Computation of Electric Field Induced Currents on Biological Bodies Near High Voltage Transmission Lines

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Abstract: In this paper, biological effects of high voltage transmission line electric fields on biological systems especially on a grounded human body standing under a high voltage transmission line have been studied. The distribution of electric field and induced currents on a human body standing underneath a high voltage overhead transmission line has been calculated. Electric field distribution around a three phase 380 kV transmission line has been calculated by using charge simulation method. Induced currents on the human body have been obtained using computed locally enhanced electric field values. Calculated induced currents and current densities are evaluated with respect to safe limits. It has been seen that these currents and current densities are below the "no effect" thresholds.

1. Introduction

AC electric and magnetic fields induce surface charges on biological bodies such as human body and a weak current flows in these bodies. This is one reason why there is a potential for electric and magnetic fields (EMFs) to cause biological effects. Recently, it has been suggested that if there is any harmful effect to health, induced currents may cause this effect.

The principle that AC fields can elicit biological effects via induced electric fields and induced currents has been known since the middle of the 19th century. but it was not until 1979 that Bernhardt [1] used this principle to organize the available data in support of quantitative limits on doses to critical organs. The brain and heart were considered critical target organs because of their functional dependence upon neural cell function. On both theoretical (Faraday's Low of Induction) and experimental grounds, Bernhardt hypothesized that currents induced by fields less than 30 kHz could, by stimulation of the nerves or cardiac system, cause biological responses of health significance.

Bernhardt calculated the "safe" upper-boundary exposure limits based upon the threshold the stimulating neurons of the central nervous system (CNS). A lower "no effect" boundary threshold, below which induced currents would not be expected to have any effect on the CNS or other electrically excitable tissues, was also calculated. This lower limit was estimated from the field strength required to induce currents equal to those generated by electrical processes in the heart and in the brain. Naturally occurring current densities in these organs were estimated to be in the range of 1 to 100 mA/m^2.

A number of national and international organizations have formulated guidelines for the limitation of occupational exposure to electric and magnetic fields (EMFs). These safety guidelines are designed to prevent short-term effects by maintaining bulk-tissue average current densities below 10 mA/m^2.

There are clear hazards posed by induced current densities sufficient to produce disturbances in rhythmic cardiac function, such as extrasystole and ventricular fibrillation. These effects are estimated to occur at current densities above 1000 mA/m^2. This value is 100-fold higher than the current density of 10 mA/m^2 suggested by guideline organizations as an upper-limit dose, and 1000-fold higher than the lower range of current densities (1 mA/m^2) naturally occurring in some tissues [2].

The maximum body current induced by electric field from a transmission line is much greater than the body current or current density induced by the magnetic field. Consequently, induced currents from electric fields are more important than the current induced by the magnetic field [3].

The electric field at the ground level under a high voltage transmission line is approximately uniform and field lines are vertical to the ground plane. In the presence of a human body beneath the high voltage line conductors, due to accumulated surface charges on the human body, the electric field at the ground level is highly perturbed that may reach eight to ten or even more times higher than the uniform (unperturbed) electric field. Therefore, accurate calculation of electric field induced currents on human body can be done only by using these locally enhanced electric field values instead of uniform electric field. Since the distribution of electric field strength varies along the surface of the body, the distribution of induced body current density varies along the body surface. The induced currents in a human body due to such enhanced electric fields may exceed the safe limits [2-6]

The object of this paper is to calculate the electric field distribution, induced body currents and current densities along the surface of a grounded human body standing beneath a 380 kV three phase high voltage overhead transmission line. Power frequency (50 Hz) electric field distribution beneath the HV line has been determined by using charge simulation method (CSM) and induced body currents have been calculated using these computed electric field values. Calculated induced currents have been evaluated with respect to national and international safety guidelines. A user friendly computer program has been developed using Visual Basic 6.0 for the calculations.

