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Investigation of Electric Field Distribution Inside 500/220 kV Transformation Substations during Different Working Conditions

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ABSTRACT

This study depicts the electric field distributions inside a typical 500/220 kV open distribution substation under actual loading conditions and during different working conditions, Hot-Stick position and Bar-Hand position. The electric field is investigated for different workers heights of 1m, 1.5m and 1.8m above ground during normal working condition (Hot-Stick position) inside this substation. This in addition to assessment of the electric field at a height levels of 8m, 11m, 14m and 17m above ground as positions for live line maintenance under 220 kV Busbars, 500 kV Busbars, 220 kV Incoming and Outgoing feeders and 500 kV Incoming and Outgoing feeders respectively. In this study the simulation results of the electric field obtained using three dimensional (3D) computer model for existing typical high voltage transformation substation are compared with field values measured inside this typical substation and presented and discussed not only in the form of contour maps but also in the form 3D surface and wireframe maps. The simulation results are good matched and agreed with measured values. This in addition to the electric field will be tabulated and compared to international guidelines for personnel exposure to electric field. This study will serve for planning service works or for inspection of equipment inside high voltage (HV) power transformation substations.

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1. INTRODUCTION

For much of the history of the electrical power system, the size of a high voltage transmission system was not of much concern because they were located in rural or heavily industrialized areas where the cost of the real estate was small and their overbearing presence was of little concern to the general public. Their exposure may be as small as walking under it or large as constructing a home or business under it.

The ever-increasing need for electrical energy has resulted in high voltage substations being placed much closer to their loads and in commercial or residential areas. To exemplify this, consider that a high voltage substation does not have a negative impact when it is constructed adjacent to a refinery or paper mill. In addition to visual impact, there is ongoing concern about the effect of exposure to electric and magnetic fields.

An area of little investigation until now is the electric fields generated by a transformation substation and how these will change as we try to decrease the size and height of the substation. Constructing a substation with a more compact design will result in increased electric field exposures to any workers in the energized substation. As the workers cannot be exposed to a potentially unsafe amount of electric field, we will have to balance the compact design with the amounts of electric field exposure.

The effect of the electric field is especially important in the areas closed to high voltage facilities. The electric field strength that occurs in the vicinity of these HV facilities must not exceed the levels proposed by environmental and health regulations and standards [1]. 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. This harmful attract an increased attention of many biomedical field researchers, scientific research communities worldwide on the health effects of electric power systems.

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 [2-6], to guarantee the life insurance of all staff working inside these substations.

Inside 500/220 kV substation, Works are connected with operative switching, equipment inspection, different repair work, etc. require presence of staff personal in various points of 500 kV and 220kV Switchyards (substation territory). Therefore, the investigation for the distribution levels of the electric fields inside these substations is an important step for solving the problem of personnel protection from the effects of these fields.

In this study, the present algorithm is carried out to assessment the distribution levels of the electric field intensity produced by different high voltage electrical power systems inside 500/220 kV air-insulated (AIS) substation. This study depicts the electric field distributions inside a typical 500/220 kV substation, Cairo 500 substation, under actual loading conditions and during different working conditions (Hot-Stick position and Bar-Hand position). The electric field is investigated for different workers heights of 1m, 1.5m and 1.8m above ground. These fields are observed during normal working condition (Hot-Stick position) inside this substation. This in addition to assessment of these fields at different height levels which represent the possible positions of workers during working as live line maintenance (Bar-Hand position) such as at heights of 8m, 11m, 14m and 17m above ground as positions for live line maintenance under 220 kV Busbars, 500 kV Busbars, 220 kV Incoming and Outgoing feeders and 500 kV Incoming and Outgoing feeders respectively. In this study the simulation results of the electric field obtained using three dimensional (3D) computer model for existing typical substation are compared with field values measured inside this typical substation and compared with international guidelines for personnel exposure to electric field [3, 4]. The results are tabulated and presented not only in the form of contour maps but also in the form 3D surface and wireframe maps. This study will serve for planning service works or for inspection of equipment inside HV power transformation substations.

2. SUBSTATION DESCRIPTION

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, main and standby bus-bars. This substation has three identical 3-ph, 500 MVA, 500/220/11 kV power transformers installed inside it, each one 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, 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. 3D spatial models of this substation, Cairo 500 substation, for all substation area, 500 kV switchyard and 220 kV switchyard are presented in Figures 1, 2 and 3 respectively.

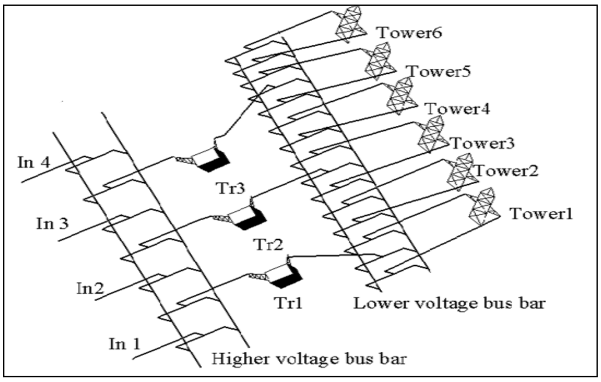

Figure 1. The 3D spatial model of Cairo 500 substation, all area.

