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POSTPROCESSING OF THE HUMAN BODY RESPONSE TO TRANSIENT ELECTROMAGNETIC FIELDS

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Abstract—The post-processing of human exposure to a transient electromagnetic fields is presented in the paper. The mathematical model is based on the cylindrical representation of the human body and the corresponding space-time Hallen integral equation. The Hallen integral equation is solved via the Galerkin-Bubnov scheme of the indirect boundary element method and the equivalent space-time current distribution along the cylindrical body model is obtained. The transient current flowing through the human body is postprocessed in terms of certain measures of quantifying the transient response. These measures arise from circuit theory and they are *average* and *root-mean square* value of time-varying current, *instantaneous power* dissipated in the body and *total absorbed energy* in the body. Illustrative numerical results are presented.

1. INTRODUCTION

Consequences of human exposure to transient electromagnetic fields are induced transient currents and fields inside the body.

The analysis of the human body transient response plays the key-role to understanding the interaction of humans with transient electromagnetic radiation [1–4].

A direct time domain simulation of the human body exposed to a transient electromagnetic field can be performed either using realistic, anatomically based models [1–3] or using the simplified human equivalent antenna model [4].

The finite-difference time-domain (FDTD) method has been used to analyse the coupling of transient electromagnetic fields to anatomically based body models [1].

The human equivalent antenna has been originally proposed for experimental dosimetry, and is valid within the frequency range from 50 Hz to 110 MHz [5]. In addition, the dimensions of the human equivalent antenna are within the thin wire approximation and the effective frequency bandwidth of the pulsed electromagnetic waveforms corresponds to the frequency range of the human equivalent antenna.

The human equivalent antenna model has been based on the Hallen integral equation. A solution of this integral equation using the time domain Galerkin-Bubnov scheme of the boundary element method (GB-BEM) has been presented in [4]. More mathematical details regarding the several applications of GB-BEM can be found in [6–8].

This paper deals with an extension of the work reported in [4], proposing some convenient measures for the analysis of the body transient response.

Further to the specific absorption (SA) concept for quantifying transient exposures, commonly used within the bioelectromagnetic community [1], this paper suggests some additional measures of the the body transient response in terms of: *average* and *root-mean square* value a of time-varying current, *instantaneous power* dissipated in the body and *total absorbed energy* by the body. It is worth noting that in [1] and [3] the total energy absorbed by the corresponding body model has been expressed in terms of fields, while the analysis presented in this paper uses the circuit theory representations.

The space time dependent current along the cylinder representing the human body is governed by the Hallen integral equation [4].

Once determining the transient response of the human body one can readily calculate a distribution of the average and root mean square values of the space-time varying current flowing through the body as a measure of the transient behaviour of the induced current.

Electromagnetic energy absorbed by the body can be quantified using the additional circuit-theory quantities in terms of instantaneous power and total absorbed energy.

It is worth noting that the main feature of the proposed formulation, when compared to more complex realistic models, is its simplicity and efficiency in getting the rapid estimation of the physical phenomena.

A number of illustrative numerical results obtained for the case of Gaussian pulse, step function, and electromagnetic pulse (EMP) is presented in the paper.

2. TIME DOMAIN MODEL OF THE HUMAN BODY

The time domain analysis of the transient electromagnetic field that illuminates the well-grounded human body standing vertically on the perfectly conducting ground, as shown in Fig. 1, is based on a cylindrical representation of the body, in accordance with the human equivalent antenna concept [4]. Technical details of the human equivalent antenna are available in [5].

The dimensions of the human equivalent antenna ($L = 1.8\,\mathrm{m}$, $a = 5\,\mathrm{cm}$) are within the thin wire approximation and the effective bandwidth of the EMP frequency spectrum is 5 MHz. This bandwidth

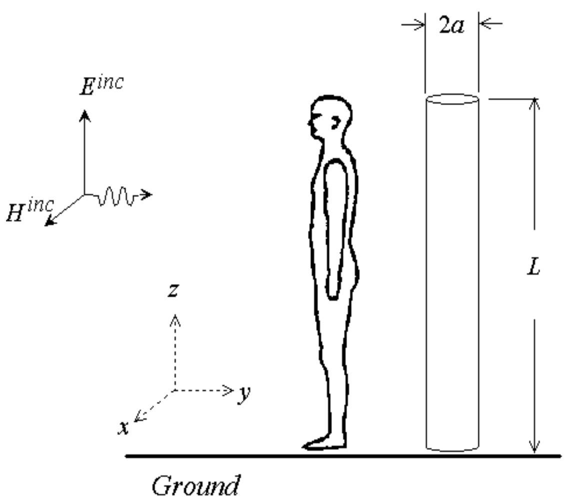

Figure 1. Cylindrical model of the human body exposed to a vertically polarized transient field.

is also within the frequency range of the human equivalent antenna.

