Analysis of Induced Current Density Inside Human Model which Stands on Conductive Ground Layer in Uniform Electric Field

Atsuo Chiba* Member
Katsuo Isaka** Member

The introduction of extremely low frequency electric fields with human body has become an increasingly important subject since potential health hazards due to the electric fields emitted by extremely high-voltage power lines. The health effect of the weak current induced in the human body as a result of the interaction between human body and power frequency electric fields has been investigated. In this paper, the finite element method is applied to the analysis of the current density distributions in the human model which stands with erect position on the conductive ground layer in the uniform electric field, and the characteristics of such internal current density distributions are clarified.

Keywords: induced current density, human model, finite element method, conductive ground layer, uniform electric field

1. Introduction

The health effect of the small currents induced in a human body exposed to the power frequency electric field has been investigated since early 1970s. The introduction of extremely low frequency electric fields with human body has become an increasingly important subject since potential health hazards due to the electric fields emitted by extremely high-voltage power lines. The health effect of the weak current induced in the human body as a result of the interaction between human body and power frequency electric fields has been investigated. Spiegele(1) analyzed the current densities inside the human model using the more accurate block model and an integral equation method, but his results disagree with experimental results mainly due to insufficient partition of the body model in the numerical calculation. Chen et al.(2) reported some results of the induced current densities in a homogeneous body of the realistic shape, but their calculations have not yet been done as to the current densities induced inside the ungrounded human model.

The finite element method is applied to the analysis of the current density distributions in the axisymmetrical human model which placed in the uniform electric field between the parallel circular plate electrodes(3)(4). A.B.Maddy et al.(5) analyzed the current density distributions inside the human model which stand on the ground soil layer, but their analytical results are not calculated in consideration of the resistivity of the conductive ground layer. Dawson et al.(6) analyzed the induced current densities inside the human model of the 3-dimensional shape in detail, but their internal current densities not calculated in consideration of the conductive ground layer.

In this paper, the finite element method is applied to the analysis of the current density distributions in the human model which stands in erect position on the conductive ground layer in the uniform electric field, and the characteristics of such internal current density distributions are clarified.

2. Analysis by the Finite Element Method

2.1 Basic Equations Considering a medium whose electrical characteristics can be described by the conductivity $\sigma$ and permittivity $\varepsilon$. If the electric field is E, the current density is J, and the space charge density is q, then the following equations hold.

$$\text{div}(\varepsilon E) = q \quad \cdots \quad (1)$$

$$\text{div} J = \text{div}(\sigma E) = -\frac{\partial q}{\partial t} \quad \cdots \quad (2)$$

If $\varepsilon$ is constant in time, from Eqs.(1) and (2) we obtain the following basic equation for the electrostatic field problem.

$$\text{div} \left( \sigma \cdot \text{grad} \phi + \frac{\partial}{\partial t} (\varepsilon \cdot \text{grad} \phi) \right) = 0 \quad \cdots \quad (3)$$

Where E=grad $\phi$ ($\phi$ is the potential).

The finite element method is a method for solving this problem by replacing it with the problem of determining the potential $\phi$ that minimizes the functional $\chi$.

$$\chi = \int \frac{\sigma}{2} \text{grad} \phi^2 \, dv + \frac{\partial}{\partial t} \int \frac{\varepsilon}{2} \text{grad} \phi^2 \, dv \quad \cdots \quad (4)$$

Here, $v$ expresses the region under analysis. When AC voltage with angular frequency $\omega$ is the object, Eq.(4) can be transformed as follows by using the complex potential $\phi = e^{j\omega}$.

$$\chi = \int \frac{1}{2}(\sigma + j\omega\varepsilon) \text{grad} \phi^2 \, dv \quad \cdots \quad (5)$$

Where $\omega$ is equal to 2$\pi$f and f is the frequency. When the three-dimensional region has symmetry about the z axis, the following equation is obtained by treating Eq. (5) as an axial symmetry problem:

$$\chi = 2\pi \int \left( \frac{1}{2}(\sigma + j\omega\varepsilon) \left[ \left( \frac{\partial \phi}{\partial r} \right)^2 + \left( \frac{\partial \phi}{\partial z} \right)^2 \right] r \, drdz \quad \cdots \quad (6)$$

Where $r$ expresses the horizontal direction of the coordinates.
and z the vertical direction. In this paper, the complex node potentials that minimizing Eq.(6) are determined by using the isoparametric elements (axisymmetrical curvilinear quadrilateral elements) in the partition of the problem region. These elements have the advantages that they are suitable for the approximation of the complex boundary and that the potentials inside the region under analysis can be determined accurately with the small number of elements.