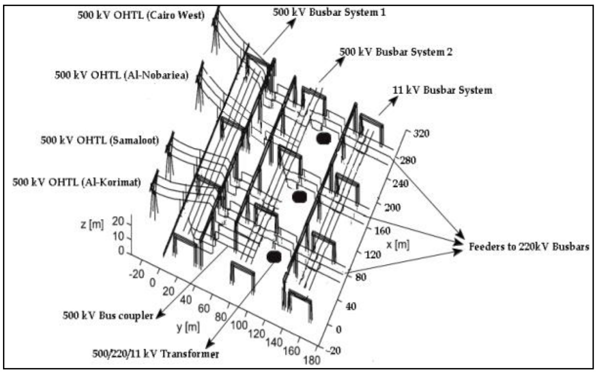

Figure 2. The 3D spatial model of Cairo 500 substation, 500 kV Switchyard

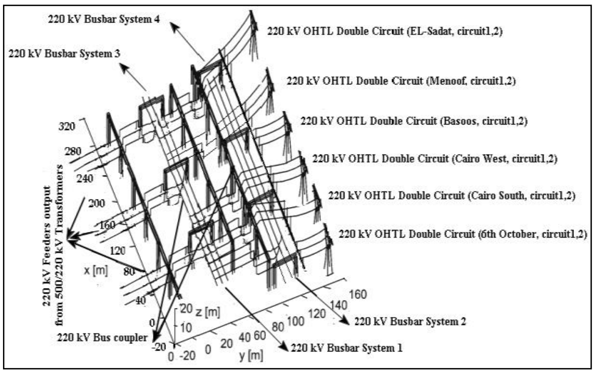

Figure 3. The 3D spatial model of Cairo 500 substation, 220 kV Switchyard.

3. SUBSTATION MODELING

In this study CSM is used to compute the electric field inside this substation produced by main substation power conductors and sub conductors. The developed M-Scripts are using the discrete fictitious finite line charges for modeling of line conductors and busbars conductors. The higher voltage (HV) 500 kV bus conductors lower voltage (LV) 220 kV bus conductors, 500 kV incoming and outgoing feeders and 220 kV ingoing and outgoing feeders are approximated by internally located fictitious finite line charges along the center axes of them. These line charges are considered as a proposed solution of Laplace equation which governs the assessment of the electric field [7-10].

The electric potential of all incoming feeders, outgoing 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 finite line fictitious charges, their potential is assumed to be zero. The electric field inside HV substations 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 study, these elements will be ignored and the influence of supporting insulators is neglected. Such a simplification is acceptable when the field is analyzed at along enough distance from the conductor, e.g. near the ground surface.

For evaluating the electric field distribution inside HV Cairo 500 substation, we consider the area of our calculations inside this substation as 300*400 m^2 around and underneath busbars; 300 m along the busbars length (lateral direction / X- direction), 400 m along the incoming and outgoing feeders length (longitudinal direction / Y- direction). This area is consist of two sections, one of them has 300 m on lateral direction and 165 m on longitudinal direction for 500 kV switchyard, the second has 300 m on lateral direction and 235 m on longitudinal direction for 220 kV switchyard. Fig. 4 and Fig. 5 show a simple graphical model of 500 kV switchyard to be simulated (arrangement of 500 kV busbars, vertical connectors, incoming feeders to busbars and outgoing feeders to transformers), while a simple graphical model of 220 kV switchyard to be simulated is simply presented in Fig. 6 and Fig. 7 (arrangement of 220 kV busbars, vertical connectors, incoming feeders from transformers to busbars and outgoing feeders to loads).

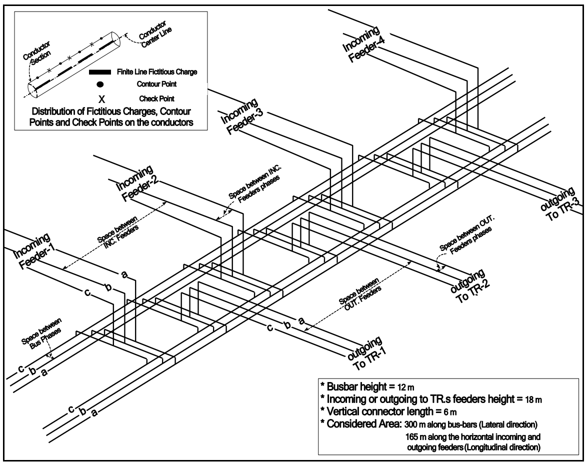

Figure 4. Developed model of 500 kV switchyard arrangement to be simulated.

4. ELECTRIC FIELD CALCULATION METHODOLOGY

In this paper the Charge Simulation Method is used to compute the electric fields. The basic principle of CSM lies in replacing the surface charge of live conductors with a set of discrete fictitious finite line

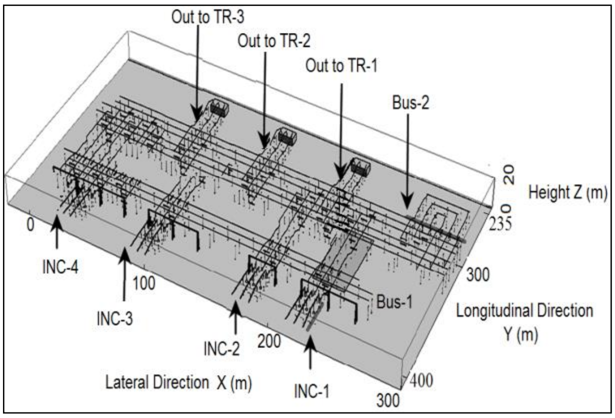

Figure 5. Graphical model of 500 kV switchyard arrangement to be simulated – 3D Spatial View.

