

Assessment of Electric Field Distribution Inside 500/220kV Open Distribution Substations during Working Conditions

Sayed A. Ward, Samy M. Ghania, Essam M. Shaalan*

Electrical Engineering Department, Faculty of Engineering at Shoubra Benha University, Cairo, Egypt

*Corresponding author, e-mail: essam.shihata@feng.bu.edu.eg

Abstract

The high level electric field intensity produced by high voltage (HV) equipments inside 500/220kV substations is harmful for the human (staff) health. Therefore the minimum health and safety requirements regarding the exposure of workers to the risk arising from electric fields produced inside these substations is still considered as a competitive topic for utility designers, world health organization (WHO) and biomedical field researchers. It is very important to have knowledge about levels distribution of electric field intensity within these high voltage substations as early stage in the process of substation design. This paper presents results of investigation 50Hz electric field intensity distribution inside 500/220kV power transmission substations in Cairo, Egypt. This paper presents a method for assessment the distribution of 50HZ electric field intensity distribution inside this substation, this method of analysis is based on the charge simulation technique (CSM). This study will serve for planning service works or for inspection of equipment on HV power transmission substations.

Keywords: charge simulation technique, electric field intensity, high voltage substations

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1. Introduction

Powerful electric systems with very high voltage are the source of harmful electromagnetic field radiation. This is because these electromagnetic field radiations represent the primary source to the resultant electrical current induced in the human body under or near electric power systems [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 [2-4], to guarantee the life insurance of all staff working inside these substations.

The 50Hz electromagnetic field is distributed unevenly in space between separate power installations inside HV substations. In open 500/220kV power transmission substations, the sum of electromagnetic field sources with grounded metal constructions creates a complex picture of the electric field. Works are connected with operative switching, equipment inspection; different repair work, etc. require presence of staff personal in various points of 500kV & 220kV Switchyards (substation territory). Therefore, the investigation of 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 paper, 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 500/220kV air-insulated substation (AIS). In addition to the investigation of levels distribution of electric field intensity inside 500/22kV AIS at 1.5m from ground surface, we will also investigate the distribution levels of electric field intensity during different working conditions and at different positions inside this substation. These calculated levels 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 500/220kV substation with all incoming and outgoing feeders by developing multi-scripts of m-file Matlab software package to calculate the distribution levels of electric field intensity inside this substation. This method is considering the complex systems, including three-dimensional multiple incoming, outgoing overhead lines and bus system inside this substation.

2. Substation Description and System Modeling

The calculations of electric fields are performed inside 500/220kV AIS, Cairo 500 substation. This substation is supplied by four 500kV 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, 500MVA, 500/220/11kV power transformers installed inside it, each one is composed of three single phase transformers. This substation is supplying six loads through six 220kV double-circuit overhead transmission lines which are outgoing from the same 220kV double bus systems, main and standby bus-bars. This substation has a simply 500kV, 220kV bus systems with 300m long and 12m, 9m height respectively. Single line diagram for this substation is presented in Figure 1.