The space-time dependent current along the equivalent cylinder representing the human body is governed by the time domain Hallen integral equation. This integral equation can be derived enforcing the condition for the total tangential electric field component at the wire surface, and taking into account the thin wire approximation. Performing some straightforward mathematical manipulation first yields the following space-time Pocklington integro-differential equation [4]:

$$-\varepsilon\frac{\partial E_z^{inc}}{\partial t} = \left[\frac{\partial^2}{\partial z^2} - \frac{1}{c}\frac{\partial^2}{\partial t^2}\right]\int_0^L \frac{i(z', t - R/c)}{4\pi R}dz' - R_L\frac{i(z,t)}{\partial t} \tag{1}$$

where $i(z', t - R/c)$ is the unknown current to be determined, E_z^{inc} is the incident field, c is the velocity of light, R is the distance from the source point in the cylinder axis to the observation point at the cylinder surface, and R_L is the resistance per unit length of the antenna length derived in [4] and given by:

$$R_L = \frac{1}{a^2\pi\sigma} \tag{2}$$

The conductivity σ of the human body taken into account through the resistive loading per unit length of the cylinder is assumed to be 0.5 S/m (conductivity at 60 Hz) since the predominant component of the induced transient current are at ELF frequencies.

Finally, performing a time domain integration of Pocklington Equation (1) results in the corresponding Hallen integral equation [4]:

$$\int_0^L \frac{i(z', t-R/c)}{4\pi R}dz' = F_0\left(t - \frac{z}{c}\right) + F_L\left(t - \frac{L-z}{c}\right) + \frac{1}{2Z_0}\int_0^L E_z^{inc}\left(z', t - \frac{|z-z'|}{c}\right)dz' - \frac{1}{2Z_0}\int_0^L Z_L(z')i\left(z', t - \frac{|z-z'|}{c}\right)dz' \tag{3}$$

where Z_0 is the wave impedance of a free space and the unknown signals $F_0(t)$ and $F_L(t)$ are related with the multiple reflections of the current wave from the wire ends.

Transient current induced in the human body due to any transient field can be obtained by solving the time domain Hallen integral Equation (3) via the space-time domain Galerkin-Bubnov scheme of the boundary element method GB-BEM.

3. MEASURE OF THE TRANSIENT RESPONSE

Once obtaining the transient current flowing through the human body it is possible to calculate certain parameters providing a measure of this body transient response.

The convenient parameters evaluating the human body transient response, arising from the basic theory of electric circuits, suggested in this work, are: the spatial distribution of *average* and *rms* values of a space-time varying current induced in the body, *instantaneous power* dissipated in the body and *total absorbed energy* in the body.

3.1. Average Value of the Transient Current

The average value of the transient current is associated with a DC component in the spectrum of a particular transient waveform. The average value of a time varying current $i(t)$ is defined as follows:

$$I_{av} = \frac{1}{T_0} \int_0^{T_0} i(t)dt \tag{4}$$

where T_0 is the time interval of interest.

The distribution of average values of current is simply given by:

$$I_{av}(x) = \frac{1}{T_0} \int_0^{T_0} i(x,t)dt \tag{5}$$

Obviously, for any waveform having approximately equal area above and below abscissa the average value tends to be equal to zero. Therefore, from this parameter one can obtain a quick estimation of the character of the given transient waveform properties.

When the space-time varying current along the cylinder at each space node z_i and time instant t_k is determined by solving the integral Equation (3), the *average value* of this current can be computed from the following relation:

$$I_{av} = \frac{1}{T_0} \sum_{k=1}^{N_t} \int_{t_k}^{t_{k+1}} \left(\{T\}^T \{I\}\right)_i dt \tag{6}$$

Performing of a straight-forward integration yields:

$$I_{av}|_{z_i} = \frac{\Delta t}{2T_0} \sum_{k=1}^{N_t} \left[(I_i^k) + (I_i^{k+1})\right] \tag{7}$$

where $\{T\}$ is the vector containing the time domain linear shape functions, and $\{I\}$ denotes the vector containing time-dependent values of current.

3.2. Root-Mean-Square Value of the Transient Current

A time varying current delivers an average power to resistive load. The amount of delivered power strongly depends on the particular waveform.

A measure of comparing the power delivered by different waveforms is the root-mean-square (rms) or effective value of a transient current. The rms value of a time-varying current is a constant that is equal to the direct current value that would deliver the same average power to a given resistance R_L and that would produce the same heating effect on R_L.

