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Assessment of Human Exposure to Electric Fields inside High Voltage Substations During Working Conditions

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***Abstract* – The minimum health and safety requirements regarding the exposure of workers to the risk arising from electric fields produced inside high voltage (HV) substations is still considered as a competitive topic for utility designers, world health organization (WHO) and biomedical field researchers. Hence, the electric fields levels inside HV substations and their induced current inside human body should be pre-evaluated as early stage in the process of substation design. The object of this paper is to present a method for assessment not only the distribution of power-frequency electric field inside HV substations and the charge at the surface of a human body underneath high voltage equipments inside HV substations, but also the induced currents and current densities along the surface of this body. This method of analysis is based on the charge simulation technique (CSM). This study will serve to explain the biological studies of possible long-term exposure effects to electric fields.**

Index Terms – HV substation, Electric fields, Induced current, Charge simulation technique, Human body.

I. INTRODUCTION

THe human exposure to electric fields and the risk arising from electric fields produced inside HV substations attract an increased attention of many biomedical field researchers, scientific research communities worldwide on the health effects of electric power systems; this is because these electric fields represent the primary source to the resultant electrical current induced in the human body under or near electric power systems [1]. As a result of this interest, the governments are playing an active role in the reduction of these exposures to electric fields by setting exposure limits for such fields which resulting from different electrical power systems / apparatus [2-4]. This is in addition to the electric fields generated from different HV electrical equipments are considered an integral part of the properties of these equipments [5]. The exposure to electromagnetic fields produced by these equipments inside HV substations is receiving more attentions to guarantee the life insurance of all persons working inside these substations. Therefore, the problem of the human exposure to electric fields has become more important with increasing the number and the size of power substations and electric power systems in general.

The maximum body current induced by electric field from different HV electrical equipments inside HV substations is much greater than the body current or current density induced by the magnetic field from these equipments. Consequently, induced current from electric fields are more important than the current induced by the magnetic field [6].

In this paper, the present algorithm is carried out to determine the distribution of the electric fields produced by different high-voltage electrical power systems / apparatus inside 500/220 kV air-insulated substation (AIS). In addition to the calculation of the distribution of external electric fields inside HV substation are performed, we will calculate the induction current densities and currents along the surface of grounded worker's body during working conditions and at different positions inside this substation. These calculated values will be compared to the standard limit levels stated by international organizations [2-4]. This developed method is based on the charge simulation technique, which simulate the typical 500/220 kV substation with all incoming and outgoing feeders from it by developing multi-scripts of m-file Matlab software package to calculate the distribution of electric fields inside this substation. Moreover, the human body is simulated and allocated within the highly exposure zones of electric fields inside this substation to determine the field distribution, induced current densities and induced currents along the surface of his body during different working conditions.

The computer program developed is considering the complex systems, including three-dimensional multiple incoming, outgoing overhead lines and bus system inside this HV substation. Moreover the induced currents and current densities along the surface of grounded human bodies are determined at the top of the head, at the middle of the neck, at the middle of the waist and at the middle of the legs and arms. These currents are correlated with the safe limits [2-4]. The body was considered to have a negligible effect on the source of the electric field and the surface charge on the live conductors, incoming, outgoing overhead lines and bus system inside this HV substation.

II. SUBSTATION DESCRIPTION and SYSTEM MODELING

A. Substation description AND *selected positions for worker*

The calculations of electric fields are performed inside 500/220 kV AIS, Cairo 500 substation. This substation is supplied by four 500 kV overhead transmission lines, single circuit, which are connected to the same 500 kV double bus systems (HV Busbars), main and standby bus-bars. This substation has three identical 3-phase, 500 MVA, 500/220/11 kV power transformers installed inside it, each transformer is composed of three single phase transformers. This substation is supplying six loads through six 220 kV double-circuit overhead transmission lines which are outgoing from the same 220 kV double bus systems (LV Busbars), main and standby bus-bars. This substation has a simply 500 kV,220 kV bus systems with 300 m long and 12 m, 9m height respectively.

The human body is allocated within the highly exposure zones of electric fields inside this substation and at three different heights to determine the field distribution, induced current densities and induced currents along the surface of his body during different working conditions (See Fig. 1).

