$B_T = B_0 + B_i\,. \tag{15}$$

The loop attenuation effectiveness depends on the induced current which itself depends on the loop impedance due to its geometric properties (width and height).

In this study, I used this last technique as a solution to reduce the biological risk by mitigating the radiation source intensity.

3. Results

3.1. Electric and magnetic field

In this study, I considered two geometries to calculate the field intensity for the reason of choosing the least radiant line during its design. The geometric parameters are shown in Table 2.

Table 2. Geometrical data of two configuration overhead line

Data	Horizontal flat	Double circuit
Height of phase 1 [m]	13.7	30.7 = h(3′)
Height of phase 2 [m]	13.7	22.2 = h(2′)
Height of phase 3 [m]	13.7	13.7 = h(1′)
Phases spacing [m]	8.5	8.5
Line span [m]	400	400
Number of sub-conductors	2	2
Sub-conductors spacing [cm]	40	40

In Fig. 5, I present the electric and magnetic fields produced by a 400 kV overhead line with 1.8 kA having two different configurations (double circuit with phases transposed and horizontal, their parameters shown in Table 2) for a comparison concerning their electromagnetic radiation, which is the lowest for a double circuit configuration. This is due to the fact that the field produced from each conductor of the double circuit will be balanced by other ones, this will reduce the radiation.

The results of Figs. 5, 6, and 7 lead us to notice that electric and magnetic fields increase while approaching the line conductors (i.e. the electromagnetic field has maximum intensity of radiation below the axis line then it decreases while moving away from it), this is also confirmed in the results published in [25–29].

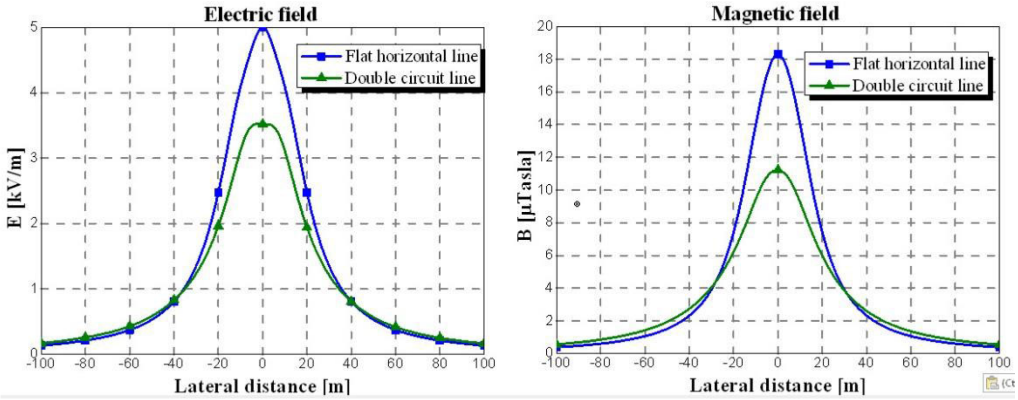

Fig. 5. Electric and magnetic fields radiated by 400 kV overhead lines at 2 m above ground

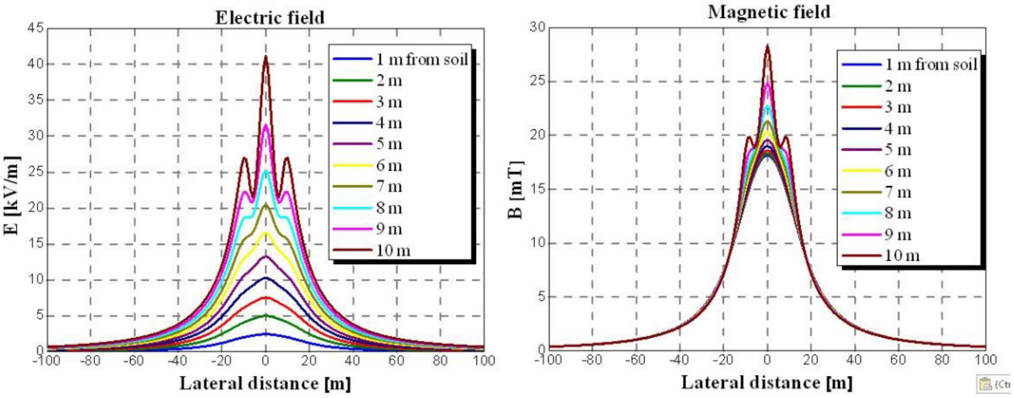

Fig. 6. Electric and magnetic field distribution for different levels above ground