2. Electric field calculation by charge simulation method (CSM)

High voltage line electric fields can be calculated by numerical methods such as Finite Element, Boundary Element or Charge Simulation Method [7-10]. In this paper Charge Simulation Method has been used to calculate the electric field.

In the Charge Simulation Method, the actual electric field is simulated by a number of discrete simulation charges which are located in the conductors. Values of simulation charges are determined by satisfying the boundary conditions at a number of contour points selected at the conductor surfaces. Once the values of simulation charges are determined, then the potential and electric field of any point in the region outside the HV line conductors can be calculated using the superposition principle as follows: if several discrete charges of any type (point, line or ring) are present in a conductor, the potential at any point at the surface of the conductor can be calculated by the summation of the potential contribution of all the individual simulation charges using the equation (1)

$$V_i = \sum_{j=1}^{n} p_{ij} \cdot q_j \qquad i = j = 1, ..., n \qquad (1)$$

where p_{ij} is the potential coefficient related to the potential of the j_{th} charge at the i_{th} point q_j is the simulation charges, n is the charge number. If the number of contour points is selected as equal to the number of simulation charges, a set of linear equations for the potentials of contour points can be given by

$$[p] \cdot [q] = [V] \qquad (2)$$

where [p] is the potential coefficients matrix, [q] is a column vector for simulation charges, and [V] is a column vector for potentials of contour points. Since these points are contour points and their potentials are known and equal to the applied AC voltage of the conductors, the values of simulation charges are calculated first by solving the equation (2). Electric field is calculated by vectorial superposition of magnitudes of its various directional components.

3. CSM model of the human body

Dosimetry studies have largely examined the effects of vertical electric fields from an overhead source for a standing person. As the vertical orientation results in the maximum induced current, exposure to electric fields of horizontal or sagittal orientations results in smaller induced currents.

In the model, the human body has been modeled by a sphere for the head, a thin cylinder for the neck, a thick cylinder for the waist and a thick cylinder but of lesser radius for the legs.

The surface charges on the human has been simulated by another set of finite line charges located at the vertical axis of the body (Fig. 1). The surface charges on the high voltage line conductors have been simulated by infinite line charges located at each line axis. Images of the simulation charges of both high voltage lines and human body with respect to the ground plane has been considered for the simulation of infinite ground plane having zero potential.

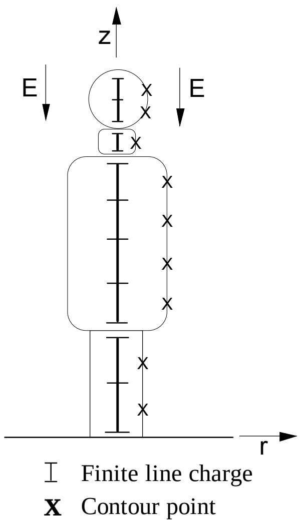

Figure 1: Charge simulation model of the human body standing under a high voltage transmission line.

The human body is treated as a conducting body because of the large conductivity and the large relative equivalent dielectric constant of the human body, about 0.1 S/m and about 100000 respectively [11-16]. This, causes the external power frequency electric field near the human body to be perpendicular to the surface of the body. Using this assumption electric fields at the surface of a grounded human standing under a high voltage line has been calculated.

Table 1. Dimensions of the human model

Body Part	Diameter (mm)	Height (mm)
Head	180	180
Neck	120	60
Waist	400	600
Legs	200	900

4. Computation of surface charges and induced body currents

Once the simulation charges and the electric fields at the surface of the body are calculated, the induced current densities and currents at the surface of the body are determined using equations (3)-(5).

The charge density σ at a boundary point on the human body surface at the height of z is expressed as

$$\sigma = \varepsilon_0 E_n \tag{3}$$

where E_n is the normal component of the electric field calculated at the boundary point and is equal to the calculated field at the boundary point on the human body. ε_0 is the permittivity of the free space. At the boundary point, the induced current density J is normal to the surface and just inside the boundary is expressed as

$$J = \omega\sigma = \omega\varepsilon_0 E_n \tag{4}$$

where ω is the angular frequency of the applied voltage to the high voltage line conductors ($\omega = 2\pi f$).