Quick view on single line diagram for this substation is presented in Fig. 2.

The first position is at a height of 1.5 m above the ground level which presents worker standing on ground with his foot in switchyards during normal operation and (hot-stick position) during live- working conditions (Scenario 1).

The second position is at a height of 11 m for 500 kV switchyard and 8.5 m for 220 kV switchyard which presents the position of the worker in (bare hand position) during live maintenance conditions (Scenario 2).

The third position is at a height of 17 m for 500 kV switchyard and 11 m for 220 kV switchyard which presents the position of the worker in (bare hand position) during live maintenance conditions (Scenario 3).

B. Electric field calculation methodology

The electric fields inside the substation under study are excited by all conductors under voltage and are deformed by metal, concrete, and ceramic (composite) elements such as tower trusses, supporting constructions, and insulators. In the electric field model presented in this paper, these elements are ignored. In this model HV and LV bus-bars, incoming 500 kV feeders and outgoing 220 kV feeders are approximated by internally located line charges.

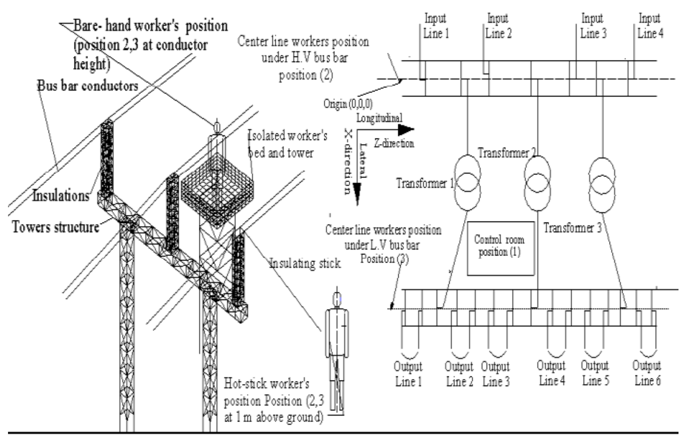
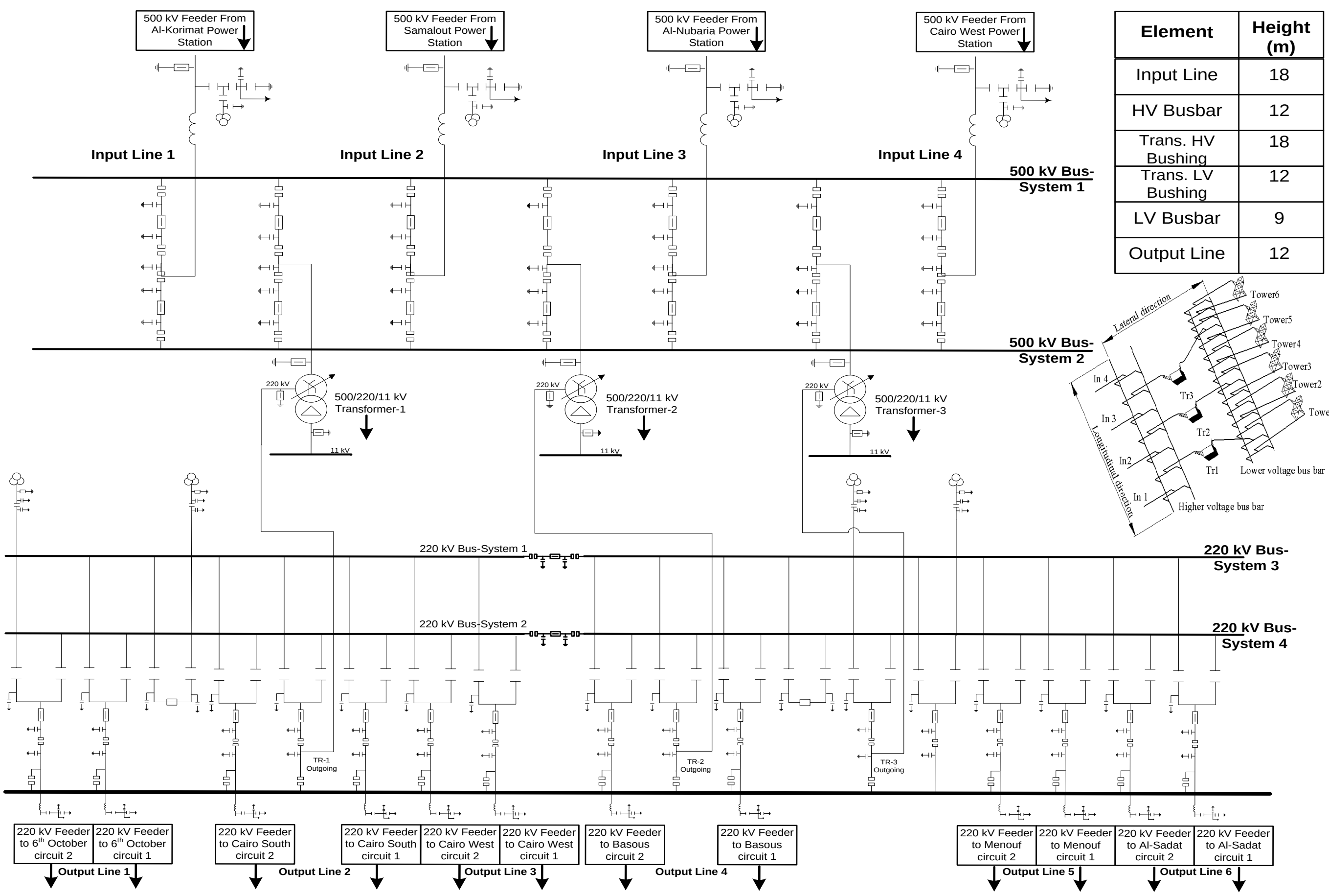