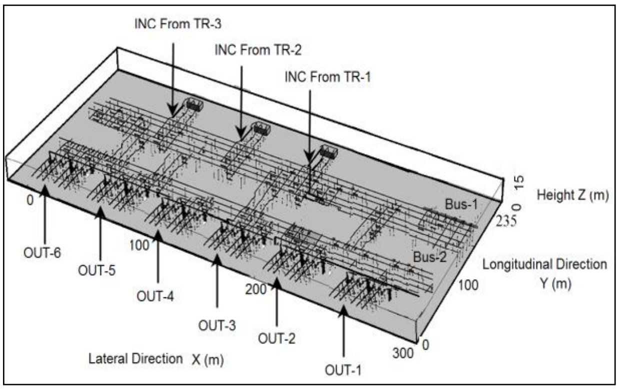

Figure 6. Graphical model of 220 kV switchyard arrangement to be simulated – 3D Spatial View.

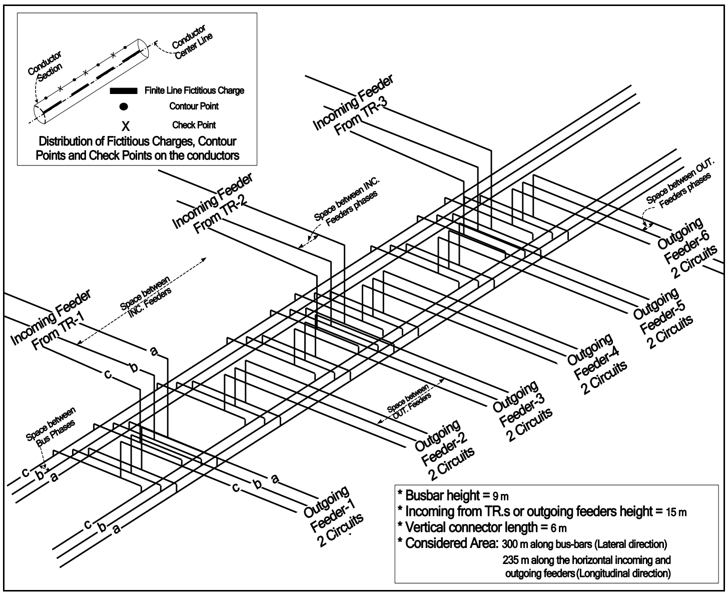

Figure 7. Developed model of 220 kV switchyard arrangement to be simulated

Charges, located inside the conductor and along the center axes of them, where these fictitious charges generate the electric field of similar intensity and direction as the original conductors in the observed zone. Figure. 8 shows a sample for the distribution of finite line charges, boundary points and check points on only one phase conductor in developed models for simulation. These finite line charges and check points are located at conductor levels while some contour points are located at conductor levels and others at ground level to satisfy the image conditions. The values of these discrete charges are determined by satisfying the boundary conditions in equation (1) at a selected number of contour points where the potentials of these fictitious charges are taken as particular solutions of Laplace equation which governs the assessment of the electric field [9, 10].

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

Where:
[Q] is a column vector of the fictitious simulation charges,
[V] is a column vector of the potential given by the boundary conditions,
[P] is the matrix of the Maxwell potential coefficients which depend on the type of fictitious simulation charges as shown in fig. 9.

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:

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

Where

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

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

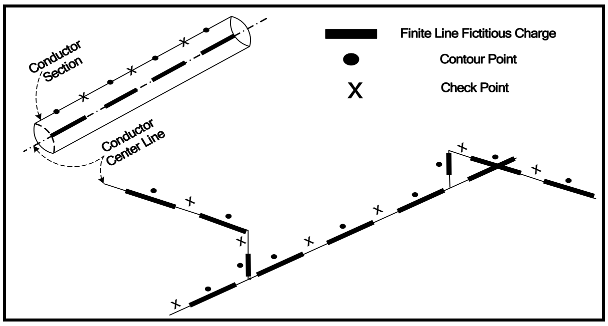

Figure 8. Distribution of finite line charges, check and boundary points on only one phase.

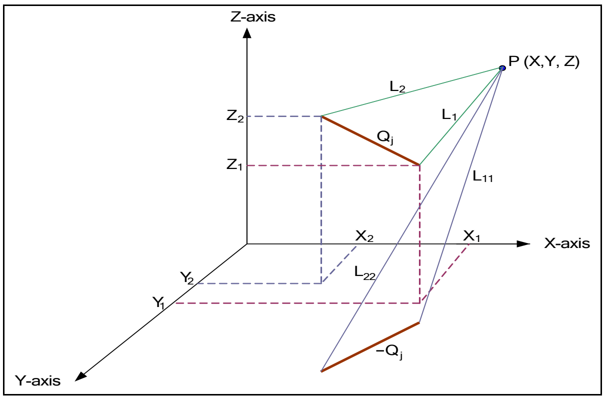

Figure 9. Finite line charge and contour point Pi in three dimensional x, y and z directions.