Instantaneous power delivered to a resistance R_L by a transient current $i(t)$ is:

$$p(t) = R_L i^2(t) \tag{8}$$

while the corresponding average power P_{av} is determined by the integral relation:

$$P_{av} = \frac{1}{T_0}\int_0^{T_0} p(t)dt = \frac{1}{T_0}\int_0^{T_0} R_L i^2(t)dt = R_L I_{rms}^2 \tag{9}$$

from which the rms current is then:

$$I_{rms} = \sqrt{\frac{1}{T_0}\int_0^{T_0} i^2(t)dt} \tag{10}$$

Consequently, the spatial distribution of the rms values of the space time current along the cylinder is given by:

$$I_{rms}(x) = \sqrt{\frac{1}{T_0}\int_0^{T_0} i^2(x,t)dt} \tag{11}$$

When the current along the wire at each node and time instant is determined, the rms value of the wire current can be computed from the following relation:

$$I_{rms} = \sqrt{\frac{1}{T_0}\sum_{k=1}^{N_t}\int_{t_k}^{t_{k+1}} \left(\{T\}^T\{I\}\right)_i^2 dt} \tag{12}$$

and by performing a straight-forward integration it follows:

$$I_{rms}|_{z_i} = \sqrt{\frac{\Delta t}{3T_0} \sum_{k=1}^{N_i} \left[(I_i^k)^2 + I_i^k I_i^{k+1} + (I_i^{k+1})^2 \right]} \tag{13}$$

Basically, the *rms* value of the transient current flowing through the body appears to be a more interesting parameter from the bioelectromagnetics point of view as it is, by its definition, directly associated with the thermal effect of a time varying current flowing through a lossy material.

3.3. Instantaneous Power

Instantaneous power delivered to a certain resistance R_L, or to some resistive medium having equivalent resistance R_L by a transient current is defined by a relation (8). On the other hand, the absorbed power in the human body expressed by the field quantities is equivalent to the concept of instantaneous power arising from the circuit theory and it is usually defined as a volume integral over power density, i.e.:

$$P_{rad}(t) = \int_V \sigma \left| \vec{E}(\vec{r}, t) \right|^2 dV = \int_V \frac{\left| \vec{J}(\vec{r}, t) \right|^2}{\sigma} dV \tag{14}$$

Assuming the transient current to be approximately constant over the cylinder cross-section yields:

$$i(z, t) = J(z, t) \cdot S \tag{15}$$

where $J(z, t)$ denotes the current density along the cylinder, and $S = a^2\pi$ is the cylinder cross-section.

The instantaneous power can be obtained by spatially integrating the squared space-time varying current:

$$P_{rad}(t) = \frac{1}{\sigma \cdot S} \int_0^L i^2(z, t) dz \tag{16}$$

Knowing the transient induced current the instantaneous power can be represented by the following relation:

$$P_{rad}(t) = \frac{1}{\sigma \cdot S} \sum_{i=1}^{M} \int_{\Delta l_i}^{L} \left(\{f\}_i^T \{I\}_i \right)^2 dz \tag{17}$$

where $\{f\}$ denotes the vector containing linear interpolation functions and $\{I\}$ stands for the induced current coefficients.

Performing of straightforward integration yields:

$$P_{rad}|_{t_k} = \frac{1}{\sigma \cdot S} \frac{\Delta z}{3} \sum_{i=1}^{M} \left[(I_i^k)^2 + I_i^k I_{i+1}^k + (I_{i+1}^k)^2 \right] \tag{18}$$

where M denotes the total number of spatial segments along the cylinder.

3.4. Total Absorbed Energy

In accordance to the circuit theory, the total absorbed energy in the resistance or resistive material can be obtained by temporally integrating the instantaneous power:

$$W_{tot}(t) = \int_0^t P_{rad}(t) dt \tag{19}$$

Using the numerical representation of the instantaneous power it follows:

$$W_{tot}(t) = \sum_{k=1}^{N_t} \int_{t_k}^{t_k+\Delta t} \{T\}_k^T \{P\}_k dt \tag{20}$$

and performing of straightforward integration gives:

$$W_{tot}|_{t_k} = \frac{\Delta t}{2} \sum_{k+1}^{N_t} \left[\left(P^k + P^{k+1} \right) \right] \tag{21}$$

where P^k and P^{k+1} stands for a discrete value of instantaneous power dissipated in the resistive medium at a time instant t_k and t_{k+1}, respectively.

4. COMPUTATIONAL EXAMPLES

There are three types of transient incident fields considered in this work: Gaussian pulse, temporal step function and standard electromagnetic pulse (EMP) waveform.