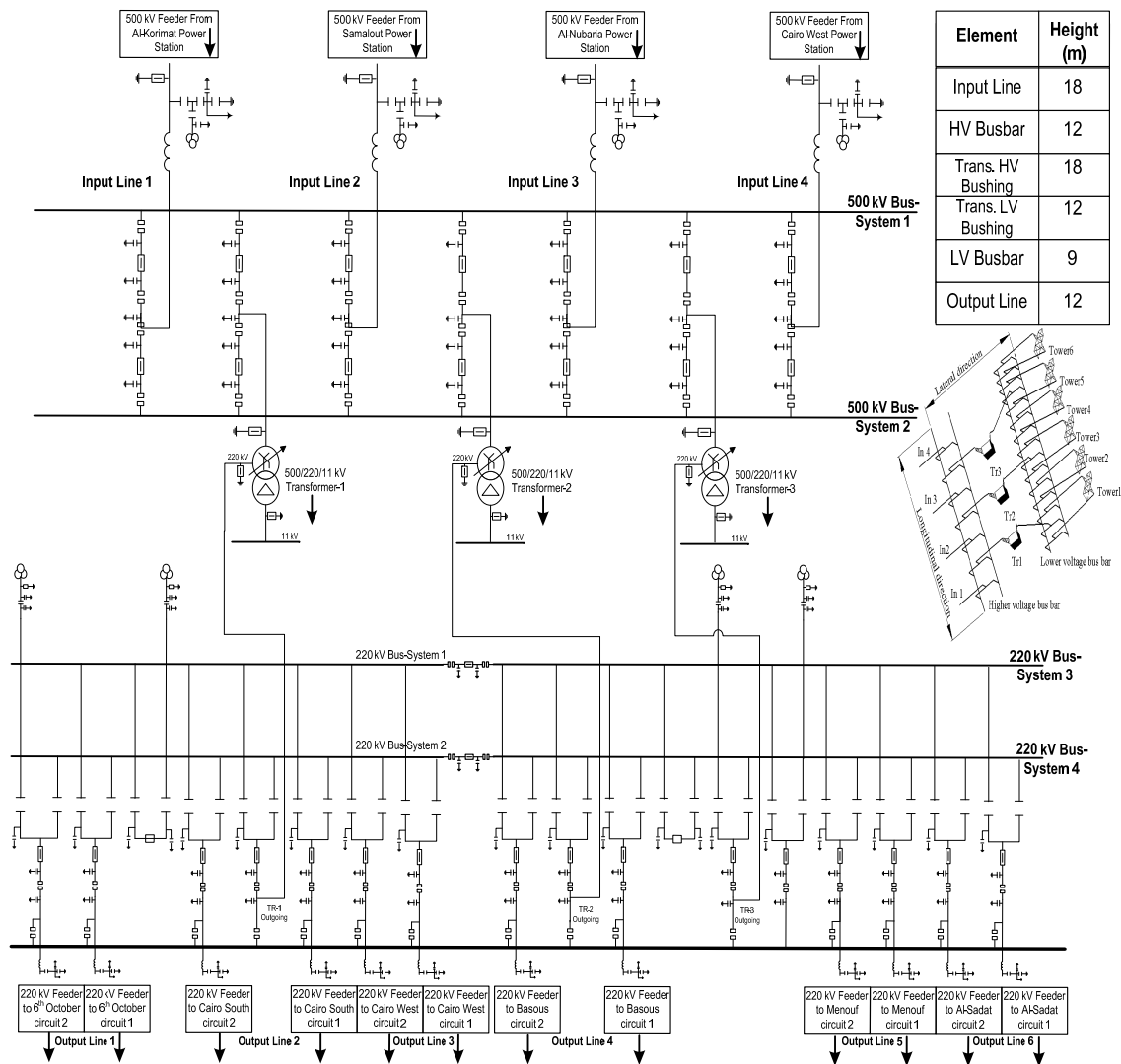


Figure 1. Single Line Diagram of Simulated 500/220kV AIS Substation, Cairo 500 Substation

The location of equipment in the open distribution substation, as usual, is asymmetrical. Some equipment is often located in separate groups. Between these equipments, there are a complex system of busbar, incoming and outgoing feeders which are similar to the web covering all open distribution substation. This complicates the task of investigation the fifty hertz electric field intensity.

The human body is allocated within the highly exposure zones of electric fields inside this substation and at different heights to determine the field distribution levels during different working conditions, Figure 2.

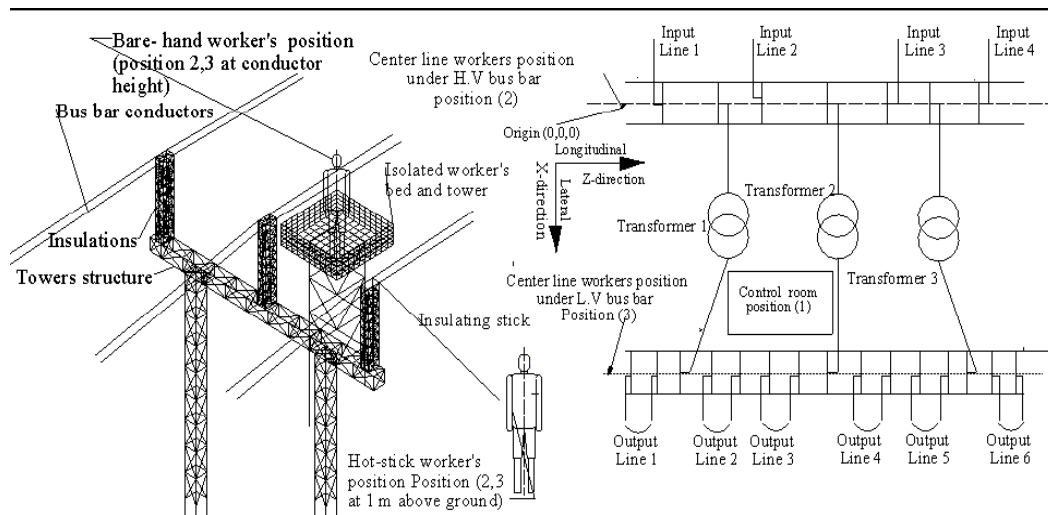


Figure 2. Different Positions of the Workers during Different Working Conditions

Works are connected with operative switching, equipment inspection; different repair work, etc. require presence of staff personal in various points of 500kV & 220kV Switchyards (substation territory). Therefore, the investigation of the distribution levels of the electric fields inside these substations is carried out during different working conditions for staff.