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 (E_i) at any point (P_i) due to a number of individual charges (n) each with charge of (Q_j) is given as:

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

Where $(F_{ij})_x$, $(F_{ij})_y$ and $(F_{ij})_z$ are the 'field intensity' or field coefficients and a_x, a_y and a_z are unit vectors in the x, y and z directions, respectively [10].
The total electric field at the i^{th} contour point is expressed as:

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

The methodology of 3D CSM used in the calculation and investigation of the electric field distribution inside selected typical HV substation is simply presented in the schematic described in Figure. 10.

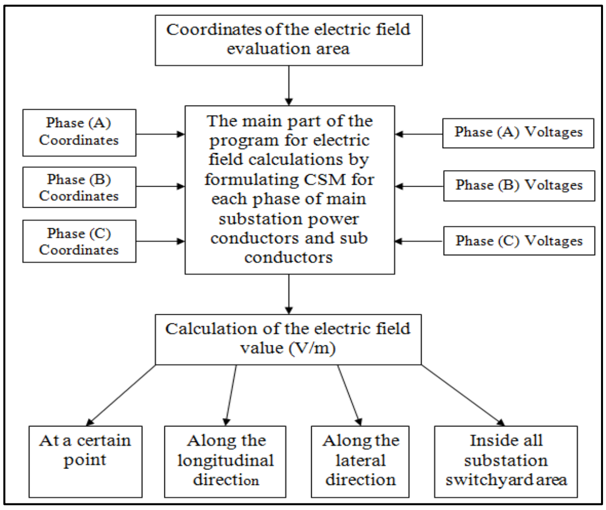

Figure 10. Simplified schematic diagram for the developed MATLAB program.

5. SIMULATION RESULTS AND DISCUSSIONS

5.1. Electric Field Distribution During Normal Conditions

The electric field is investigated inside a typical 500/220 kV substation under actual loading conditions for different workers heights of 1m, 1.5m and 1.8m above ground during normal working condition (Hot-Stick position) inside this substation. Figures 11, 12 and 13 present the electric field distribution over all territory of selected substation for different workers heights of 1m, 1.5m and 1.8m above ground in the form of contours maps respectively. From these figures, it is noticed that by increasing the workers/calculation height, the density of electric fields' contour lines nearby the busbars, ingoing and outgoing feeders increased and the maximum, average and minimum values of the electric field strength increased also as shown in Table 1. This in adition to except for the areas nearby the busbars the contour lines are aligned with the line conductors with electric field values related to the lines' voltage values.

Table 1. Electric field values for different workers heights of 1m, 1.5m and 1.8m inside HV 500/220 kV substation.

Workers / Calc. Height	**Max Elec. Field**		**Min. Elec. Field**		**Avg. Elec. Field** (kV/m)
	Value (kV/m)	Position (X, Y) m	Value (V/m)	Position (X, Y) m	
1 m	24.23	x=220 y=300	71.92	x =0 y=137.5	8.49
1.5 m	25.78		76.53		9.04
1.8 m	27.11		80.47		9.5

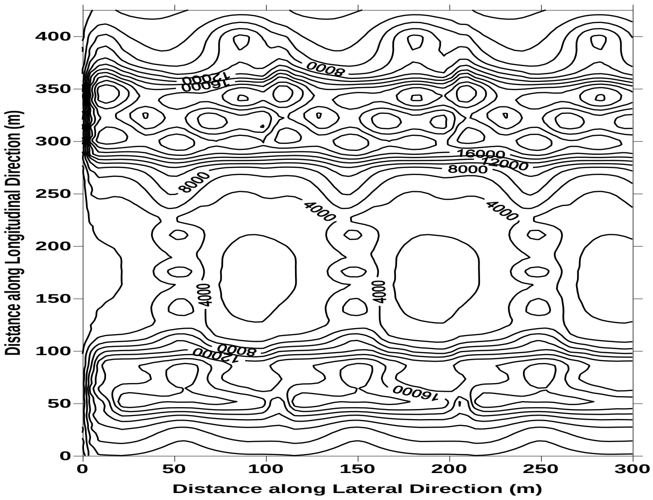

Figure 11. Contour map for the electric-field distribution throughout all the substation area, at 1m above ground level.

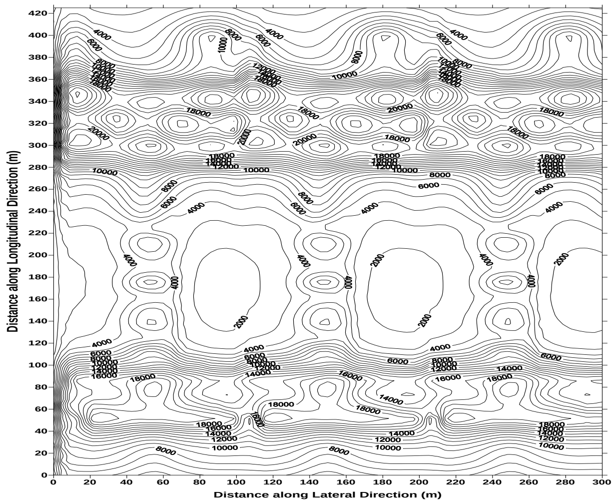

Figure (12): Contour map for the electric-field distribution throughout all the substation area, at 1.5m above ground level