All incident fields are assumed to be vertically polarized in order to analyse the maximum coupling to the body. Figure 2 shows

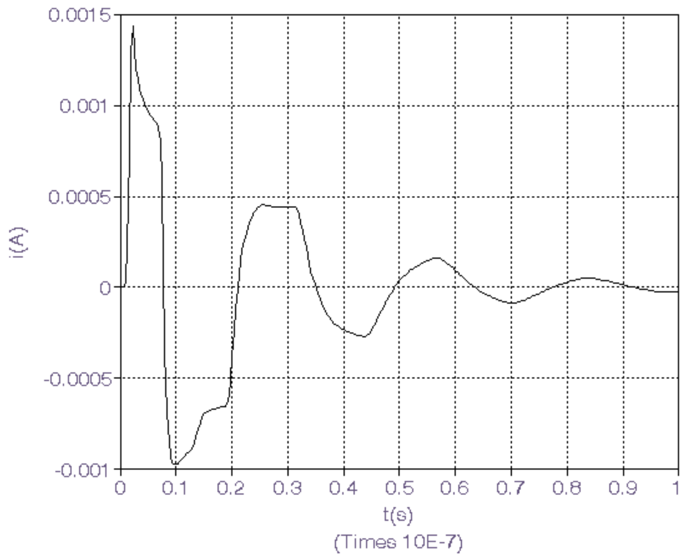

Figure 2. Transient current induced in the feet due to the Gaussian pulse exposure.

the transient current induced in the feet due to the Gaussian pulse exposure:

$$E_z^{inc}(t) = E_0 e^{-g^2(t-t_0)^2} \tag{22}$$

with following parameters: $E_0 = 1\,\mathrm{V/m}$, $g = 2 * 10^9\,\mathrm{s}^{-1}$ and $t_0 = 2\,\mathrm{ns}$.

As this pulse is a numerical equivalent of Dirac pulse the obtained transient exposure can be regarded as an impulse response of the human body. Transient response to any other incident waveform then can be obtained by performing a simple convolution [7, 8].

The spatial distribution of the average values of the space-time varying current flowing through the cylindrical body model is shown in Fig 3. For the case of Gaussian pulse this measure seems to be almost useless, as it tends to be zero.

On the contrary, more information regarding the heating effect due to the Gaussian pulse exposure can be obtained from the spatial distribution of the *rms* values of the transient current, shown in Fig 4. What can be observed from Fig 4 is that Gaussian pulse that induces the peak value of current around 1.5 mA in the feet corresponds to the equivalent DC current that is equal to appx. 0.4 mA. In other words, the transient current induced in the feet shown in Fig. 2. would produce the same heating effect as the constant DC current of 0.4 mA.

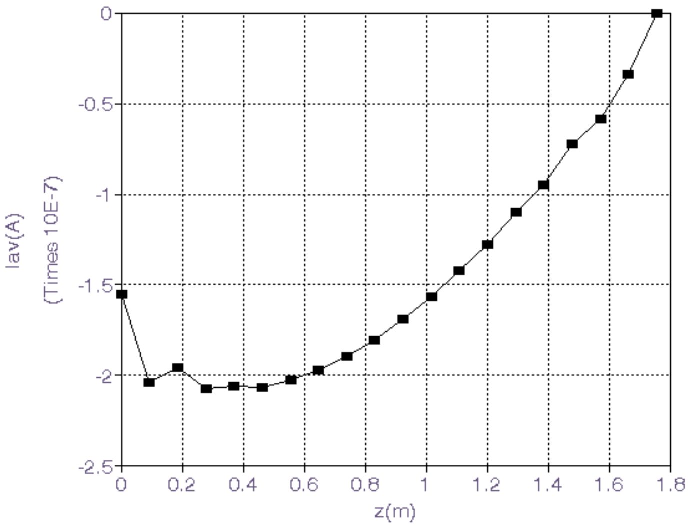

Figure 3. Spatial distribution of average values of the transient current due to the Gaussian pulse exposure.

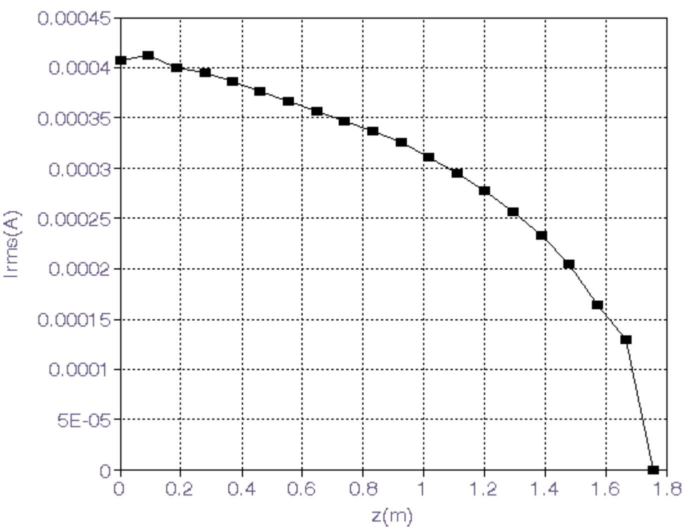

Figure 4. Spatial distribution of average values of the transient current due to the Gaussian pulse exposure.