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

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

The third Scenario is carried out at a height of 17m for 500kV switchyard and 14m for 220kV switchyard, which presents the position of the worker (staff) in (bare hand position) during live maintenance conditions for 500kV and 220kV incoming and outgoing feeders (Scenario 3).

In the electric field model presented in this paper, 500kV bus-bars (HV bars) and 220kV bus-bars (LV bars), incoming 500kV feeders and outgoing 220kV feeders are approximated by internally located line charges. 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 500kV feeders, outgoing 220kV 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 [5], 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:

$$[V] = [P][Q] \quad (1)$$

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, 6].

In our developed model, we simulate HV and LV bus-bars, incoming 500kV feeders and outgoing 220kV feeders by internally located line charges on their axes. Therefore the potential coefficient is given by [7]:

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

Where,

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

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

Where,

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

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:

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

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 [7].

The total electric field at the i^{th} contour point is expressed as:

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

3. 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 11m for 500kV switchyard and 8.5m for 220kV switchyard (Scenario 2) and at a height of 17m for 500kV switchyard and 14m for 220kV 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.

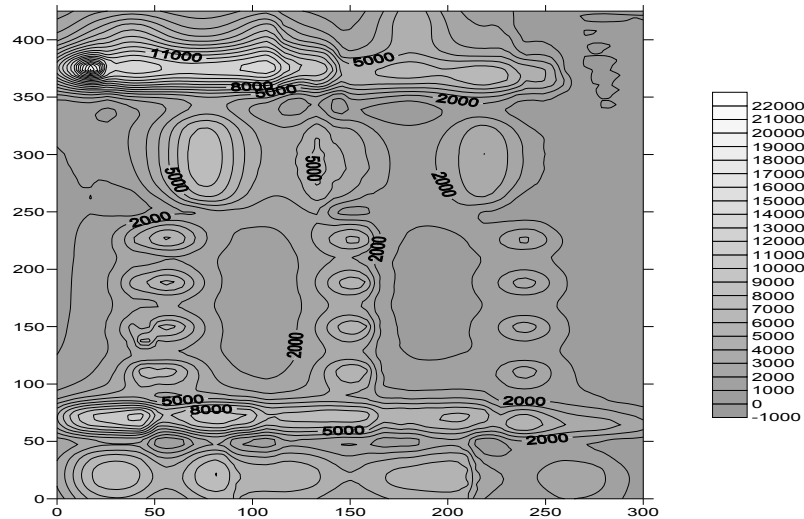


Figure 3. Map of the Electric Field (V/m) Distribution inside Cairo 500 Substation during Scenario 1

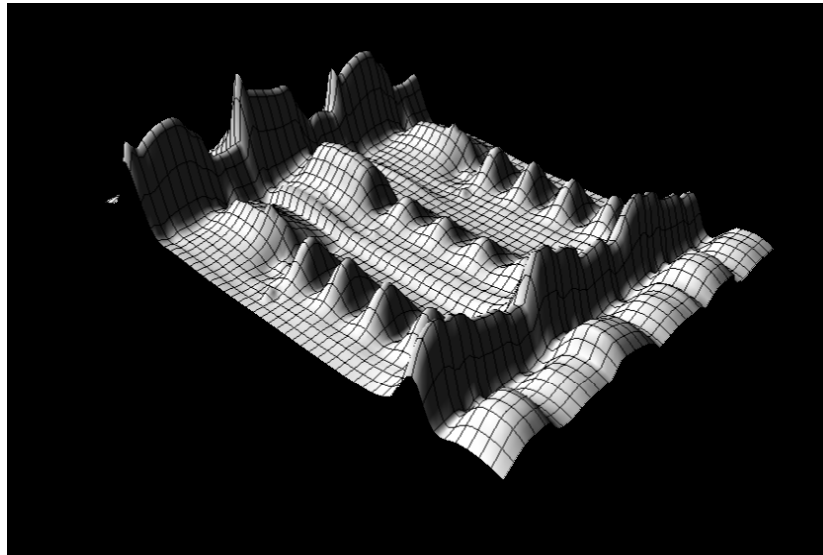


Figure 4. The Electric Field Distribution (V/m) inside Selected Substation Switchyard during Scenario 1