### 2.2 Calculative Model
The electric field over flat ground under the lines is vertical and uniform near the ground level. Therefore, the human model is placed in a uniform field between the parallel circular plate electrodes (plate diameter: 30m) as shown in Fig.1. The bottom of the ground layer is solidly grounded as shown in Fig.1. The realistic ground is in the complex configuration, and composed of many conductive layers. However, we consider, as the first step of the research, the case that the uniform conductive layer having the different resistivity and thickness exists on the perfect conductor. The voltages induced in the human model in erect position on the conductive ground layer were analyzed in the case that the thicknesses of the conductive ground layer are 2 and 5m\(^3\). In this paper, the current densities induced inside the human model which stands in erect position on the conductive ground layer are calculated by using the mentioned thicknesses from 2 to 5m. This model shown in Fig.2 stands in erect position on the center of the conductive ground layer. With the energized upper electrode at 10 kV, the unperturbed electric field in the air is about 1 kV/m.

The axisymmetrical human model used in the analysis is shown in Fig.2. It has a height of 1.7m and a trunk diameter of 0.27m.

The region under discussion is divided into 378 curvilinear quadrilateral elements of axisymmetry as shown in Fig.3(a). The number of nodes in the division pattern is 1217. Fig.3(b) illustrate the enlarged division pattern inside and in the vicinity of the human model. When the axisymmetrical human model shown in Fig.2 is grounded, the region under discussion is divided into 280 curvilinear quadrilateral elements of the axisymmetry as shown in Fig.4. The number of nodes in the division pattern is 909. This division pattern is the same as the Fig.3(a) except the conductive ground layer. Fig.5 shows the comparison between the calculated and measured current densities induced inside the human model. Good agreement between them confirms the validity of this division pattern\(^5\).

### 2.3 The External Field Strengths
Fig.6 shows the characteristics of the external field strengths at the height of 1m above the ground surface for the resistivity of the conductive ground layer. In this figure, the thicknesses d of the conductive ground layer are 2 and 5m. It seen from this figure that the minimum external field strength shows the decrease of 1.36% for the external field strength 1kV/m when the resistivity and the thickness of the conductive ground layer are 100 M\(\Omega\)·m and 5m, respectively. The external field strength of the region under discussion is defined as the unperturbed field that exists without

---

**Fig. 1.** Outline diagram for the calculating model

**Fig. 2.** Configuration of the axisymmetrical human model

**Fig. 3.** Division pattern

**Fig. 4.** Division pattern inside and in the vicinity of the human model
The potential $V_2$ of the ground level is calculated as $0.271 + j1.624$ kV. Since the external field strength, $E_{ext}$, is given as $E_{ext} = (V_1 - V_2)/l$ (see Fig. 7(a)), the calculated result is $0.9729 - j0.1624$ kV/m. That is, the external field strength shows the decrease of only 1.36% of the external field strength of 1 kV/m.

3. Analytical Results

Since we consider the case that the conductive ground layer is made of the insulating material like the marble whose resistivity is from $10^5$ to $10^6$ $\Omega \cdot m$. The resistivity of the conductive ground layer is assumed in the range from 1 to 100 $\Omega \cdot m$.

Fig. 8 shows the characteristics of the current density distributions induced inside the human model in the case that the resistivities of the conductive ground layer are 1, 2, 5, 10, 20, 50 and 100 $\Omega \cdot m$, and its thickness $d$ is 3 m. Here, the induced current density is obtained by averaging the current densities distributed on the horizontal cross section area of the human model. The average induced current density defined in this paper cannot be used for the discussions on the basic restriction of the ICNIRP guideline. It is seen from this figure that the current densities induced inside the human model increase when the resistivity of the conductive ground layer become small. The current densities induced inside the human model become large at the neck or the ankle part which close section areas are small.

When the resistivity of the conductive ground layer increases, the voltage of the human model becomes higher than that of the surface of the ground near the human model. Accordingly, the currents induced in the human model flow through the capacittance between the human model and the ground. As the result, especially, the current densities induced inside the ankle part of the model show an extremely decrease as shown in Table 1.
Fig. 8. Characteristics of the induced current densities in the human model for the resistivities of the conductive ground layer

Table 1. Induced current densities in the human model standing on the conductive ground layer (d=3m)

<table>
<thead>
<tr>
<th>crosssection area (m²)</th>
<th>current density (mA/m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Neck</td>
</tr>
<tr>
<td>Grounded</td>
<td>0.471</td>
</tr>
<tr>
<td>ρ = 1[MΩ·m]</td>
<td>0.476</td>
</tr>
<tr>
<td>(0.02%)</td>
<td>(0.05%)</td>
</tr>
<tr>
<td>ρ = 10[MΩ·m]</td>
<td>0.4636</td>
</tr>
<tr>
<td>(2.83%)</td>
<td>(3.11%)</td>
</tr>
<tr>
<td>ρ = 100[MΩ·m]</td>
<td>0.2816</td>
</tr>
<tr>
<td>(40.85%)</td>
<td>(51.30%)</td>
</tr>
</tbody>
</table>

( ): the decreasing rate of the current density.