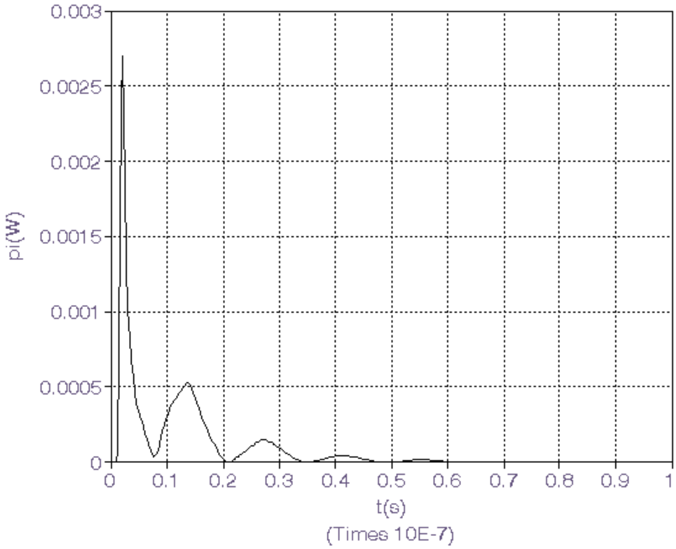

Figure 5. Instantaneous power dissipated within the body due to the Gaussian pulse exposure.

Furthermore, the transient behaviour of the instantaneous power dissipated in the body is shown in Fig. 5. It can be noticed that the power dissipation, with the peak value slightly above 2.5 mW occurs in the early time within the first 50 ns.

The same conclusion can be drawn from the Fig. 6 representing the total energy absorbed in the body versus time. It is clearly visible that body does not absorb any significant amount of energy after first 50 ns.

Therefore, a very little energy is absorbed by the human body exposed to pulsed field. This occurs due to a very limited time duration (up to 100 ns) of the incident pulse for which significant values of current can be induced in the body.

Figure 7 shows the transient current induced in the feet due to the temporal step exposure:

$$E_z^{inc}(t) = u(t) \tag{23}$$

where $u(t)$ denotes the unit step. The first current peak appears to be around 7 mA.

Figures 8 and 9 show the related spatial distribution of the average and *rms* values of current for the case of the unit temporal step excitation, respectively.

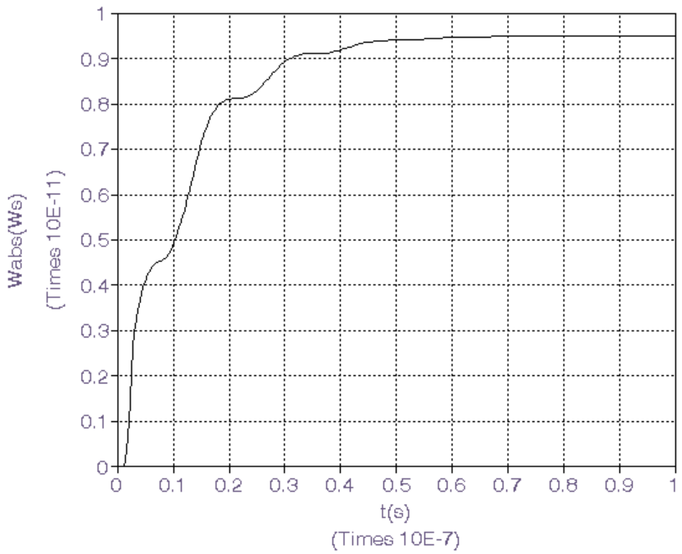

Figure 6. Total energy absorbed in the body due to the Gaussian pulse exposure.

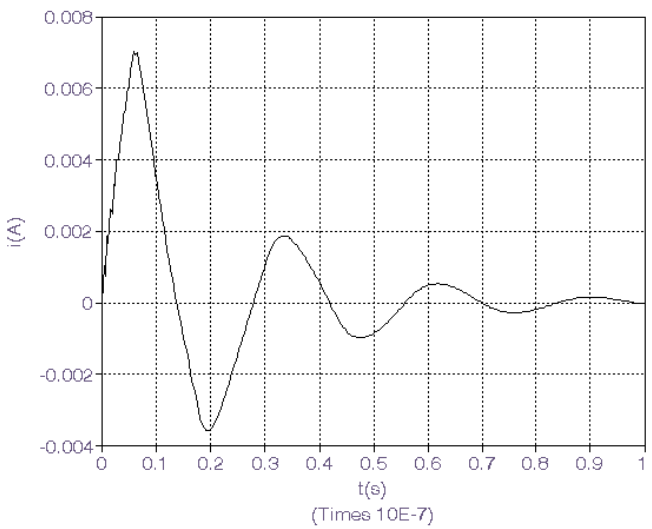

Figure 7. Transient current induced in the feet due to the step function exposure.