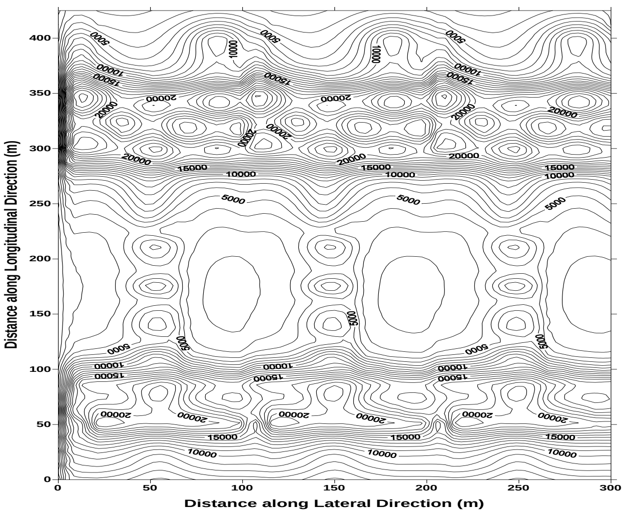

Figure 13. Contour map for the electric-field distribution throughout all the substation area, at 1.8m above ground level.

These results obtained for electric field exposure entire all territory of the modeled substation are analyzed and compared with international exposure limits and safety guidelines for electric field exposure for the working personnel. Table (2) shows, in percent, values of zones entire all territory of this substation with electric field intensities below and above international exposure limits and safety guidelines for electric field exposure for different workers heights of 1m, 1.5m and 1.8m. While Table (3) and Table (4) show the distribution of Electric Field strength over all territory of 220 kV and 500 kV switchyards area for different workers heights of 1m, 1.5m and 1.8m respectively.

Table 2. Zones entire all territory of Cairo 500 substation with electric field below and above international exposure limits for different workers heights, 1m, 1.5m and 1.8m.

E Range (kV/m)	**Electric field below Public exposure limit ($0\leq E<5$)**	**Electric field below ICNIRP occupational exposure limit ($5\leq E<10$)**	**Electric field above ICNIRP occupational exposure limit or below IEEE occupational exposure limit ($10\leq E<20$)**	**Electric field above ICNIRP or IEEE occupational exposure limit ($E>20$)**
Territory,%, For workers of height 1m	45.5%	23.81%	28.07%	2.62%
Territory,%, For workers of height 1.5m	43.39%	23.99%	27.42%	5.20%
Territory,%, For workers of height 1.8m	42.03%	23.57%	25.97%	8.43%

Table 3. The distribution of Electric Field strength over all territory of 220 kV switchyard area for different workers heights.

	The part of 220 kV switchyard territory,%, where the electric field is in the range (E in kV/m)		
E Range (kV/m)	**$0\leq E<5$**	**$5\leq E<10$**	**$10\leq E<15$**
Territory,%, For workers of height 1m	76.7%	23.3%	0%
Territory,%, For workers of height 1.5m	72.29%	25.32%	2.39%
Territory,%, For workers of height 1.8m	71.56%	24.03%	4.29%

Table (4): The distribution of Electric Field strength over all territory of 500 kV switchyard area for different workers heights.

E Range	0≤E<5	5≤E<10	10≤E<15	15≤E<20	20≤E<25	25≤E<30
	The part of 500 kV switchyard territory,%, where the electric field is in the range (E in kV/m)					
Territory,%, For workers of height 1m	24.81	32.54	14.71	21.76	6.18	0
Territory,%, For workers of height 1.5m	22.56	31.68	15.81	18.35	11.14	0.46
Territory,%, For workers of height 1.8m	20.37	30.35	16.39	15.41	15.58	1.9

According to all investigations achieved above for different workers heights during working in live condition at normal operation, the maximum values of the electric field strength obtained at most territory of this substation are less than 20 kV/m (the guidelines of the IEEE Std. C95.6 for occupational exposure) except only at certain few points (not exceeds 2.62% for workers of 1m height, 5.2% for workers of 1.5m height and 8.43% for workers of 1.8m height of overall substation territory) in this substation it reaches and exceeds 20 kV/m. These results are good matched and agreed with other related studies [11-13].

5.2. Electric Field Distribution During Live Line Maintenance

This study was conducted not only for a workers standing on the ground surface with his foot in switchyards during normal operation (hot-stick position), but also for a workers in live line maintenance position (bare hand position) under actual loading conditions. This field is calculated inside this modeled typical HV substation at a height levels of 8m, 11m, 14m and 17m above ground, approximating the height level of a workman above ground level during live line maintenance, as positions for live line working condition inside this substation nearby and underneath 220 kV busbars, 500 kV busbars, 220 kV ingoing and outgoing feeders and 500 kV ingoing and outgoing feeders respectively. This field is calculated without considering the effects of insulating/protective clothes. Figures 14-a, 14-b, 15-a, 15-b, 16-a, 16-b, 17-a and 17-b present the electric field distribution over all territory of 500 kV and 220 kV switchyards at live line maintenance height levels described previously in the form of contours map and 3D surface map respectively.