In this Table, the heights of the neck, the pelvis and the ankle part are 1.406, 0.870 and 0.095m, respectively.

Fig.9 shows the characteristics of the current density distributions induced inside the human model in the case that the thicknesses of the conductive ground layer d are 2, 3, 4 and 5m, and its resistivity ρ is 10MΩ·m. It is seen from this figure that the current density distributions induced inside the human model are approximately same if the thicknesses d are varied from 2 to 5m.

Fig.10 shows the effect on the resistivities of the conductive ground layer for the induced current densities at the neck, the pelvis and the ankle part of the human model. In this figure, the thickness d of the conductive ground layer is 3m. As seen from this figure, when the resistivity ρ of the conductive ground layer increase, the induced current densities at the neck, the pelvis and the ankle part decrease. When the resistivities of the conductive ground layer change from 1 to 100MΩ·m, the values of the induced current densities at the neck, the pelvis and the ankle part show the decrease of about 43.7%, 56.7% and 81.9%, respectively.

Fig.11 shows the relations between the thicknesses d of the conductive ground layer and the induced current density distributions at the neck part of the human model as the parameter of the resistivities ρ (ρ = 1, 2, 3, 5, 10, 20, 50, 100MΩ·m). It is found from this figure that the induced current densities at the neck part only depend on the resistivity ρ of the conductive ground layer, and for the variety of the thickness d, the values of the induced current densities are approximately constant. When the resistivity ρ of the conductive ground layer increase, the induced current densities at the neck part decrease.

Similarly, Fig.12 shows the relations between the thicknesses d of the conductive ground layer and the induced current density distributions at the ankle part as the parameter of the resistivity ρ. These characteristics of the induced current density distributions are similar tendency to the neck part as shown in Fig.11.

When the current densities induced inside the human model,
standing on the perfect conductor, do not exceed the value of 10 mA/m² given as the ICNIRP guideline, those current densities remain below the ICNIRP basic restriction regardless of resistivities of the conductive ground layer. However, since the human body has the potential to the grounded objects, it is considered that a small discharge will occur when the human body touches the grounded objects.

4. Conclusions

In this case that the resistivities of the ground layer are 125,10,20,50 and 100 MΩ·m, and its thicknesses are 2.3,4 and 5m, the current densities induced inside the human model which stands erect position on the conductive ground layer in the uniform field are discussed. The conclusions are as follows.

(1) The characteristics of the current densities induced inside the human model which stands erect position on the conductive ground layer have been made clear.

(2) The current densities induced inside the human model become high at the narrow sections of the neck and the ankle part. The induced current densities become large when the resistivities of the conductive ground layer decrease.

(3) When the resistivities of the conductive ground layer change from 1 to 100 MΩ·m, the values of the induced current densities at the neck, the pelvis and the ankle part show the decrease of about 43.7%, 56.7% and 81.9%, respectively.

(4) The induced current densities at the neck and the ankle part only depend on the resistivity of the conductive ground layer, and for the various thickness of the conductive ground layer, the values of the induced current densities are approximately constant in the case that the thickness of the conductive ground layer are varied from 2 to 5m.

(Manuscript received Feb. 13, 2004, revised July 26, 2004)

References


Atsuo Chiba (Member) graduated from the Department of Electrical Engineering, Tottori University, in 1970 and became a research assistant in the Department of Electrical Engineering of Yonago National College of Technology and is currently a professor. He is engaged in research on the electrical characteristics of static induction in the human body. He has a D.Eng. degree. He is a member of the Institute of Electronics, Information and Communication Engineers, the Japan Society for Simulation Technology.

Katsuo Isaka (Member) graduated from Hiroshima University in 1996. He completed the M.S course in 1968 and the doctoral course in 1971 in the Engineering Research Division, University of Tokyo. He started work in the Department of Electrical Engineering, The University of Tokushima, in the same year and has been a professor since July 1988. He has a D.Eng. degree. He received a Paper Award of the IEEE Japan in May 1975. He is a member of the static Electricity Society, the Environmental Science Society, and IEEE.