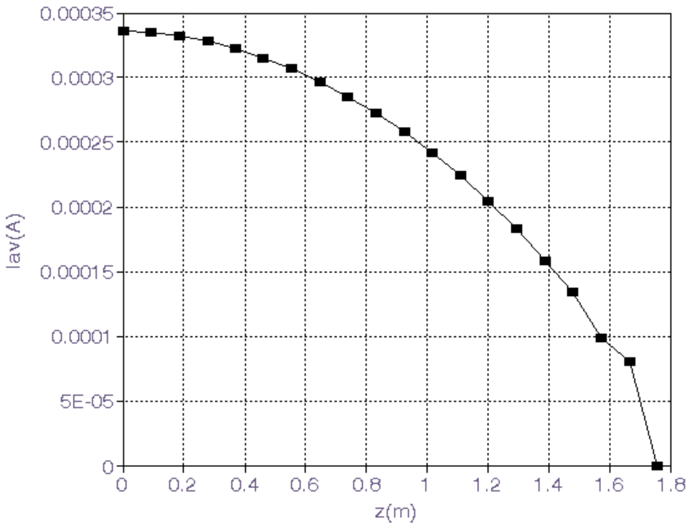

Figure 8. Spatial distribution of average values of the transient current due to the step exposure.

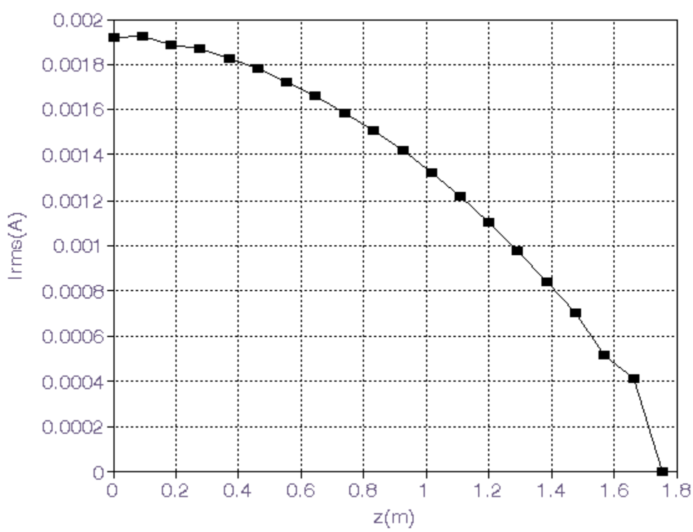

Figure 9. Spatial distribution of *rms* values of the transient current due to the step exposure.

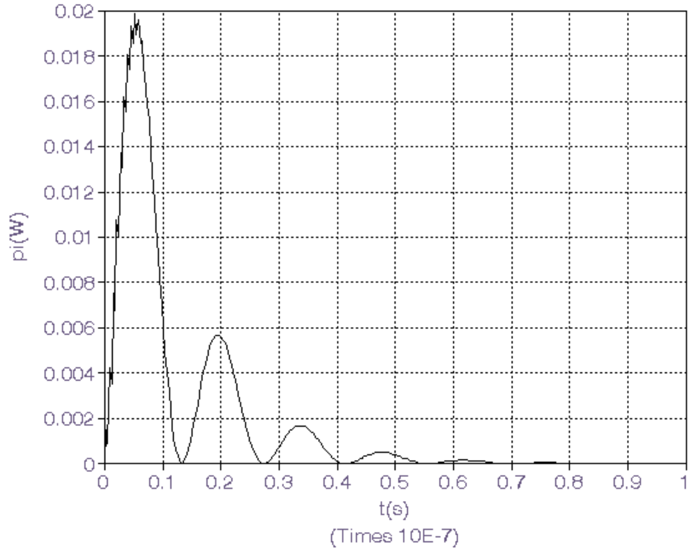

Figure 10. Instantaneous power dissipated within the body due to the step exposure.

In this case the peak value of the current induced in the feet corresponds to the average value of the current equals to approximately 0.34 mA, as it can be seen from Fig. 8.

In addition, the peak value of the current induced in the feet corresponds to the *rms* value of the current equals to approximately 1.9 mA. It is obvious that the average and *rms* values of the transient response to step excitation are significantly higher comparing to the results obtained for the case of Gaussian exposure.

Figure 10 shows the transient behaviour of the transient waveform of the instantaneous power. This transient behaviour is similar to the case of Gaussian pulse, i.e., there is negligible power dissipation in the second half of 100 ns time interval.

However, the peak value of the dissipated power is for the order of magnitude higher, while the absorbed energy is about twice higher than in previous case of the Gaussian pulse exposure.

Fig. 12 shows the transient current induced in the feet due to the standard double-exponential electromagnetic pulse (EMP) waveform:

$$E_z^{inc}(t) = E_0(e^{-at} - e^{-bt}) \tag{24}$$

where $E_0 = 1.05\,\mathrm{Vm}^{-1}$, $a = 4 * 10^6\,\mathrm{s}^{-1}$, $b = 4.76 * 10^8\,\mathrm{s}^{-1}$.