Fig. 1 Different positions of the workers during different working conditions



Element	Height (m)
Input Line	18
HV Busbar	12
Trans. HV Bushing	18
Trans. LV Bushing	12
LV Busbar	9
Output Line	12

Fig. 2 Single line diagram of simulated 500/220 kV substation, Cairo 500 substation.

Such a simplification is acceptable when the field is analyzed at a long enough distance from the conductor, e.g. near the ground surface. The electric potential of incoming 500 kV feeders, outgoing 220 kV feeders and bus-bar surfaces has been defined as complex potentials and assumed to be equal to their phase voltage. These assumptions lead to a charge simulation method formulation. The standby bus-bars are represented by line charges, their potential is assumed to be zero. The influence of tower insulators is neglected when the field is calculated. In this paper the HV systems of alternating current are considered, therefore the potential and charge densities are complex quantities.

In this paper the Charge Simulation Method is used to compute the electric fields [7], where the live conductors are simulated by a number of discrete simulation charges located on the axis of these 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 conductors can be calculated using the superposition principle using the following equations:

$$[V] = [P][Q] \tag{1}$$

Where: [Q] is a column vector of the fictitious simulation charges, [V] is a column vector of the potential given by the boundary conditions and [P] is the matrix of the Maxwell potential coefficients which depend on the type of fictitious simulation charges [5, 7].

In our developed model, we simulate HV and LV bus-bars, incoming 500 kV feeders and outgoing 220 kV feeders by internally located line charges on their axes. Therefore the potential coefficient is given by [8]:

$$P_{ij} = \frac{1}{4\pi\varepsilon d} \ln\left\{ \frac{(L_1 + L_2 + d)(L_{11} + L_{22} - d)}{(L_1 + L_2 - d)(L_{11} + L_{22} + d)} \right\} \tag{2}$$

