Human Exposure to Outdoor PLC System

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Abstract— In this paper, human exposure to a simple outdoor PLC system is assessed. An electric field irradiated by the PLC configuration is calculated using the wire antenna model. For the frequency range from 1 to 10 MHz the human body is represented by the equivalent thick cylindrical antenna, while in the range from 10–30 MHz a parallelepiped body model is used. The axial current density distribution induced along the body as well as the values of surface and whole body averaged SAR, are calculated and compared with limits defined by relevant international standards.

1. INTRODUCTION

The purpose of Power Line Communications (PLC) system is to ensure necessary communication means via existed power line network and electrical installations in houses and buildings. A serious shortcoming of this new technology is related to electromagnetic interference (EMI) problems, as overhead power lines at the PLC frequency range (1 MHz to 30 MHz) act as transmitting or receiving antennas, respectively.

There are significant number of papers dealing with different models for accurate EMC analysis of the PLC systems and their influence to radio and telecommunications equipment [1–4].

On the other hand, human exposure to the PLC electromagnetic radiation is almost entirely neglected EMC aspect of the PLC technology although the human body, when exposed to electromagnetic radiation, behaves as a receiving antenna in this frequency region.

In this paper, human exposure to a simple outdoor PLC system is assessed. An electric field irradiated by the PLC configuration is calculated using the accurate wire antenna model presented in [5]. In order to estimate effects of the PLC electromagnetic radiation on the humans, two simple body models are used.

For the frequency range from 1 to 10 MHz the human body is represented by the equivalent thick cylindrical antenna in order to calculate the axial current density distribution induced along the body. The values of the induced surface and whole body averaged SAR are, on the other hand, obtained in the frequency range from 10 to 30 MHz using parallelepiped body model. Obtained results are compared to the exposure limits proposed by ICNIRP [6, 7].

2. ANTENNA MODEL OF A SIMPLE PLC SYSTEM

The geometry of a simple PLC system analyzed within the scope of this paper is shown in Fig. 1. The system consists of two conductors placed in parallel above each other at the distance d. The conductors are suspended between two poles of equal height, thus heaving the shape of the catenary.

The geometry of a catenary is fully represented by such parameters as the distance between the points of suspension, L, the sag of the conductor, s, and the height of the suspension point, h, as shown in Fig. 1. The imperfectly conducting ground is characterized with the electrical permeability ε_r and conductivity σ, respectively. The conductors are modelled as thin wire antennas excited by the voltage generator V_g at one end, and terminated by the load impedance Z_L at the other end.

The current distribution over the multiple wires of arbitrary shape is governed by the set of coupled integro-differencial equations of the Pocklington type [5]. The influence of the lossy ground is taken into account by the Fresnel reflection coefficient.

Governing set of integral equations is numerically solved using the Galerkin-Bubnov scheme of the Boundary Element Method.

Once the equivalent current distribution over the wires is obtained, the values of the radiated electric and magnetic field at arbitrary point are readily obtained.

3. PARALLELEPIPED MODEL OF THE HUMAN BODY

The exposure of humans to RF electromagnetic radiation is quantified by Specific Absorption Rate (SAR). SAR is defined as the mass average rate of energy absorption in tissue:

$$SAR = \frac{dP}{dm} = \frac{d}{dm}\frac{dW}{dt} = \frac{d}{dt}\frac{dW}{dm} = \frac{d}{dt}\frac{dW}{\rho dV} \tag{1}$$

and it is expressed in W/kg.

If the human body is illuminated by the plane wave, SAR induced on the surface of the human body could be calculated analytically by following formula [8]:

$$SAR_{surf} = \frac{\sigma}{\rho}\frac{\mu\omega}{\sqrt{\sigma^2+\varepsilon^2\omega^2}}\left(1+\gamma_{pw}\right)^2\frac{\left|E^{inc}\right|^2}{Z_0^2} \tag{2}$$

where E^{inc} is root-mean-square value of the incident electric field, while γ_{pw} stands for simplified plane wave reflection coefficient given by:

$$\gamma_{pw} = \frac{2\left|\sqrt{\varepsilon_{eff}}\right|}{\left|\sqrt{\varepsilon_{eff}}+\sqrt{\varepsilon_0}\right|} - 1 \tag{3}$$

If the human body is approximated by the parallelepiped with dimensions: 180 cm×40 cm×20 cm (Figure 2), whole body average SAR induced inside the human body is given by [8]:

$$SAR_{WB} = \frac{1}{HD}\int_0^H\int_0^D SAR_{surf}e^{-\frac{2x}{\delta_{skin}}}dxdz = \frac{\delta_{skin}}{2D}\left(1-e^{-\frac{2D}{\delta_{skin}}}\right)SAR_{surf} \tag{4}$$

where δ_{skin} is skin depth defined by:

$$\delta_{skin} = \sqrt{\frac{2}{\omega\mu\sigma}}. \tag{5}$$

4. CYLINDRICAL MODEL OF A HUMAN BODY

The human body standing on the ground and exposed to electromagnetic radiation at the PLC frequencies can be represented by the conducting cylinder of the full length L and radius a, as it is shown in Figure 3.