The induced current (I_k) just inside the boundary of the part of the body, say k^{th}, is obtained by integrating J over the surface area (S_k) of this part.

$$I_k = \oint_{S_k} J.dS = \oint_{S_k} \omega\sigma\, dS = \omega\varepsilon_0 \oint_{S_k} E_n dS \tag{5}$$

On the other hand, the current density distribution inside the body depends on the material constants assigned to the human organs filling the volume of the body. The induced current also varies considerably depending on whether the person has one or both feet grounded or whether the person's arms are raised.

5. Numerical Results

The height of the triple bundle conductors of a three phase 380 kV line over the ground plane is 15 meters (Fig. 2).

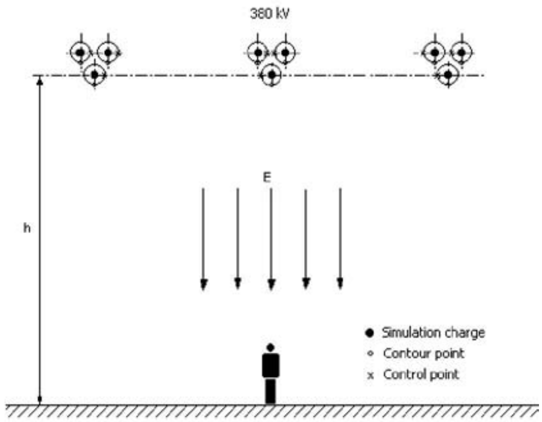

Figure 1: 380 kV transmission line configuration.

Diameters and spacing between subconductors are 27,7 mm and 400 mm respectively. Horizontal distances between phase lines are 9 meters. Potentials of the phase conductors have been defined as the complex potentials. The human body assumed as having zero potential. The electric field of the HV line has been simulated with the electric field created by the infinite line charges located at the axis of each subconductor. The number of charges used for the computations were 8 for the legs, 8 for the waist, 4 for the neck, 3 for the head and 9 for the high voltage line conductors. The maximum potential error was 0.62% in this solution. Table 2 shows the computation results.

Table 2: Numerical results

Body Part	Avg. Induced Current Density ($\mu A/m^2$)	Induced Current (μA)
Head	46.18301	4.70086
Neck	20.05116	0.45355
Waist	18.30917	13.80479
Legs	6.80272	5.77027

It is quite clear from Table 2 that induced current density values increase along the length of the body, starting from the legs to the head, due to the increase in the surface electric field values. Maximum induced current has been obtained at the waist due to the higher electric field values and larger surface area. Total induced current on the grounded human body has been obtained as 24.72947 µA, which is well below the 1 mA level. This level is the value of current at which a person is just able to detect a slight tingling sensation on his/her hands or fingers due to current flow [17].

Moreover, the induced currents for the grounded body are larger then those for the insulated body [9]. However, underneath a HV line the electric field changes from point to point, and the induced current in the human body changes accordingly and this change follows the pattern of the electric field distribution underneath the HV line. Lateral profile of the electric field at ground level for various line configurations can be seen in high voltage textbooks and published papers [9].

6. Conclusion

Accurate calculation of power frequency electric field induced currents and current densities on a grounded human body standing beneath a 380 kV three phase high voltage overhead transmission line has been made using the perturbed electric field distribution determined by Charge Simulation Method. A computer program has been developed for the calculations. Equipotential lines and electric field lines can also be drawn using this software.

It has been seen that induced current density values increase along the length of the body, starting from the legs to the head, due to the increase in the surface electric field and values of induced body current densities are well below the 10 mA/m^2 "no effect" upper-limit. Total induced current on the grounded human body is also well below the 1 mA level. However, if the distance between the body and the high voltage lines is so small, then these computed values might exceed the safe limit.

However, the cardiac cells may be affected these lower value induced current densities.

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