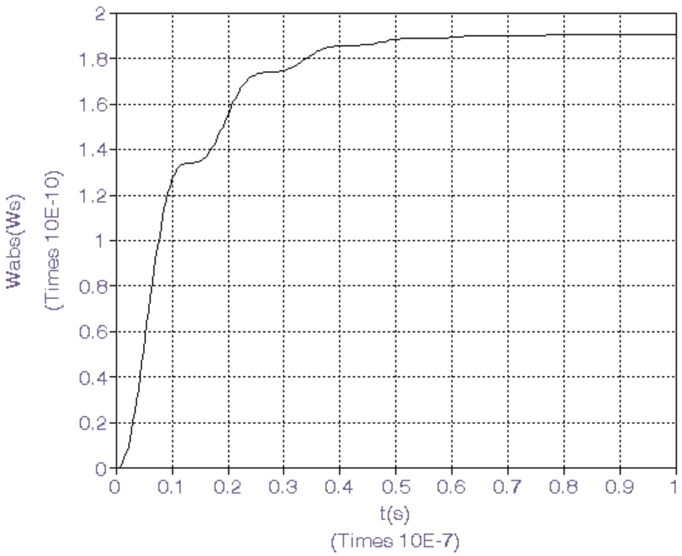

Figure 11. Total energy absorbed in the body due to the step exposure.

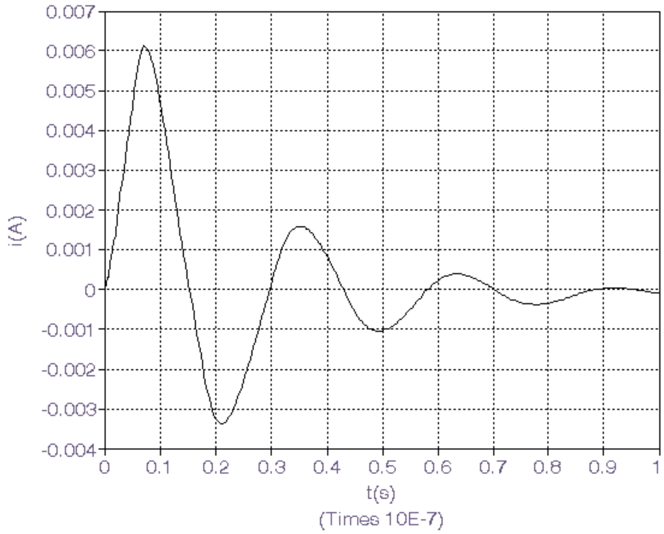

Figure 12. Transient current induced in the feet due to the EMP exposure.

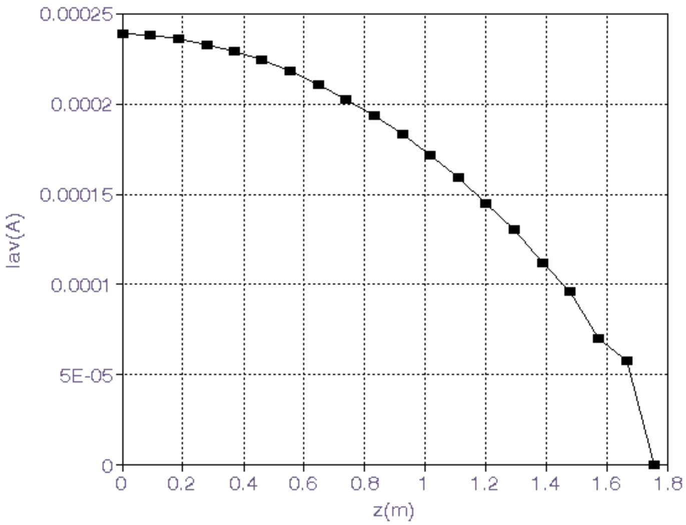

Figure 13. Spatial distribution of average values of the transient current due to the EMP exposure.

Figures 13 and 14 show the related spatial distribution of the average and *rms* values of current for the case of EMP, respectively.

This time the peak value of the current induced in the feet corresponds to the averaged value below 0.25 mA, as it is visible from Fig. 13.

In addition, the peak value of the current induced in the feet corresponds to the *rms* value equals to approximately 1.8 mA. The average and *rms* values of the transient response to EMP exposure are comparable to the step exposure results and they are appreciably higher comparing to the results obtained for the case of the Gaussian pulse exposure.

Figure 15 shows the transient behaviour of the instantaneous power. The transient behaviour is similar to the case of the step exposure though the peak values are slightly lower and the dissipation in the body occurs up to almost 60 ns.

The same conclusion can be drawn for the energy graph shown in Fig. 16.

It is worth noting that very little energy is absorbed by the human body due to an exposure to transient fields of rather limited time duration.

