

*Original Article*

## Numerical analysis of biological effects on several organs inside human body exposed to electric field from 500 kV OHTLs

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### Abstract

There is concern about the human health from electromagnetic field which is emitted from the high voltage overhead transmission lines (OHTLs). The biological effects inside human body depend on electric field intensity and current density flowing through the organs when they exposed to electric field due to OHTLs. There are harmful effects to these organs if current density exceed safety limit. In this work, the mathematical models of electric field distribution which is emitted from 500 kV OHTLs, induced electric field and current density distributions inside human body which is standing under OHTLs are systematically calculated using Finite Element Method. These quantities will be compared to the guidelines for safety limit which set by The International Commission on Non-Ionizing Radiation, ICNIRP. It is found that the incident electric field intensity on human body model under OHTLs at mid-span exceeded the safety limit. But the induced current density is much lower than that of the safety limit.

**Keywords:** current density, organs, human body, electric field, transmission lines

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### 1. Introduction

During the last few decades, the electrical power demand in Thailand increases very rapidly. In order to fulfill the vast need of electrical power in the large city, the high voltage OHTLs are constructed to carry electricity from the power plant to the very long distance electrical power station with minimize the power loss of electricity. In Thailand, the Electricity Generating Authority of Thailand (EGAT) has been constructed the enlarge transmission capacity by installing high voltage power transmission lines, the maximum voltage is 500 kV (Pao-la-or *et al.*, 2010; Tupsieet *et al.*, 2009). There is concern about the possible health hazards for general public from these extra high voltage OHTLs, because they can generate electromagnetic field to the environment. For the improving of living standard, the consciousness of environment

protection and health for people who live near the passing transmission lines area and the workers who climb on the high voltage post to maintain the transmission lines needs to be increasing. The extremely low frequency (ELF) of 50-60 Hz is a very important health concern. Some international organizations have provided guidelines to limit electromagnetic field which is exposed to human body such as The International Commission on Non-Ionizing Radiation (ICNIRP). Recently, it has been suggested that if there is any harmful effect to health due to the electromagnetic field, induced current may cause this effect (International Commission on Non-Ionizing Radiation Protection [ICNIRP], 2010). The amount of the current, even if a human is directly under a transmission line, is extremely small. These biological effects from extremely low frequency electric and magnetic fields have been studied to investigate its harmful on living bodies especially on human beings from worldwide researchers (Abd-Allah, 2006; Darabant *et al.*, 2012; Duyan *et al.*, 2008; El Deinet *et al.*, 2010; El-Makkawy, 2007; King *et al.*, 2004; Maalejet *et al.*, 2009; Min, *et al.*, 2009; Siauveet *et al.*, 2003; Yildirim *et al.*, 1998). However,

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the electromagnetic field distributions and induced current inside human body are difficult to measure. Therefore, the numerical methods are used to calculate electric and magnetic fields which are emitted from high voltage OHTLs and induced current inside human body. Many researchers both of power electrical engineering and biomedical engineering fields have developed the techniques to calculate the electric and magnetic fields around the area of high voltage OHTLs by using theory and simulation such as Charge Simulation Method (CSM) (Ismail *et al.*, 1998; Santos Jr. *et al.*, 2010), Finite Element Method (FEM) (Pao-la-or *et al.*, 2008; Pao-la-or *et al.*, 2010; Tupsie *et al.*, 2009). These quantities were compared with guidelines for limiting the exposure which set by ICNIRP. However, most studies of the electric field, magnetic field and induced current density are calculated at the surface of human body. They have been not considered these effects inside human body with complicated organs of several types of tissue.

In this work, the electric field distributions and biological effects on several organs inside human body model which is standing under 500 kV OHTLs will be calculated because they had been not considered from the previous reviews and they did not have report in Thailand. The Finite Element Method is used to calculate the extremely low frequency electromagnetic field, 50 Hz, which is emitted from 500 kV OHTLs. This power line is the maximum voltage which is installed in Thailand. For the biological effects, the induced electric field and current density inside a 2-D human cross sectional model which has several organs inside such as brain, lungs, heart, liver and intestine exposed to extremely low frequency electromagnetic field and high voltage are calculated. These calculated quantities will be compared with the ICNIRP limitation.