The research results which are presented in this paper were carried out at the same actual schedule of working conditions for selected substation. These results have been presented in form of the electric field distribution maps and surface distribution (Figure 3 &

Figure 4). The results of work are currently used for organization of the regular works on open distribution substations. Presentation of results in the form of maps, contours and three dimensional figures provides great visibility and a convenience in practical application. For example, when it is necessary to select a proper route for inspection substation or when choosing the proper protective equipment necessary for working personal without turned off above voltage, etc.

Table 1. The Distribution of Electric Field in the Zone of Open Distribution Substation (Scenario 1)

| The part of the open distribution substation territory,%, where the electric field is in the range (E in kV/m) | | | | | | |
|---|-------|--------|---------|---------|---------|---------|
| E Range | 0≤E<5 | 5≤E<10 | 10≤E<15 | 15≤E<20 | 20≤E<25 | 25≤E<30 |
| Territory,%, | 42.3 | 21.5 | 11.3 | 10.7 | 7 | 7.2 |

According to recommendations of SanPiN 2.2.4.1191-03 [8], employees, serving electrical installations are permitted to:

- 1) Stay in the 50-HZ electric field with the intensity of up to 5kV/m during the working day;
- 2) Stay in the 50-HZ electric field with the intensity from 5 to 20 kV / m during limited time, calculated as follows:

$$T = \frac{50}{E} - 2 \quad (6)$$

Where E is the electric field intensity in kV/m in the controlled area, T is the time in hrs.

Therefore when the electric field intensity is in range from 20 to 25 kV/m, stay of the staff in this electric field should not exceed 10 minutes;

- 1) Maximal permitted level of the electric field intensity in open distribution substation is 25 kV/m.
- 2) Staying in the electric field with the intensity of more than 25kV/m without use of the protective equipment is not permitted.

Going along the calculated electric field intensity, it is determined the points where the electric field intensity reaches the maximum exposure limit values 5, 10, 15, 20kV/m. Table 1 depicts, in percents, values of zones with electric field intensities less 5kV/m (zone of security) and higher 5kV/m (zone of influence) at scenario 1. Results of calculated data analysis in (Table 1) are showed that, in average; 42.3% of the open distribution substations occupy the territory on which the electric field does not exceed 5kV/m (zone of security). And the territory of open distribution substations at which the electric field is greater than 5kV/m, where it requires limited stay time for safety performance of work, is called the zone of electric field influence. This territory takes, in average, about 57.7% of the open distribution substation.

The distribution of the electric field intensity in the zone of electric field influence where the electric field intensity higher 5kV/m is as follows:

- 1) 21.5% of the territory falls on the zone with the electric field from 5to 10kV/m,
- 2) The zone from 10kV to 15kV/m is much smaller (about 11.3% of the territory of AIS).
- 3) The zone from 15kV to 20kV/m is about 10.7% of the territory of AIS.
- 4) The percentage of the zone with the intensity from 20 to 25kV/m, where the permission stay time is not exceed 10 minutes, is about 7% of the territory of AIS.
- 5) The intensity of the electric field more than 25kV/m, where the presence without personal protective equipment is prohibited, and the value of such zones is the about 7.2% of the territory of AIS.

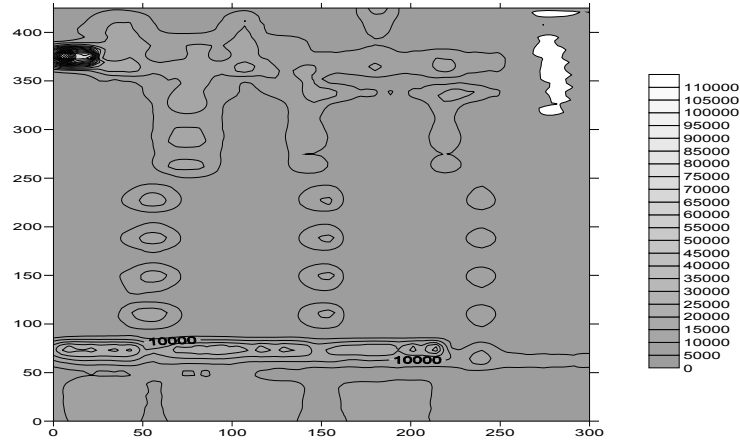


Figure 5. Map of the Electric Field (V/m) Distribution inside Cairo 500 Substation during Scenario 2