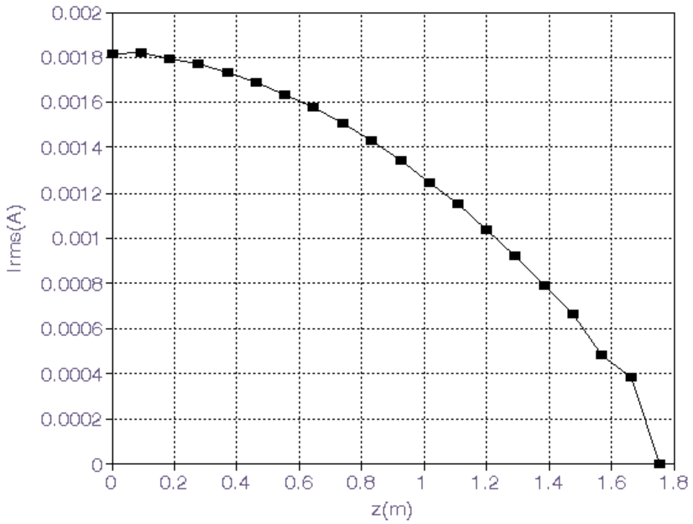

Figure 14. Spatial distribution of *rms* values of the transient current due to the EMP exposure.

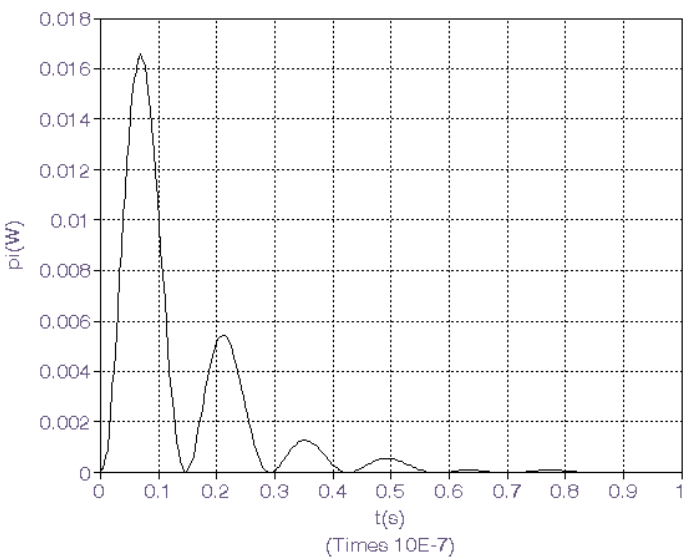

Figure 15. Instantaneous power dissipated within the body due to the EMP exposure.

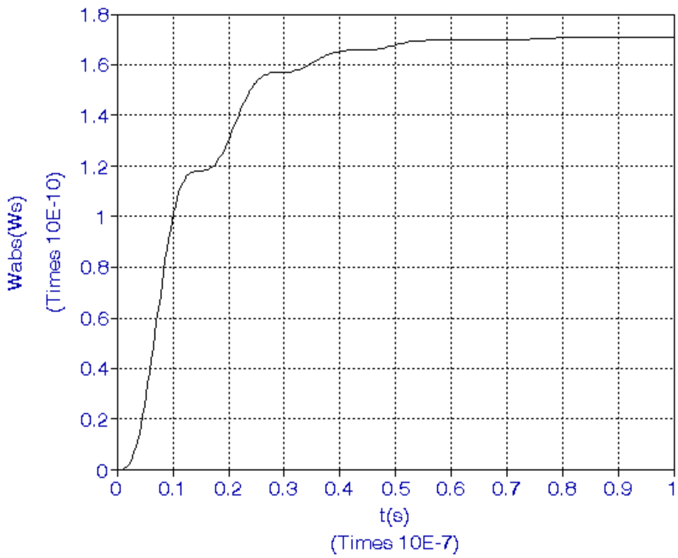

Figure 16. Total energy absorbed in the body due to the EMP exposure.

5. CONCLUSION REMARKS

Various measures for the transient response of the human body are presented in this work. The time domain formulation is based on the human equivalent antenna representation of the human body and the related space-time Hallen integral equation approach. The transient current induced in the human body is obtained by solving the Hallen integral equation via the time domain variant of the Galerkin Bubnov boundary element method (GB-BEM).

Once obtaining the transient induced current it is possible to calculate the measures of the transient response in terms of the average and root-mean-square value of space-time varying current, instantaneous power and absorbed total energy in the body.

It should be pointed out that the principle feature of the proposed model, when compared to some realistic and more accurate body models, is its simplicity and efficiency.

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Electromagnetic Fields, WIT Press, 2003; and an edited book: *Time Domain Techniques in Computational Electromagnetics,* WIT Press, 2003. Professor Poljak is the member of IEEE, reviewer of the IEEE Trans. on Electromagnetic Compatibility, member of Editorial Board of the journal Engineering analysis with Boundary Elements, and co-chairman of WIT Int. Conference on Computational Methods in Electrical Engineering and Electromagnetics. He is also editor of WIT Press Series Advances in Electrical Engineering and Electromagnetics.