**2. Methods and Models**

The high voltage and extremely low frequency OHTLs, 500 kV and 50 Hz, are installed by EGAT in Thailand. They are three phases of double-circuit configuration. Each phase has 4-bundled conductors as illustrated diagrammatically by Figure 1(a). The area of this study is 2-D cross section at mid-span (maximum sag allowance) of conductors as shown in Figure 1(b). The height of the lowest conductor are 13.00 m above the ground level and phase conductors are 795 MCM(diameter = 0.02772 m), while overhead ground wires (OHG) are 3/8 inch (diameter = 0.009114 m). The maximum current load density is 3.15 kA per phase (Tupsie *et al.*, 2009).

The first step in evaluating the biological effects of a certain exposure to electromagnetic field due to high voltage OHTLs on several organs inside human body is the determination of electric field and its spatial distribution on human body. Thereafter, the induced electric field and current density distributions inside human body are considered. The system of the governing equations as well as initial and boundary conditions are solved numerically using the Finite Element Method (FEM) via COMSOL™ Multiphysics to demonstrate the phenomenon occur within the human body exposed to electromagnetic field.

The 2-D human body model which is used in this study has the height of 1.80 m. It composes of five internal organs in human trunk and head such as brain, lungs, heart, liver, and intestine. The shapes of these organs are expressed by cylinders, spheroids and circle as shown in Figure 2. These organs have different dielectric properties at the frequency of 50 Hz as shown in Table 1 (Gandhi *et al.*, 1992; Wessapanet *et al.*, 2011). The relative permeability ( $\mu_r$ ) is 1 and relative permittivity ( $\epsilon_r$ ) of all organs is  $2 \times 10^7$ .

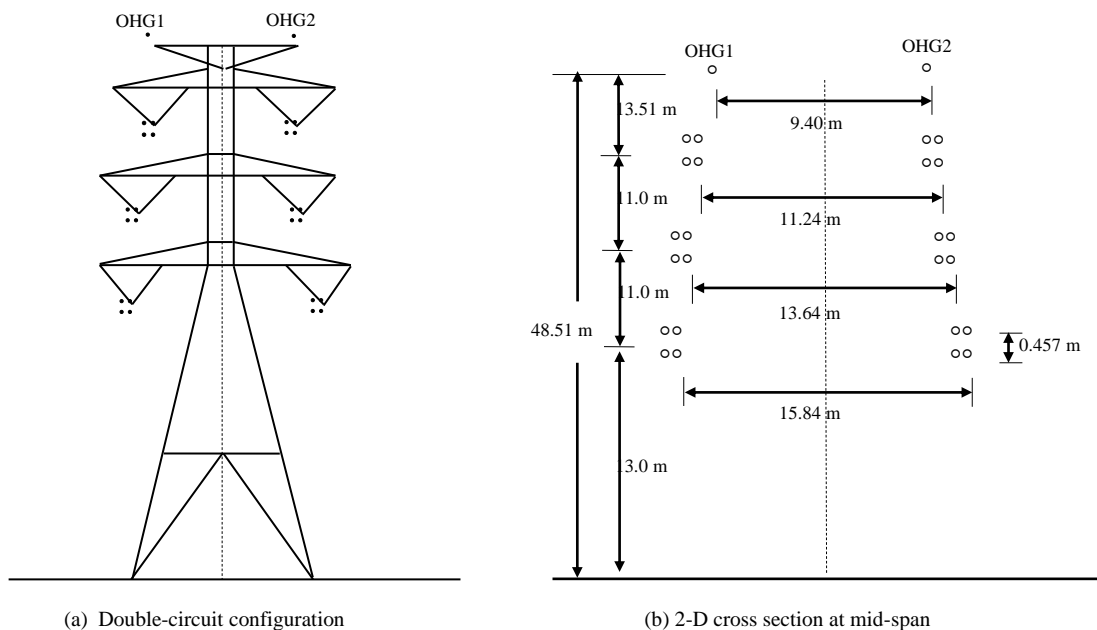


Figure 1. The 2-D cross section diagrammatically of 500-kV transmission lines (Pao-la-or *et al.*, 2010)

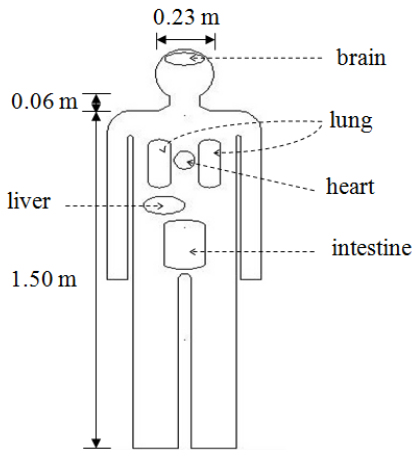


Figure 2. The 2-D human body model

Table 1. Dielectric property of tissues (Yildirim *et al.*, 1998)