Where

$$L_1 = \sqrt{(X - X_1)^2 + (Y - Y_1)^2 + (Z - Z_1)^2}$$
$$L_2 = \sqrt{(X - X_2)^2 + (Y - Y_2)^2 + (Z - Z_2)^2}$$
$$L_{11} = \sqrt{(X - X_1)^2 + (Y - Y_1)^2 + (Z + Z_1)^2}$$
$$L_{22} = \sqrt{(X - X_2)^2 + (Y - Y_2)^2 + (Z + Z_2)^2}$$
$$d = \sqrt{(X_1 - X_2)^2 + (Y_1 - Y_2)^2 + (Z_1 - Z_2)^2}$$

$$\begin{cases} F_x = \frac{1}{4\pi\varepsilon d}\left\{ \left(\frac{X - X_1}{L_1} + \frac{X - X_2}{L_2}\right)\Gamma 1 - \left(\frac{X - X_1}{L_{11}} + \frac{X - X_2}{L_{22}}\right)\Gamma 2 \right\} \\ F_y = \frac{1}{4\pi\varepsilon d}\left\{ \left(\frac{Y - Y_1}{L_1} + \frac{Y - Y_2}{L_2}\right)\Gamma 1 - \left(\frac{Y - Y_1}{L_{11}} + \frac{Y - Y_2}{L_{22}}\right)\Gamma 2 \right\} \\ F_z = \frac{1}{4\pi\varepsilon d}\left\{ \left(\frac{Z - Z_1}{L_1} + \frac{Z - Z_2}{L_2}\right)\Gamma 1 - \left(\frac{Z + Z_1}{L_{11}} + \frac{Z + Z_2}{L_{22}}\right)\Gamma 2 \right\} \end{cases} \tag{3}$$

Where

$$\Gamma 1 = \frac{1}{(L_1 + L_2 - d)} - \frac{1}{(L_1 + L_2 + d)}$$
$$\Gamma 2 = \frac{1}{(L_{11} + L_{22} - d)} - \frac{1}{(L_{11} + L_{22} + d)}$$

Therefore the net field ($\underline{E}_i$) at any point (P_i) due to a number of individual charges (n) each with charge of (Q_j) is given as:

$$\vec{E}_i = \left[\sum_{j=1}^{n} (F_{ij})_x * Q_j\right]\vec{a}_x + \left[\sum_{j=1}^{n} (F_{ij})_y * Q_j\right]\vec{a}_y + \left[\sum_{j=1}^{n} (F_{ij})_z * Q_j\right]\vec{a}_z \tag{4}$$

Where $(F_{ij})_x$, $(F_{ij})_y$ and $(F_{ij})_z$ are the 'field intensity' or field coefficients and $\underline{a}_x$, $\underline{a}_y$ and $\underline{a}_z$ are unit vectors in the x, y and z directions, respectively [8].

C. Model of worker's body and calculation of surface charges and induced body currents

In the system under study, surface charges on the HV and LV bus-bars, incoming 500 kV feeders and outgoing 220 kV feeders are simulated by finite line charges located at each line axis. 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 and arms. The human body is treated as a conducting body because of the large conductivity and the large relative equivalent dielectric constant of it. The simulated charges distribution for the human body are simulated as ring charges for the human head, neck, waist and legs while the arms are simulated as finite line charges as shown in Fig. 3. Typical values for the human body dimensions are 80 mm for the head radius, 40 mm for the neck radius, 200 mm for the waist radius, and 80 mm for the leg radius (Fig. 3). The length of the neck is 100 mm, the length of the waist/crotch is 720 mm, and the length of the legs is 820 mm, for a person of 1800 mm height.

The potential is calculated at the location of contour points chosen on the human body surface and consequently the induced electric field, induced current densities and currents are calculated on the surface of the human body at different parts.

The total electric field at the i[th] contour point is expressed as:

$$E_i = \sqrt{(E_{xi}^{\ 2} + E_{yi}^{\ 2} + E_{zi}^{\ 2}} \tag{5}$$

Once the simulation charges and the electric fields at the surface of the body are calculated, the induced current