From these figures, it is noticed that the maximum electric field values imposed to the human body during bare-hand position are 64.99 kV/m for height of 8m and occurs at position (x=210 m and y=90 m) located under 220 kV Bus-2, 134.02 kV/m for height of 11m and occurs at position (x=288 m and y=345 m) located under 500 kV Bus-1, 200.62 kV/m for height of 14m and occurs at position (x=60 m and y=75 m) located underneath 220 kV Buses and 214.89 kV/m for height of 17m and occurs at position (x=66 m and y=295 m) located under 500 kV Bus-1. According to all investigations achieved above for all cases and positions of workers during working in live line maintenance, the maximum values of the electric field strength obtained are good matched and consistent with other related studies [14,15].

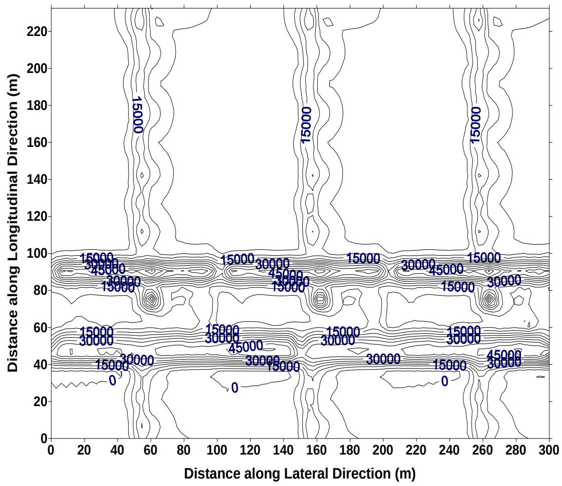

Figure 14. a. Contour map for the electric-field strength distribution throughout 220 kV switchyard area, at 8m above ground level.

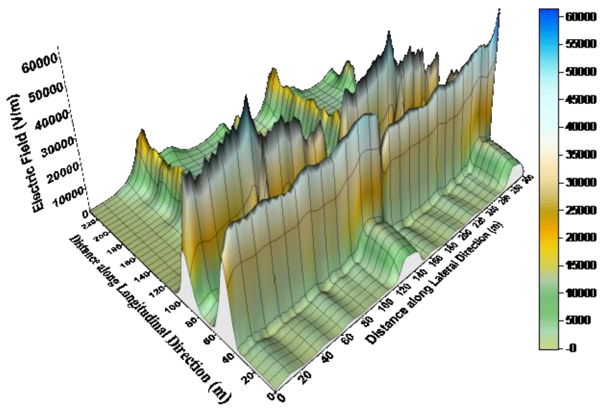

Figure 14.B. Surface map for the electric-field strength distribution throughout 220 kV switchyard area, at 8m above ground level.

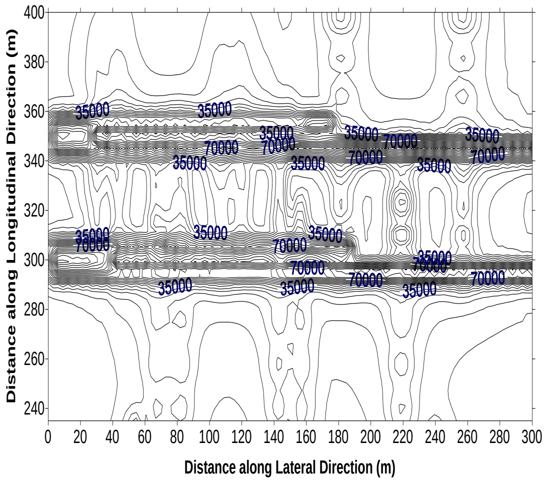

Figure (15-a): Contour map for the electric-field strength distribution throughout 500 kV switchyard area, at 11m above ground level.

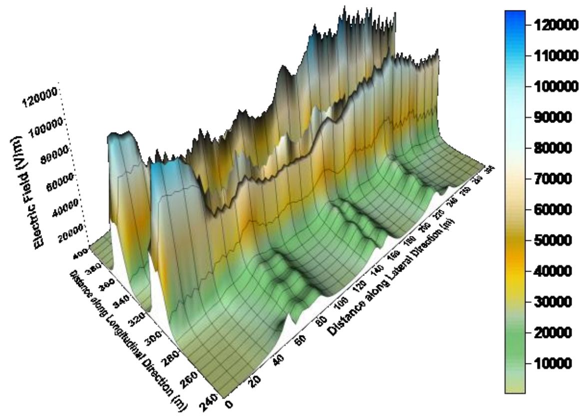

Figure (15-b): Surface map for the electric-field strength distribution throughout 500 kV switchyard area, at 11m above ground level.

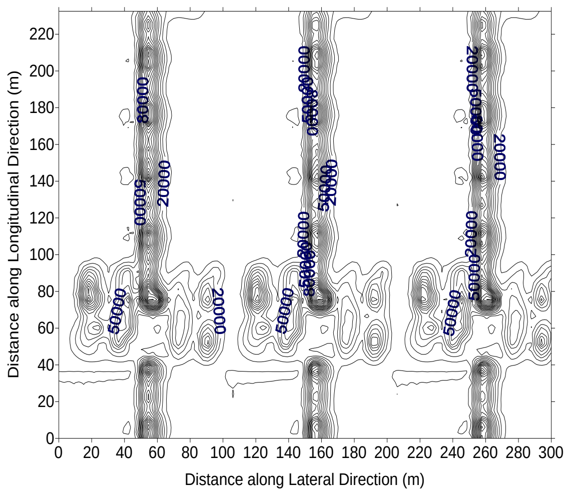

Figure 16.a. Contour map for the electric-field strength distribution throughout 220 kV switchyard area, at 14m above ground level.