Organs	$\rho$ (kg/m <sup>3</sup> )	$\sigma$ (S/m)
body	1062	0.2160
brain	1050	0.0533
lung	1050	0.0684
liver	1030	0.0367
heart	1058	0.0827
Intestine	1043	0.5220

## 2.1 Governing equations

### 2.1.1 Electromagnetic field distribution

The electromagnetic field emits from high voltage OHTLs to the environment around phase conductors. Mathematical models are developed to predict the electromagnetic field distribution around phase conductors. For OHTLs, high voltage and extremely low frequency system, the most important field for biological effects inside human body is electric field (Peratta *et al.*, 2010). The electric field distribution in the area under phase conductors at mid-span where is human body standing is investigated. To simplify the problem, the assumptions are made.

1. The 2-D cross section of high voltage OHTLs is the x-y plane.
2. The wire conductors at mid-span are straight lines in z-direction.
3. The computational space is truncated by scattering boundary condition.
4. There is no interference of electromagnetic fields due to each conductor phase line.

The electromagnetic field propagation in space can be calculated by Maxwell's equation. It can be described electric and magnetic field distributions. The general form of Maxwell's equation is simplified to demonstrate the electromagnetic field distribution as the following equation:

$$(j\omega\sigma - \omega^2\varepsilon_0\varepsilon_r)\vec{A} + \nabla \times (\mu_o^{-1}\mu_r^{-1}(\nabla \times \vec{A})) - (\sigma\vec{v} \times (\nabla \times \vec{A})) = \sigma\frac{\Delta V}{L} + J_e \tag{1}$$

The magnetic field distribution can be calculated by curl of magnetic vector potential as equation:

$$\vec{B} = \nabla \times \vec{A} \tag{2}$$

The electric field distribution due to high voltage OHTLs composes of static electric field and alternating electric field. The static electric field can be calculated by gradient of electric scalar potential, while the alternating electric field is associated with magnetic field. It can be calculated by time derivative of magnetic vector potential as equation:

$$\vec{E} = -\nabla V - \frac{\partial \vec{A}}{\partial t} \tag{3}$$

The first term in the right hand side of Equation 3 is the electric field due to gradient of electric potential from conductor lines to anywhere around them. The intensity of this electric field depends on the distance from conductor lines. The second term is the time-harmonic electric field due to alternating current of the OHTLs. It can be derived from Equation 3 and Maxwell's equation as:

$$\nabla \times \vec{E} = -\frac{\partial \vec{B}}{\partial t} \tag{4}$$

The propagation of time-harmonic of magnetic flux density with the angular frequency  $\omega$  can be written as equation:

$$\vec{H} = H e^{-j\omega t} \hat{r} \tag{5}$$

Thus, the relation between time-harmonic electric field and magnetic flux density as shown in equation:

$$\nabla \times \vec{E} = j\omega\mu\vec{H} \tag{6}$$

$$\nabla \times \vec{H} = (\sigma + j\omega\varepsilon)\vec{E} \tag{7}$$

The electrical conductivity, permittivity and permeability in air are very low. For extremely low frequency of electromagnetic field, the right hand side of Equation 6 and Equation 7 are approximately to zero. Therefore, the dominant of electric field distribution around the high-voltage OHTLs with extremely low frequency is electric field due to the gradient of electric potential.

### 2.1.2 Electric field and current density distributions inside human body

In the extra low frequency electromagnetic field, biological tissues behave as electrolytic conductors and insulator at the same time as they are made of polar molecules, such as water. Charges inside biological tissues, positive and negative ions, will be moved to the surface in response to the electric field when they exhibit conductor. In case of insulator, the external electric field will be reduced by relative permittivity property inside human body according to the following equation:

$$\vec{E}_{in} = \frac{\vec{E}_{ext}}{\epsilon_r} \tag{8}$$

The current density inside human body can be evaluated by electric field distribution which is occurred on each surface of organs inside human body. It can be expressed as (El Deinet *et al.*, 2010):

$$J = \sigma E_{in} \tag{9}$$

To simplify the problem for calculating the electric field and current density distributions inside human body, the assumptions are made.