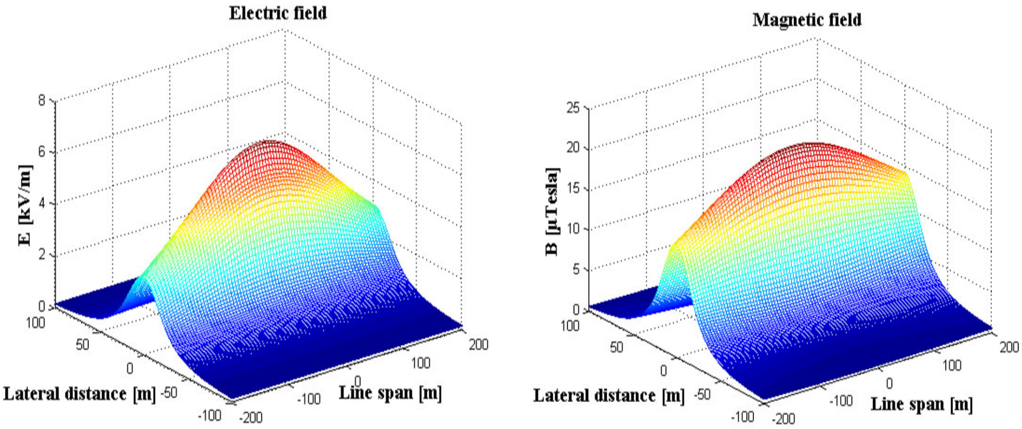

Fig. 7. Electric and magnetic field distribution at 2 m above ground

3.2. Induced current

For a person of 1.75 m height and homogeneous conductivity (0.2 S/m) and permittivity (this hypothesis makes it possible to obtain a unidirectional polarization) exposed to electric and magnetic fields radiated by a 400 kV flat horizontal high-voltage overhead lines (geometric parameters are shown in Table 2) in different points for a period of 4 hours assumed to be short-time.

Using Equations (9)–(11) based on the prolate spheroid model, the density of the current induced in an isolated or grounded person is shown in Fig. 8, and determined for different distance from the line. I can indicate that an induced current due to the electric field is more significant than that created by the magnetic field, and the worker is more protected if he wears insulating shoes.

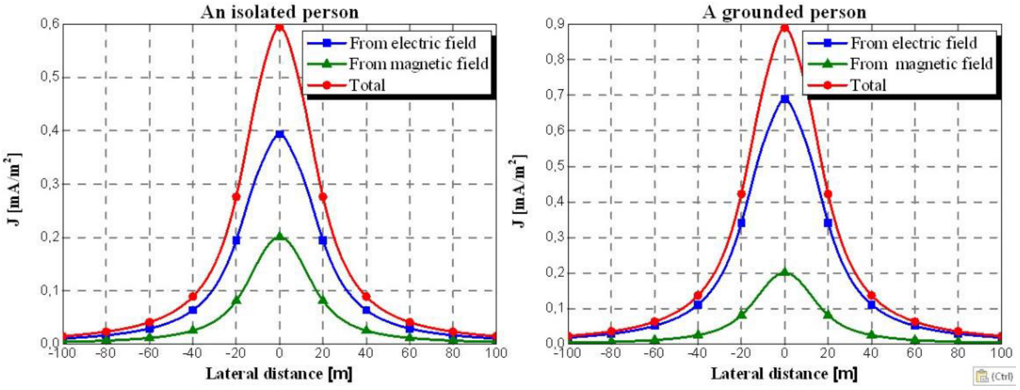

Fig. 8. Induced current density in homogenous human body with σ = 0.2 S/m

All the results obtained are clearly below standard safe limits of electromagnetic radiation given by the International Commission on Non-ionizing Radiation Protection (ICNIRP). For the general public the exposure limits are lower because of safety margins (see Table 3).