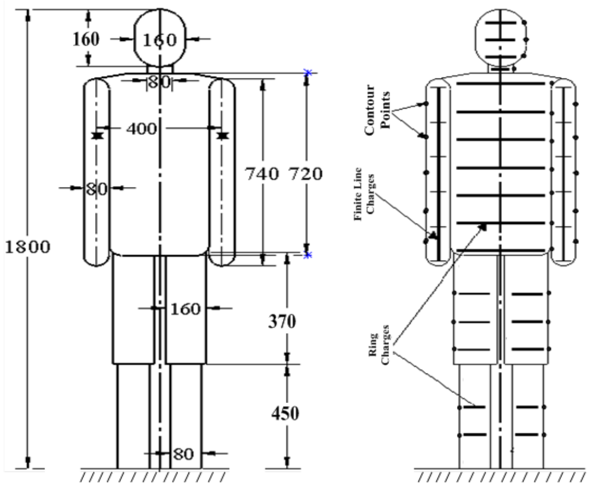


Fig. 3 Dimensions and charge simulation model for Worker's body.

densities and currents at the surface of the body are determined [9-11].

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

$$\sigma_s = \varepsilon_0 E_n \tag{6}$$

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 surface of the worker's 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:

$$J = w\sigma_s = w\varepsilon_0 E_n \qquad (7)$$

Where ω is the angular frequency of the applied voltage to the high voltage line conductor (ω= 2π f).
The induced current (I_k) just inside the boundary of any part inside the worker's body, say k^{th}, is obtained by integrating J over the surface area (S_k) of the part.

$$I_k = \oint_{s_k} J.ds = \oint_{s_k} w\sigma_s ds = w\varepsilon_0 \oint_{s_k} E_n ds \qquad (8)$$

On the other hand, the current density distribution inside the body depends on the material constants (conductivity and relative equivalent dielectric constant) assigned to the human organs filling the volume of the body. The various conductivity and relative equivalent dielectric constant of human Tissue [12] is given in Table 1.

III. SIMULATION RESULTS and DISCUSSIONS

This study was conducted not only for a workers standing on the ground surface with his foot in switchyards during normal operation and (hot-stick position) during live-working conditions (Scenario 1), but also for a workers in live line maintenance position (bare hand position), at a height of 11 m for 500 kV switchyard and 8.5 m for 220 kV switchyard (Scenario 2) and at a height of 17 m for 500 kV switchyard and 11 m for 220 kV switchyard (Scenario 3). The human body was assumed to be standing in free space and not in contact with electrical ground. Workers in bare-hand working operate very close to live conductors and they wear special conductive clothing which protects them against the exposure of the electric field. These clothes are ignored in our simulation.

TABLE 1
TISSUE CONDUCTIVITY AND PERMITTIVITY VALUES AT 50 HZ

Tissue	Relative Permittivity ϵ_r	Conductivity $\sigma(S/m)$
Fat	$1.14\text{x}10^6$	0.019
Muscle	$1.77\text{x}10^7$	0.23
Bone	8867.8	0.02
Cartilage	$1.64\text{x}10^6$	0.17
Skin(dry)	1136	$2\text{x}10^{-4}$
Nerve	$1.61\text{x}10^6$	0.027
Heart	$8.66\text{x}10^6$	0.083
Blood	5260	0.7
Brain White matter	$5.29\text{x}10^6$	0.053
Brain Grey matter	$1.21\text{x}10^7$	0.075

Figures 4-a, 4-b, 4-c, 4-d and Fig.5 show the electric field distribution inside Cairo 500 substation for the three scenarios mentioned previously while Table 2 summarizes the maximum electric field values and their total induced currents and current densities for different working conditions.

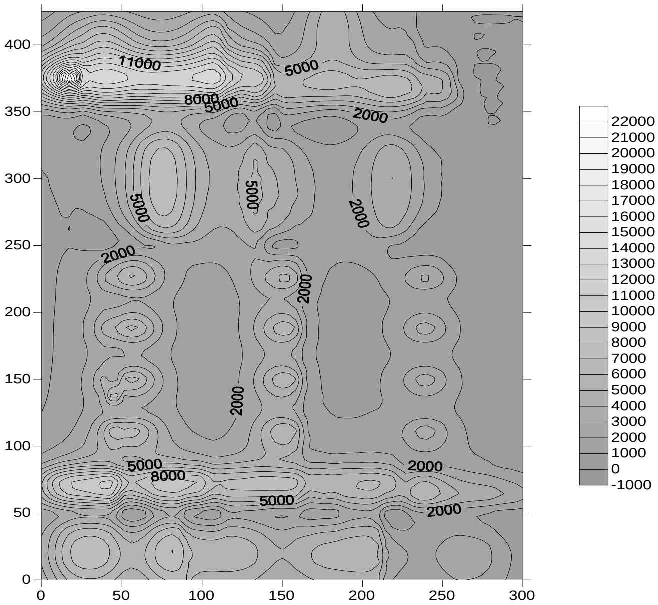


Fig. (4-a) The electric field distribution inside Cairo 500 substation during scenario 1.