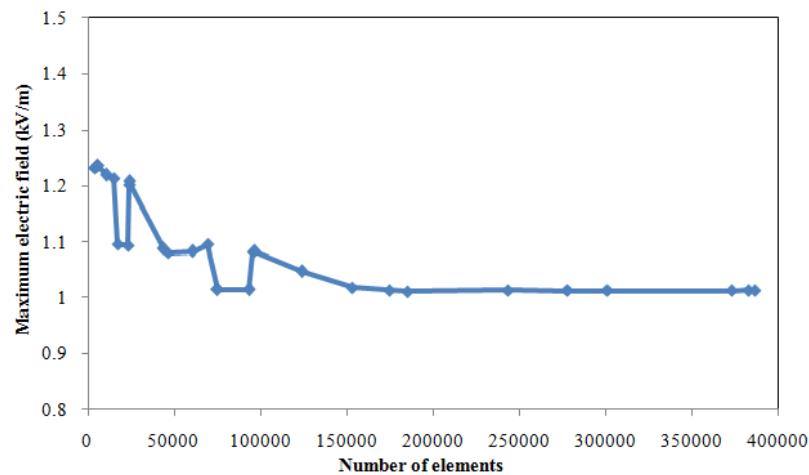
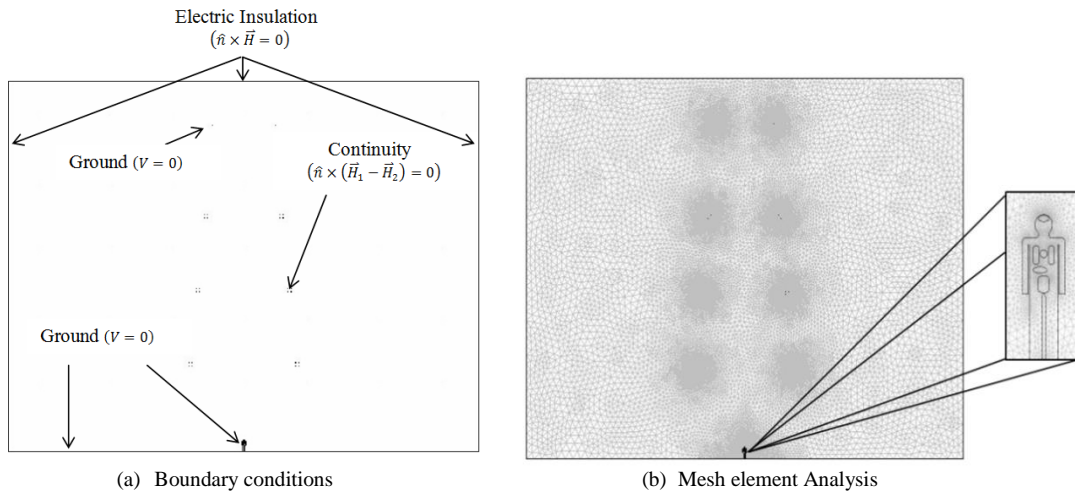
1. Human body organs are biomaterial with the constant dielectric properties.
2. There is no energy exchange throughout the human body.
3. There is no chemical reaction within the organs.
4. Human body model is standing on ground under OHTLs at mid-span.

### 2.2 Boundary conditions

The electromagnetic field is emitted from AC high voltage OHTLs to the environment and strikes the human body which is standing under high voltage OHTLs at the mid-span. Therefore, the boundary conditions for electromagnetic field distribution are shown in Figure 3(a).

### 2.3 Calculation procedure

The Finite Element Method is selected to analyze the problems in this work. In order to obtain a good approximation, a fine mesh is specified in the sensitive area. The coupled model of electromagnetic field and DC conductive media is solved by the finite element method model. It is implemented in COMSOL™ Multiphysics to demonstrate the phenomenon of electromagnetic field distribution and biological effects inside human body exposed to electromagnetic field. The 2-D model is discretized using triangular elements as shown in Figure 3(b). The Lagrange quadratic is used



(c) The convergence test of the maximum electric field at the 1 m above ground

Figure 3. Boundary conditions, mesh element analysis and convergence test of electric field

to vary the electric field propagation from high voltage OHTLs, induced electric field distribution and current density on several organs inside human body across each element. The convergence test of the maximum electric fields at the height 1 m from ground is carried out to identify the suitable number of element required. This convergence test is shown in Figure 3(c). It is found that the maximum electric fields are stable after number of element around 180,000 elements. In order to save time and material of computation, the number of mesh element which is selected to use in this work is 193,500 elements.