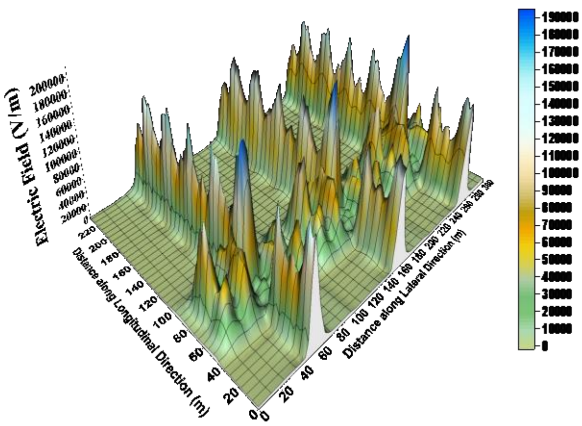

Figure 16.b. Surface map for the electric-field strength distribution throughout 220 kV switchyard area, at 14m above ground level

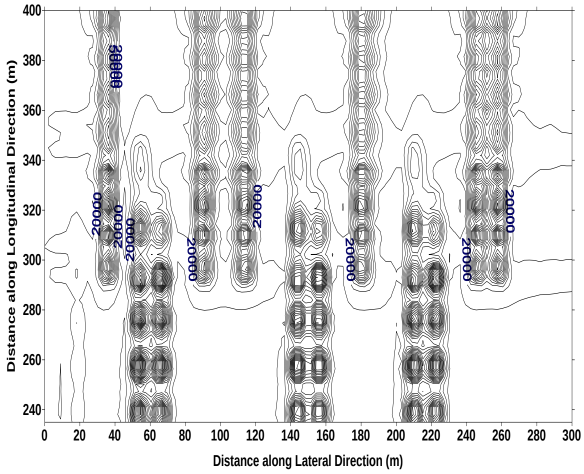

Figure 17.a. Contour map for the electric-field strength distribution throughout 500 kV switchyard area, at 17m above ground level.

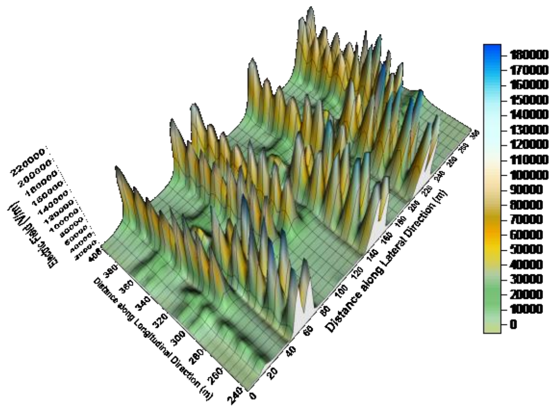

Figure (17-b): Surface map for the electric-field strength distribution throughout 500 kV switchyard area, at 17m above ground level.

6. MEASUREMENTS RESULTS AND DISCUSSIONS

The electric field produced inside this typical 500/220 kV substation is measured and profiled at a longitudinal distances along 500kV and 220kV ingoing and outgoing lines, while it has been measured at a lateral distances, along 500kV and 220kV bus bars. During these measurements, the electric sensor module (HI 3604 ELF Survey Meter) should be placed far away from the human on a wooden tripod base unit, such that the human body interference on the electric field measurements is avoided, and a fiber optic cable is used to connect it to the base unit [16, 17]. The methodology of electric field measurements under buses and lines conductors was conducted at a height of 1.5m above the ground to study the field levels experienced by human beings through 301 measurement points under each phase of buses' conductors, 76 measurement points under each phase of 500 kV incoming feeders' conductors, 91 measurement points under each phase of 500 kV outgoing feeders' conductors, 161 measurement points under each phase of 220 kV incoming feeders' conductors and 71 measurement points under each phase of 220 kV outgoing feeders' conductors. Figures 18, 19, 20 and 21 show the longitudinal electric field profiles measured and calculated along 500kV and 220kV bus bars and along 500kV outgoings and 220kV ingoings respectively.

These measurements showed that the electric field strength values are higher than the safe occupational exposure limits at certain positions inside this substation. Table (5) shows the maximum measured and calculated electric field strength values along all buses and feeders mentioned above. From these tables, it is observed that the simulation results are consistent with the measured values with very small tolerance 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.

Table 5. Maximum measured and calculated electric field values along all buses and feeders of Cairo 500 substation at height of 1.5m

Location	Max. Measured Elec. Field (kV/m)	Max. Calculated Elec. Field (kV/m)	Error, %
Along 500 kV Buses	24.7	25.6	3.6%
Along 500 kV INC.s	16.68	16.23	2.7%
Along 500 kV OUT.s	16.66	16.82	0.96%
Along 220 kV Buses	10.56	11	4.2%
Along 220 kV INC.s	10.51	10.17	3.2%
Along 220 kV OUT.s	10.44	9.97	4.5%

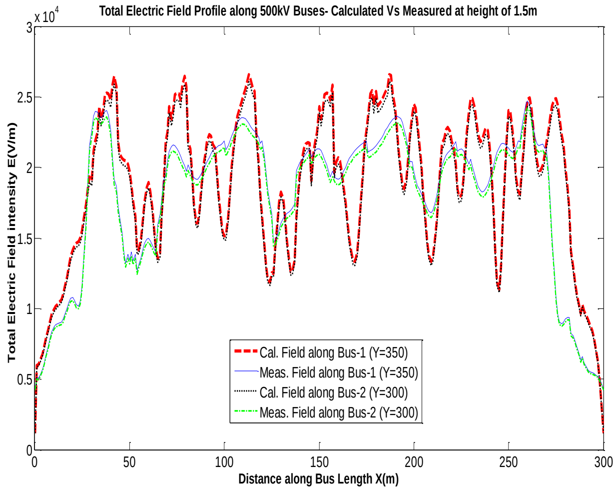

Figure 18. Longitudinal electric field profiles measured and calculated along 500kV Buses inside Cairo 500 Substation.