Table 3. Electric and magnetic field exposure guidelines at 50 Hz set by the ICNIRP (1998) [14]

	Electric field [kV/m]	**Magnetic field [µT]**	**Current density [mA/m^2]**	
Reference level			**Basic Restriction**	
Occupational	10	500	Occupational	10
Public	5	100	Public	2

Based on our results and those published in [27–29], I can, therefore, conclude that the risk is low in this study, but it will be more important if the field exposure time will be longer, especially for people living near substations and workers.

The Fig. 9 illustrates that the induced current density vary depending on the electrical conductivity of different organs and their situation in the human body as shown in Table 1. It can be observed from this result the organ most affected by electromagnetic radiation.

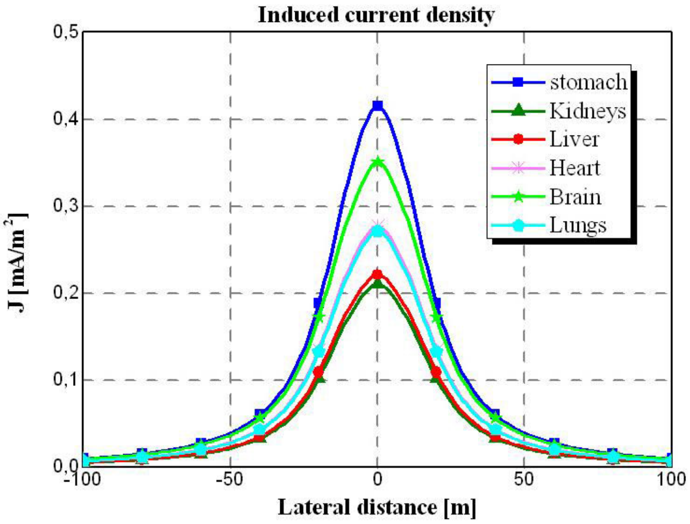

Fig. 9. Induced current density in organ of the human body

3.3. Reduction of induced current

The result of Fig. 10 shows the reductive effect of the loop on the induced current density. So, using this method is a way of minimizing electromagnetic radiation and subsequently the safety of people especially workers.

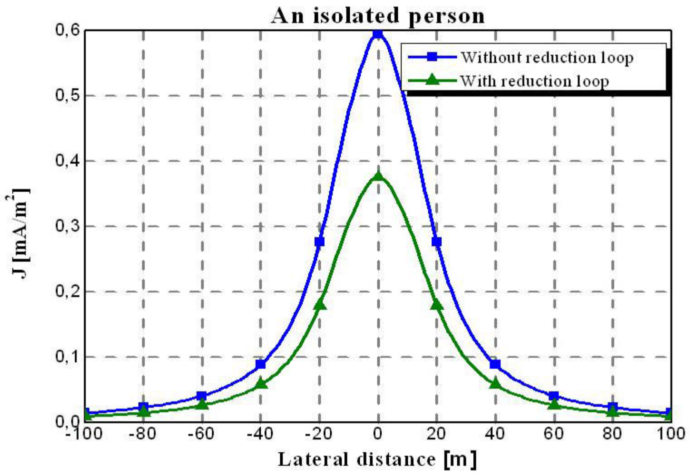

Fig. 10. Induced current density with and without reduction loop

4. Conclusion

As part of this paper, I presented the diagnosis and control of electromagnetic pollution in the vicinity of high-voltage overhead lines to establish the exposure levels of workers in the various tasks at the level of electrical substations. Therefore, workers in and around electrical installations should be informed and sensitized of the potential risks of electromagnetic fields to take the necessary protective measures against exposure to these fields. For example, a safety program could be established to protect maintenance personnel inside substations when performing repairs on line phases often with inductive and capacitive crosstalk coupling.

The highest calculated internal currents caused by electric fields are higher than the currents caused by magnetic fields. This result is fortunate since it is generally easier to protect from electric fields than magnetic fields.

It is noticed that the maximum calculated induced current densities are clearly below the ICNIRP standard guidelines (10 mA/m^2) that may produce any significant biological effects. It should be noticed that these induced current densities from short-term exposure (few hours) may cause minor transient effects on health but long term exposures may cause dangerous effects.

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