**3. Results and Discussion**

In this work, the Finite Element Method is used to analyze the biological effects on several organs inside human body model exposed to electric field due to high voltage OHTLs. The electric field distribution in the area under 500 kV overhead transmission lines at mid-span is calculated. After that, the induced electric field and current density distributions on several organs inside human body exposed to electric field due to OHTLs are systematically investigated.

**3.1 Verification of the models**

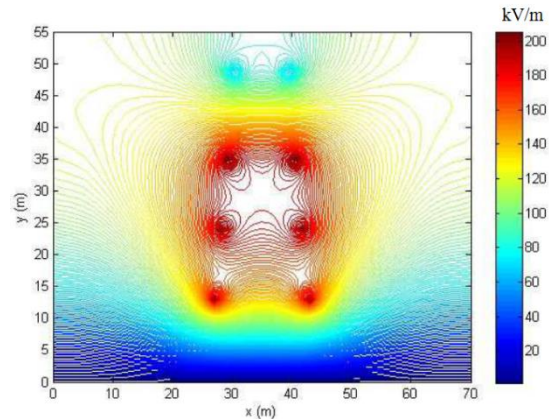
It must be noted that it is difficult to make a direct comparison of the models in this study with the experimental results because there is no measured report of the 500 kV OHTLs configurations. In order to verify the accuracy of the present numerical models, the electric field distribution of the simulated result is then validated against the numerical result with the same configuration of double-circuit 500 kV OHTLs which are installed in Thailand, obtained by Tupsie S. (Tupsie *et al.*, 2009).

The comparison of the electric field distribution of double-circuit 500 kV OHTLs between the reference and present simulated results without human body model are illustrated in Figure 4(a) and (b). It is seen that the pattern of electric field distribution in present simulated result is similarly as the reference simulated result, both of low and high electric field region and characteristic of equi-electric field lines. Moreover, the electric field distribution at 1 m above ground in the area under 500 kV OHTLs at mid-span is compared. This area is the place of human body standing. Figure 4(c) clearly shows a good agreement of the reference and present simulated electric field distributions. The relative root mean square (RMS) deviation is used to quantify the comparison. It is found that the RMS deviation is equal to 2.35%.

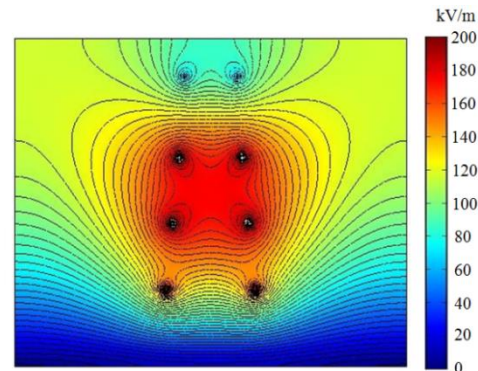
**3.2 Electromagnetic field distribution**

The simulation results of electromagnetic field distribution which are propagated in the environment around the OHTLs conductors are shown in Figure 5. The arrows in Figure 5(a) show the direction of time-harmonic magnetic field. It can be seen that the time-harmonic of magnetic field is in the x-y plane, while the time-harmonic electric field is in z-direction. The arrows in Figure 5(b) show the direction of the electric field due to gradient of electrical potential around transmission lines in the x-y plane. It can be seen that the direction is from conductors to ground. The electric field due to gradient of electrical potential in Equation 3 shows that it

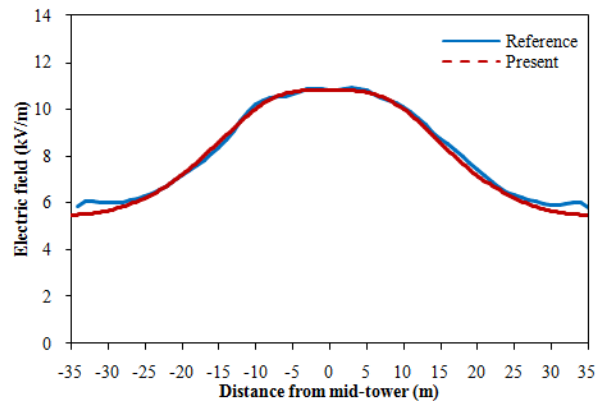
depends on the distance from transmission line conductors. The intensity of time-harmonic electric field is not change at any point in the area as shown in Equation 6. Thus, the magnitude of electric field due to high voltage OHTLs and extremely low frequency is constant at each point. It is seen that the electric field intensity in the area between phase line conductors is very high when compare with the area under OHTLs conductors. This is because the areas under OHTLs near the bottom phase line conductors.