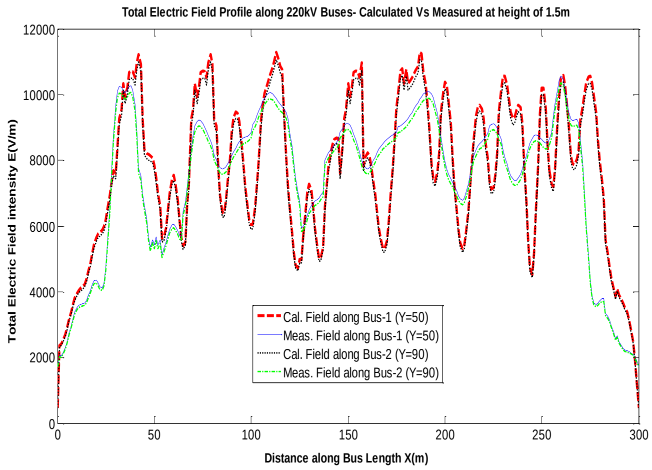

Figure 19. Longitudinal electric field profiles measured and calculated along 220kV Buses inside Cairo 500 Substation.

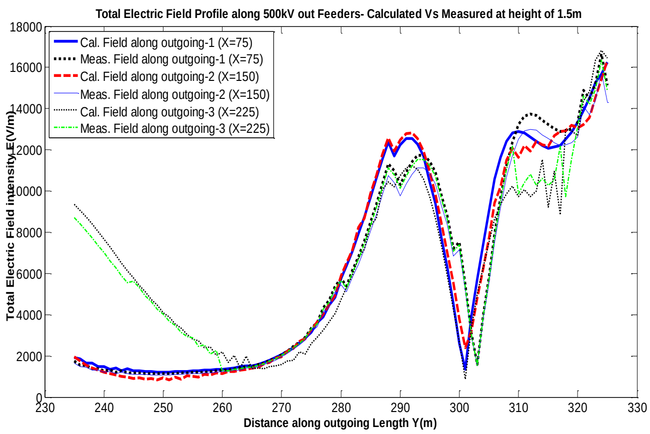

Figure 20. Longitudinal electric field profiles measured and calculated along 500kV OUT.s inside Cairo 500 Substation.

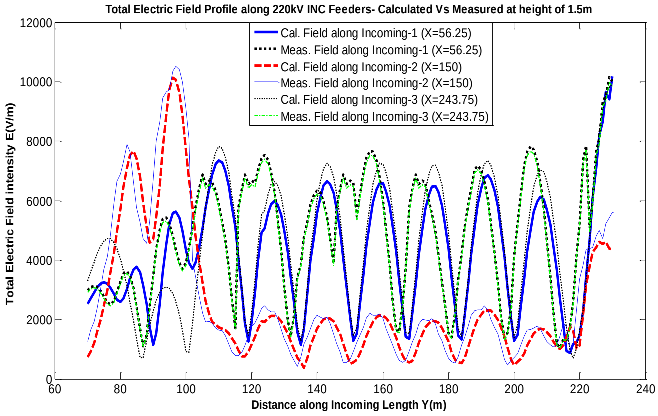

Figure 21 Longitudinal electric field profiles measured and calculated along 220kV INC.s inside Cairo 500 Substation.

7. CONCLUSIONS AND RECOMMENDATIONS

In this study, a method is proposed for investigation the distribution of the electric field produced inside HV substations. This method is based on the charge simulation technique and the most important results from this study are as follows:

- During working in live condition at normal operation inside 500/220 kV substations (hot-stick position), the maximum values of the electric field strength at most territory of this substation are less than 20 kV/m (the guidelines of the IEEE Std. C95.6 for occupational exposure) except only at certain few points (not exceeds 2.62% for workers of 1m height, 5.2% for workers of 1.5m height and 8.43% for workers of 1.8m height of overall substation territory) it exceeds 20 kV/m.
- By increasing the workers/calculation height, the density of electric fields nearby and underneath busbars, ingoing and outgoing feeders increased and the area of zone of security (E<5 kV/m) entire territory of modelled substation decreased while the area of zone of influence (E>5 kV/m) increased.
- During working in live condition as live line maintenance inside 500/220 kV substations (Bar-hand position), the values of the electric field strength are more danger while its maximum values exceed 25 kV/m with about 8.6 times, where the presence without personal protective equipment is much prohibited.
- All simulation results are good matched and consistent with measurements results and other related studies.
- It is recommended for using this study for planning service works or for inspection of equipment inside high voltage power transformation substations.

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