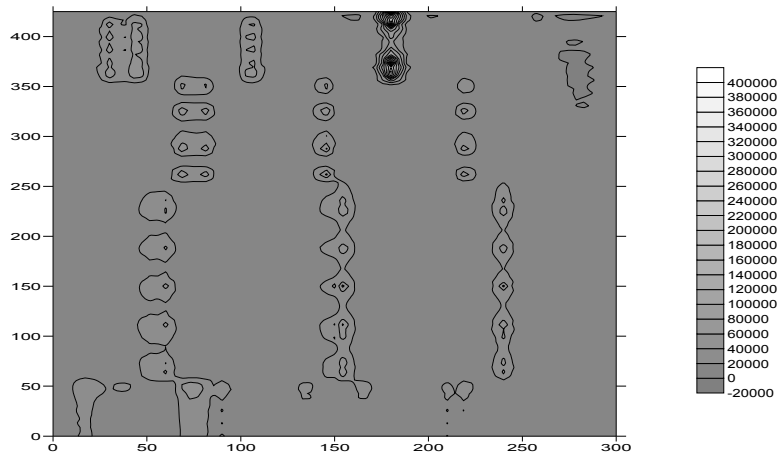


Figure 6. Map of the Electric Field (V/m) Distribution inside Cairo 500 Substation during Scenario 3

Table 2. The Maximum and Average Electric Field Values for Different Working Conditions

| Field calculation | Height | Electric Field | Scenario A (Standby Off) | Scenario B (Standby On) |
|-------------------|--------|--|--------------------------|-------------------------|
| | | Et (Max) (kV/m) inside all sub | 21.98 | 23.5 |
| 1.5 m | | Et (Max) (kV/m) inside 220 kV Switchyard | 18.77 | 22.78 |
| | | Et (Avg) (kV/m) | 7.91 | 9.99 |
| | | Et (Max) (kV/m) inside all sub | 103.35 | 129.99 |
| 8.5 m | | Et (Max) (kV/m) inside 500 kV Switchyard | 83.71 | 75.36 |
| | | Et (Avg) (kV/m) | 9.04 | 13.94 |
| | | Et (Max) (kV/m) inside all sub | 123.34 | 158.55 |
| 11 m | | Et (Max) (kV/m) inside 220 kV Switchyard | 99.09 | 98.17 |
| | | Et (Avg) (kV/m) | 9.70 | 14.44 |
| 14 m | | Et (Max) (kV/m) inside all sub | 127.73 | 135.69 |
| | | Et (Avg) (kV/m) | 10.97 | 14.38 |
| 17 m | | Et (Max) (kV/m) inside all sub | 149.46 | 152.73 |
| | | Et (Avg) (kV/m) | 10.69 | 12.55 |

Figure 5 and Figure 6 show the electric field distribution inside Cairo 500 substation for the other two scenarios 2 & 3 mentioned previously, while Table 2 summarize the maximum and average electric field values for different working conditions.

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 23kV/m, and the average calculated electric field imposed to the human body during hot-stick position (scenario 1) is about 10kV/m while the average measured electric field imposed to the human body during this position (scenario 1) is about 9.6kV/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 [9-11]. It is also found that the maximum calculated electric field imposed to the human body during bare-hand position (scenario 2) is about 158.6kV/m and that for scenario 3 is about 152.7kV/m (without considering the effects of insulating clothes) which are consistent with other related study [12].

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.

4. Conclusion

In this study, a method is proposed for determining the distribution of the electric field produced inside high-voltage open distribution substations. This method is based on the charge simulation technique. And the most important results from this study are as follows:

- 1) It is found that the electric field changes from point to point inside substation switchyard. According to this investigation results, a map of electric field intensity distribution was build for this substation. This map depicts location of areas with different level electric field intensity. This map is used for planning and conducting works inside substations and for moving inside substation for equipment inspection.
- 2) This investigation showed that, in average, about 42.3% of the open distribution substations occupy the territory on which the electric field does not exceed 5 kV / m (zone of security), and the maximum electric field intensity at this substation is less than 25kV/m and only at certain points in some open distribution substations reaches avalue greater than 25kV/m.
- 3) 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.

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