(a) Reference simulated result



(b) Present simulated result



(c) The electric field distributions at 1 m above ground under high voltage OHTLs.

Figure 4. The comparison of the reference and present simulated electric field distributions at 1 m above ground under high voltage OHTLs.



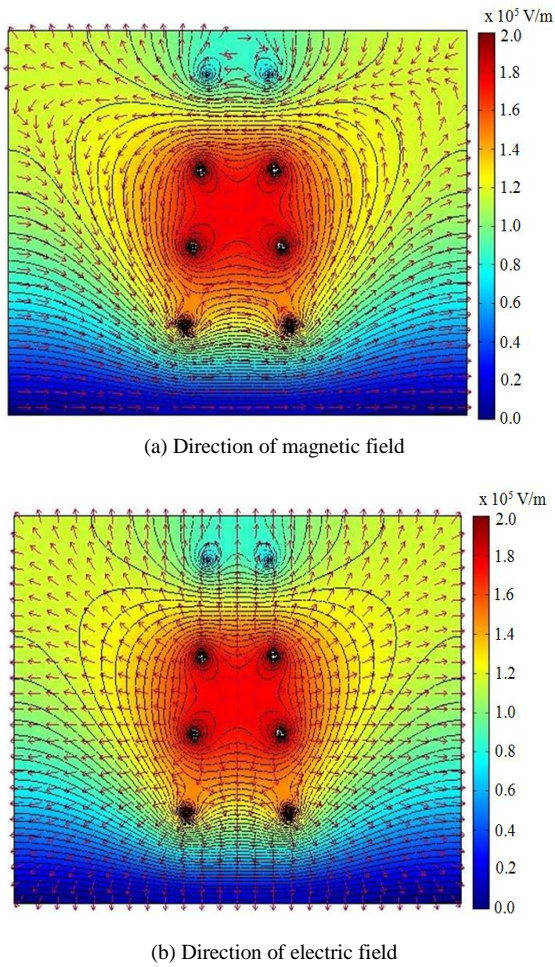


Figure 5. The electromagnetic field distribution due to 500 kV OHTLs

Figure 6 shows the simulation results of electric field intensity distribution at some levels above ground in the area under OHTLs, without and presence the human body model under OHTLs. It is seen that the electric field intensity is increased when the level above ground is high, especially near the OHTLs conductors. Moreover, the electric field distributions when presence and without human body model under high voltage OHTLs are same intensity, except the area near human body model. The electric field of human body model perturbs the electric field due to OHTLs. This is because the human body model behaves an electrical conductor in extra low frequency of electromagnetic wave. However, this perturbation is occurred only the area near the height of human body model. Table 2 shows that the averages of electric field intensity at each height above ground are not much different both of presence and without human body model. The guidelines for limiting exposure to electric field for occupational and general public exposures which set by ICNIRP are 10 kV/m and 5 kV/m, respectively (ICNIRP, 2010). It is seen that the maximum incident electric field on human body model is approximately 17 kV/m. It is higher than that of safety limit for both of occupational and general public exposures when the human body model stands under high voltage OHTLs at mid-span.

**3.3 Electric field distribution inside human body**

The maximum incident electric field due to these transmission lines on human body model at mid-span is approximately 17 kV/m as shown in Table 2. The directions of incident electric field are perpendicular to the surface of human body model. Charges inside each organ are move to the surface response to the electric field because biological tissues exhibit characteristics of electrolytic conductor. In extra low frequency, charges can be trapped at the interface of organs. The amount of charges which are transport inside organs may be reduced, yield to effective internal polarization. These charges on the surface of each organ cause to the