The current distribution along the cylinder representing the human body can be obtained by solving the corresponding thick wire integral equation of the Pocklington type [8]:

$$E_z^{inc} = -\frac{1}{j4\pi\omega\,\varepsilon_0}\int_{-L}^{L}\left[\frac{\partial^2}{\partial z^2}+k^2\right]g_E(z,z')I(z')dz' + Z_L(z)I(z) \tag{6}$$

For the RF range of frequencies the load impedance Z_L is given by [8]:

$$Z_L(z) = \frac{1}{a^2\pi\sigma}\left(\frac{ka}{2}\right)\frac{J_0(j^{-1/2}ka)}{J_1(j^{-1/2ka})} + Z_c \tag{7}$$

and the corresponding induced current density is readily obtained using the following expression [8]:

$$J_z(\rho,z) = \frac{I(z)}{a^2\pi}\left(\frac{ka}{2}\right)\frac{J_0(j^{-1/2}k\rho)}{J_1(j^{-1/2}ka)}. \tag{8}$$

5. NUMERICAL RESULTS

The computational examples are related to the simple PLC circuit shown in Figure 1. The distance between the poles is $L = 200$ m, with the radii of wires $a = 6.35$ mm. The wires are suspended on the poles at heights $h_1 = 10$ m, and $h_2 = 11$ m above the ground, respectively. The sag of the conductor is assumed to be $s = 2$ m and ground parameters are $\varepsilon_r = 13$ and $\sigma = 0.005$ S/m. The impressed power is 1 mW (average power required for the PLC system operation) and operating frequency is changed from 1 MHz to 30 MHz. The value of the terminating load Z_L is 50 Ω.

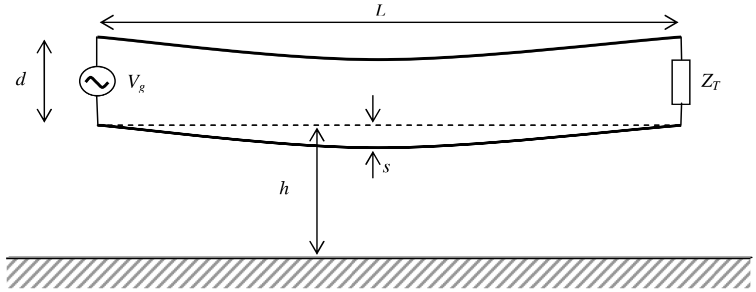

Figure 1: Simple outdoor PLC circuit.

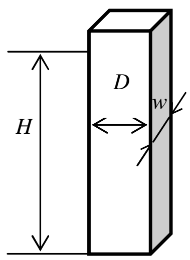

Figure 2: Parallelepiped body model.

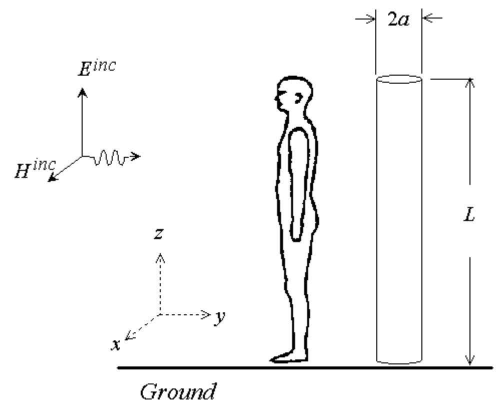

Figure 3: Cylindrical body model.

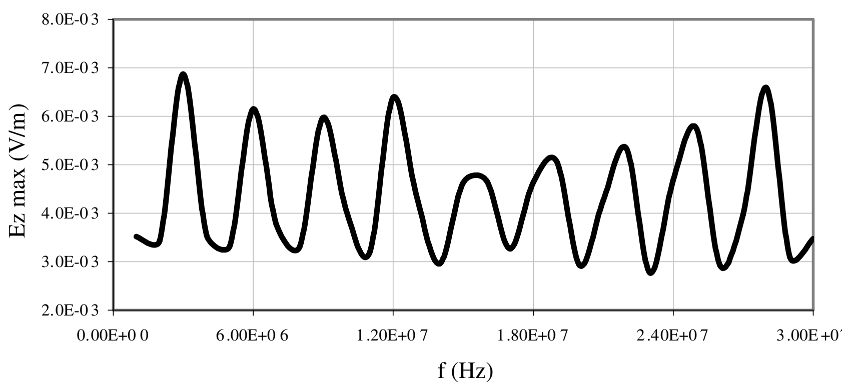

Figure 4: Maximal value of E_z component below the conductor ($z = 1.75\,\mathrm{m}$).

The maximum values of the z component of the radiated electric field for the worst case scenario (person standing directly under the power lines) for the frequency range from 1 MHz to 30 MHz and are calculated and shown in Figure 4.

Thus obtained values of the incident electric field are then used as an input data for the calculation of the induced current densities and SAR inside the human body.