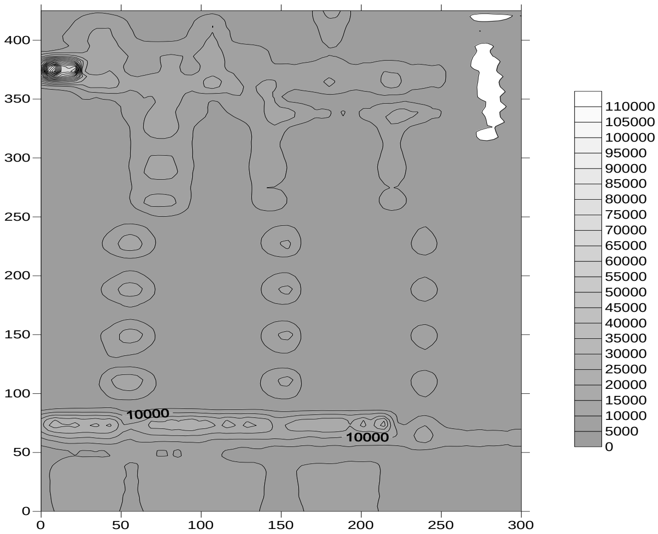


Fig. (4-b) The electric field distribution inside Cairo 500 substation during scenario 2.

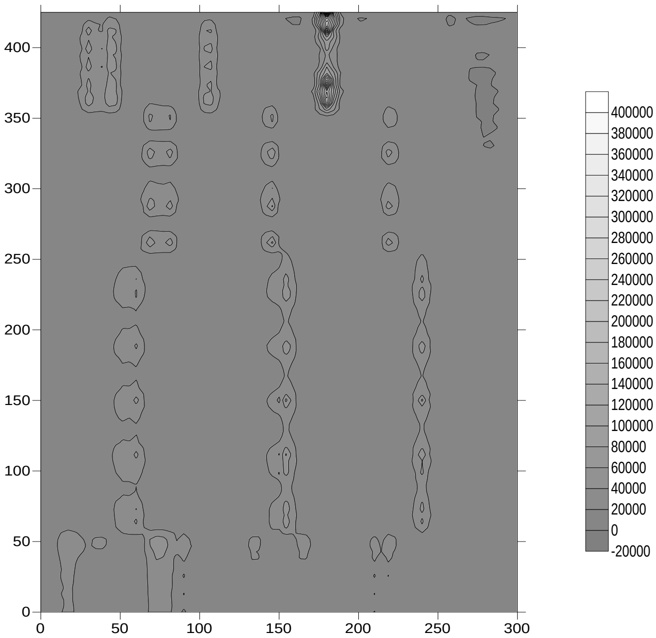


Fig. (4-c) The electric field distribution inside Cairo 500 substation during scenario c.

TABLE 2
MAXIMUM ELECTRIC FIELD AND THEIR INDUCED CURRENTS AND CURRENT DENSITIES FOR DIFFERENT WORKING CONDITIONS.