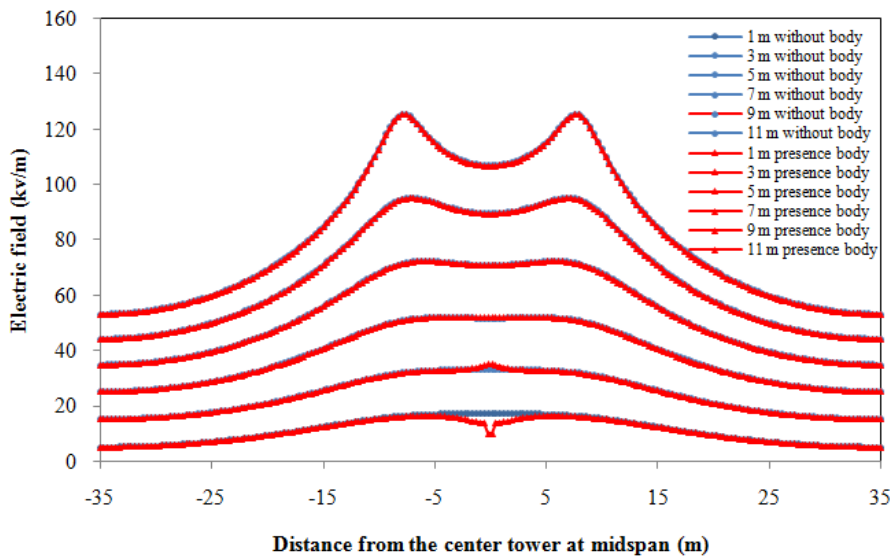


Figure 6. Electric field distributions under HV overhead transmission line

Table 2. The average electric field intensities at each height above ground

y (m)	Average electric field (kV/m)	
	without human body	presence human body
1	11.06	10.65
2	17.05	17.13
3	23.84	23.82
4	30.93	30.87
5	38.15	38.07
6	45.45	45.34
7	52.79	52.66
8	60.16	60.00
9	67.56	67.38
10	74.98	74.79
11	82.46	82.26
12	90.10	89.87
13	97.10	96.85

internal electric fields inside human body, their directions are perpendicular to each point of all organs. These electric field intensities are very high at the surface of each organ while are vanished inside organs, because almost of charges are trapped on the surfaces at the extremely low frequency. It is seen that the maximum electric field intensities occur on the surface of organs as shown in Figure 7(a). The electric field intensities on the surface of the organ which has small width are higher than that of large width. This is because the distance of charge carrier between the surfaces of each organ is shorter than that of large width.

### 3.4 Current density distribution inside human body

Figure 8(a) shows induced current density distributions on several organs inside human body. These induced current densities are conduction current density resulting by the transport of charges of each organ due to electric field is given by Equation 9. The current densities are occurred on the surfaces of each organ in the same place as induced electric field.