First, the induced current distributions along the human body are calculated for frequency range from 1 MHz to 10 MHz with frequency step of 1 MHz using the cylindrical model of the human body. Obtained current distribution for the frequency $f = 4\,\mathrm{MHz}$ is shown in Figure 5. It is obvious from the picture that highest level of current is induced at the feet (connection with ground) while the current induced at the top of the head is equal to zero due to the applied boundary condition.

Furthermore, for the frequencies up to 10 MHz corresponding current densities inside human body are calculated using Equations (7) and (8) and compared with basic restrictions defined by ICNIRP [6]. The obtained results are shown in Table 1.

According to the ICNIRP for the case of simultaneous exposure to fields of different frequencies these exposures are additive in their effects. For the frequencies up to 10 MHz induced current

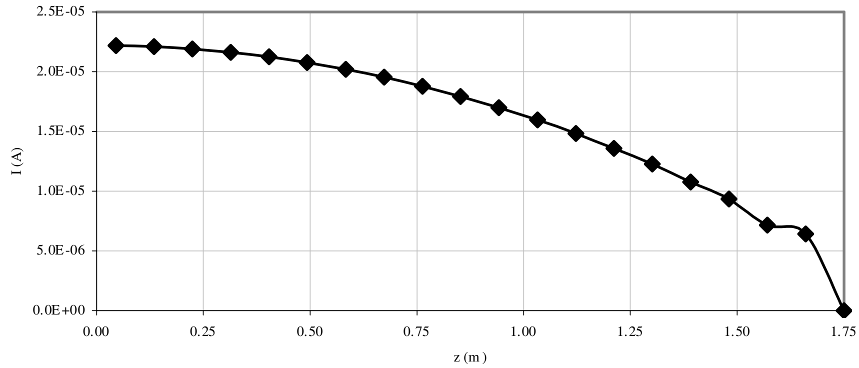

Figure 5: Current density induced along the body ($f = 4\,\mathrm{MHz}$).

Table 1: Maximum values of the induced current density inside the human body compared to the basic restrictions.

f [MHz]	$I_{\max}$ [A]	$J_{\max}$ [A/m^2]	$J_{\max}/J_{ref}$ workers	$J_{\max}/J_{ref}$ public
2	2.77E-06	4.60E-05	1.63E-06	8.13E-06
4	2.22E-05	3.74E-04	6.62E-06	3.31E-05
6	1.59E-05	2.73E-04	3.22E-06	1.61E-05
8	4.45E-06	7.78E-05	6.88E-07	3.44E-06
10	4.22E-06	7.50E-05	5.30E-07	2.65E-06

Table 2: Induced values of SAR inside the body.

f [MHz]	SAR_{surf} [nW/kg]	SAR_{WB} [nW/kg]
5	0.0119	0.0068
10	0.0347	0.0162
15	0.0668	0.0272

f [MHz]	SAR_{surf} [nW/kg]	SAR_{WB} [nW/kg]
20	0.0352	0.0129
25	0.1676	0.0560
30	0.0727	0.0225

$SAR_L = 0.4\,\mathrm{W/kg}$ (workers), $0.08\,\mathrm{W/kg}$ (public) [5].

densities should be added according to [6]:

$$\sum_{i=1\,\mathrm{Hz}}^{10\,\mathrm{MHz}} \frac{J_i}{J_{L,i}} = 1.31 \cdot 10^{-4} \ll 1$$

It is obvious that current densities levels induced inside human body due to radiation of the outdoor PLC system are for the couple orders of magnitude under the limits proposed by the international standards.

Next, based on the parallelepiped model of the human body induced values of surface SAR and whole body average SAR are calculated using Equations (1) and (4). Again, the previously calculated maximum values of the radiated electric field from the PLC system are used as input values for the incident field.

Obtained results are shown in Table 2. Compared to the basic restrictions ($SAR_L = 0.4\,\mathrm{W/kg}$ for workers, $0.08\,\mathrm{W/kg}$ for general public) induced levels are obviously insignificant (8 orders of magnitude smaller!).

Finally, the SAR values for all frequencies are added in order to assess the cumulative effect for the public population:

$$\sum_{i=1\,\mathrm{MHz}}^{30\,\mathrm{MHz}} \frac{SAR_i}{SAR_L} = 8.93 \cdot 10^{-9} \ll 1$$

The obtained results clearly show that heating effect due to the electromagnetic radiation of the outdoor PLC system is negligible.

6. CONCLUSION

In the scope of this paper, the originally developed wire antenna model, taking into account the conductor sag, is used for calculation of the spatial distributions of the radiated electric field in the frequency range from 1 to 30 MHz. Maximum levels of the calculated electric fields represent the worst case scenario incident values for the assessment of the human exposure to a simple outdoor PLC system electromagnetic radiation.

For the frequency range from 1 to 10 MHz the human body is represented by the equivalent thick cylindrical antenna, while in the range from 10 to 30 MHz the parallelepiped body model is used. The axial current density distributions induced along the body are calculated for a number of frequencies and some illustrative numerical results have been presented. Also, the assessment of both the surface and whole the body averaged SAR has been undertaken. The obtained values of both the current density and SAR stay well below the exposure limits proposed by ICNIRP.

However, if the PLC should become widely applied technology, the question about cumulative effects of the multiple signals should be raised.

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