	Calculated Field Values		Measured Field Values		Calculated Current & Current Density Values	
	Max. Value of Total Elec. Field Et (Max) (kV/m)	AVG. Value of Total Elec. Field Et (Avg) (kV/m)	Max. Value of Total Elec. Field Et (Max) (kV/m)	AVG. Value of Total Elec. Field Et (Avg) (kV/m)	Max J (mA/m^2)	Total Current I (mA)
Scenario 1	23.47	10.57	22.90	9.64	0.0652	0.0407
Scenario 2	118.54	21.63	-----	-----	0.3296	0.2056
Scenario 3	396.07	23.73	-----	-----	1.1012	0.6869

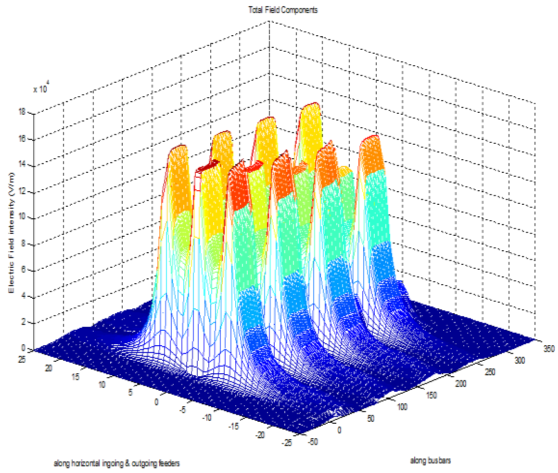


Fig. (4-d) The electric field distribution under 500 kV switchyard during scenario 2.

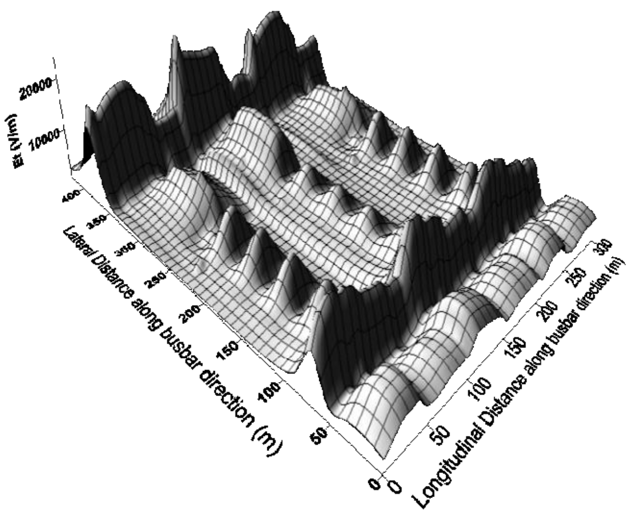


Fig. 5 The electric field distribution inside all substation switchyard during scenario 1.

From these figures and table presented above, it is found that the maximum calculated electric field imposed to the human body during hot-stick position (scenario 1) is about 23.5 kV/m while the maximum measured electric field imposed to the human body during this position (scenario 1) is about 23 kV/m, and the average calculated electric field imposed to the human body during hot-stick position (scenario 1) is about 10.6 kV/m while the average measured electric field imposed to the human body during this position (scenario 1) is about 9.6 kV/m. Therefore the simulation results are matched with the measured values with very small tolerance (about 2.2%) which is because of the assumption taken during the simulation and due to the field meter used in the measurements is dependent on the natural of place where the electric field is measured [13, 14].

It is also found that the maximum calculated electric field imposed to the human body during bare- hand position (scenario 2) is about 118.5 kV/m and that for scenario 3 is about 396 kV/m (without considering the effects of insulating clothes) which are consistent with other related study [15].

Following the electric field during live line maintenance, the electric field intensity is higher, exceeds, the exposure limit. So the workers should not last for more than several minutes in live line maintenance position.

Computed induced current densities are evaluated with respect to safe limits, and it is found that these current densities are not exceeds the safe limit of 10 mA/m^2 while total induced current on the human body is also well below the 1 mA level in all cases of study [2-4].

IV. CONCLUSIONS

In this study, a method is proposed for determining the distribution of the electric fields, induced charges, and currents in a human body standing in high electric fields produced inside high-voltage substations. This method is based on the charge simulation technique. And the most important results are as follows:

- It is found that the electric field changes from point to point and the induced current in the human body changes accordingly.
- The value of electric field during live line maintenance is higher, exceeds, the exposure limit. So the workers should not last for more than several minutes in live line maintenance position.
- Induced current density values increase along the length of the body, starting from the legs to the head except neck, due to the increase in the surface electric field.
- a good agreement has been found on the values of the fields and induced currents calculated in different sections of the human body.

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VI. BIOGRAPHIES

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