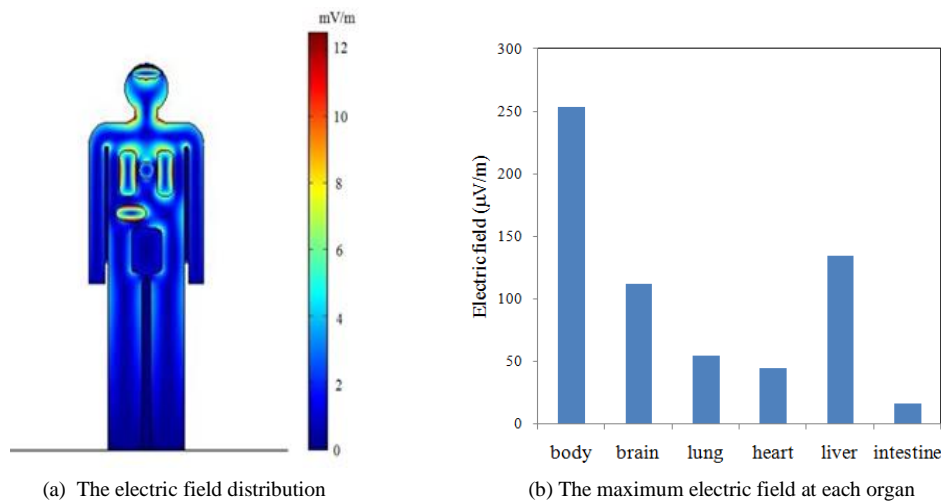


Figure 7. The induced electric field distribution inside human body

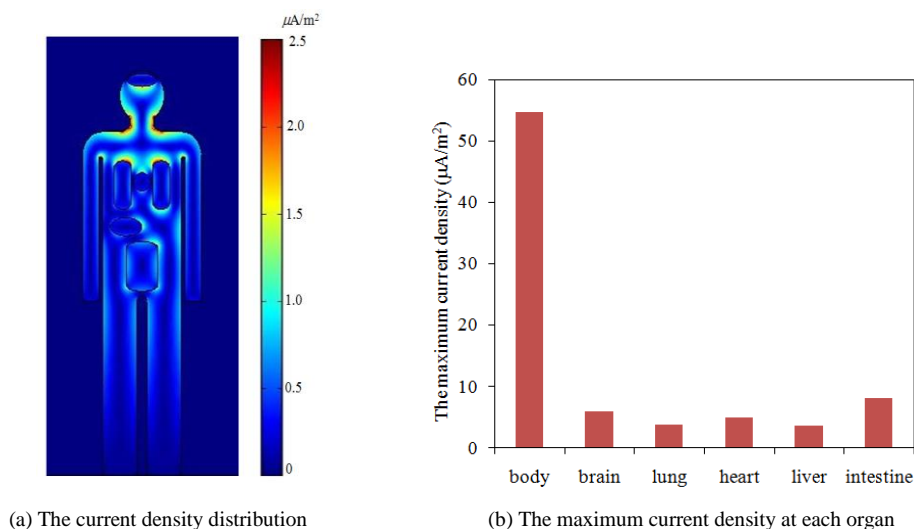


Figure 8. The current density distribution on each organ inside human body

Figure 8(b) shows that the maximum current density on the organs inside human body model is occurred at the top of lungs,  $54.86 \mu\text{A}/\text{m}^2$ . This is because these regions have high electric field intensity and the electrical conductivity of human body is high. While the maximum current densities on the surface of other organs are lower. The maximum current densities on the surface of brain, lungs, heart, liver and intestine are 5.97, 3.78, 4.92, 3.64 and  $8.24 \mu\text{A}/\text{m}^2$ , respectively. Although the maximum electric field intensity on the surface of intestine is lowest but the maximum current density at this surface is higher than that of brain, lungs, heart and liver. This is because the electrical conductivity of intestine is highest when compare with the others.

#### 4. Conclusions

This study presents the numerical simulation of electric field distribution which is emitted from 500 kV and 50 Hz of AC OHTLs. Thereafter, the induced electric field and induced current density distributions on several organs inside human body model which is standing under OHTLs at mid-span are simulated.

For the distribution of electric field intensity, it depends on the distance from the OHTLs conductors. It is very high intensity in the area near the phase line conductors. While it is lower in the area under OHTLs conductors. The maximum incident electric field to the human body model is approximately 17 kV/m. This electric field intensity exceeds the guideline of safety limiting electric field exposure for occupational and general public exposure which set by IC-NIRP, 10 kV/m and 5 kV/m, respectively.

The human body which is standing under high voltage OHTLs behaves electrolytic conductor and insulator at the same time. The incident electric field can be reduced by relative permittivity of tissue organs inside human body. The induced electric field intensity on several organs inside human body are different because of their permittivity of each organ. The maximum induced electric field of each organ occur on surfaces because the biological tissues exhibit characteristic of electrolytic conductor. The induced electric field intensity inside each organ are vanished because almost of charges are trapped on the surface at the extremely low frequency. The maximum induced electric field intensity inside human body is occurred at the top of lungs,  $253.98 \mu\text{V}/\text{m}$ . The maximum electric field intensity on intestine is lower than that of other organs,  $15.79 \mu\text{V}/\text{m}$ .

The biological effect inside human body model exposed to high voltage and extremely low frequency is induced current density. It depends on electric field intensity and electrical conductivity of each tissue. Moreover, both of the induced electric field intensity and current density of each organ are depend on size of body. The maximum induced current density inside human body is occurred in the area between body and lungs at the top of lungs,  $54.86 \mu\text{A}/\text{m}^2$ . This is because they have high induced electric field intensity and electrical conductivity. Although the induced electric field intensity on intestine is lowest but the maximum induced current density is higher than that of other organs, except body

region. This is because the electrical conductivity of intestine is highest when compare with the others. However, the maximum induced current density which is occurred inside human body is not exceeding the guideline of safety limiting current density for occupational and general public exposure which set by ICNIRP,  $10 \text{ mA}/\text{m}^2$  and  $2 \text{ mA}/\text{m}^2$ , respectively.

However, this study is preliminary study of biological effects on several organs inside human body model due to extremely low frequency. The organs inside human body model in this study are not realistic. They are ideal geometric shapes and some of simplifications are used in this study. It may be affected the accuracy of the simulation results because the organs inside human body are very complicated. Thus, the results from this study is the approximately biological effect values because of these reasons but they can be guided for the future works for more accuracy and the consciousness of human hazard from electromagnetic field due to OHTLs for the people who live or have some activities near OHTLs. In the future work, some ideas will be added for studying the biological effects due to extremely low frequency electromagnetic field for more accuracy. The three dimensions of human body and organs, the realistic of organs inside human body and the frequency-dependent dielectric properties of human tissues will be needed to use for studying the biological effects inside human body.

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