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Evaluation of magnetic induction inside humans at high voltage substations

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Abstract

The exposure to power frequency magnetic fields including those resulting from electrical power substations is playing a vital role in the human biological study. This paper presents a thorough investigation into the evaluation of the internal induced electric fields and induced current densities that are induced inside the human body due to the exposure to the external magnetic fields produced by a conventional 220/66 kV power substation.

The effects of different parameters such as human location, human dimensions and the incident angle of the external magnetic field on the induced electric fields and current densities inside the human body are considered, through the theoretical cases. On the other hands, a typical case is presented to account for the induction levels over the human height due to external magnetic fields corresponding to the actual measured values at different locations in the substation.

Keywords: Electric power systems; High voltage; Substations; Magnetic induction; Human body

1. Introduction

The high voltage substations are considered major elements in the electric power systems. As the power system installations, including substations nowadays, operate at higher voltages and currents, the resultant electric and magnetic fields are expected to be higher. Accordingly, the risk of the adverse health effects is getting higher [1,2].

Unlike the case of power lines, the electromagnetic environment at substations is very complex. The substation environment is characterized by conducting metallic structures, multiple lines, buses and other current-carrying elements associated with variable current values and directions over time. This would complicate the characterization of the electromagnetic field at the substations especially those of higher voltages.

Limited work is noticed in the literature that deals with full measurements over the substation area [3–5]. Although many articles addressed the induced electric fields and current densities inside human bodies due to the exposure to the magnetic fields [6,7], it is noticed that very limited work investigated the induction due to actual magnetic field measurements at substations.

Based on magnetic field measurements at a typical 220/66 kV substation, this paper presents the evaluation of the induced electric fields and current densities inside a human standing at different locations at the substation. The different variables that characterize the resultant induced electric field and current inside the human body are subject to extensive analysis in order to obtain insight and wide investigation of the electromagnetic field environment in high voltage substations.

2. Layout of 220/66 kV substation and measurement protocol

The high voltage substation under study is a typical 220/66 kV open-air substation located near the 10th of Ra-

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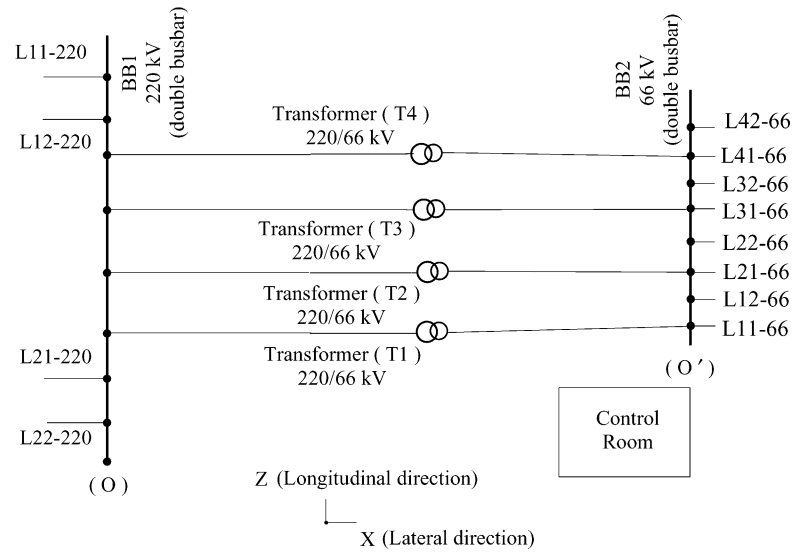

Fig. 1. Simple plan layout of the 220/66 kV substation.

madan City about 70 km north-east Cairo, Egypt. The selected substation has two ingoing lines and four outgoing lines, as shown in Fig. 1. Table 1 presents the main data of the substation while, Table 2 provides the substation loads during the measurement time.

The magnetic field is measured under 220 kV busbar, near the transformers, under 66 kV busbar and at other places inside the entire area of the 220/66 kV substation.

3. Magnetic field measurements

The magnetic fields in the substation are measured using a commercially available magnetic field meter (MFM10) with the following specifications:

- Designed to measure extremely low frequency (ELF) magnetic fields (10–1000 Hz).
- With three orthogonal coils for field direction independence for a wide range of (10 nT–10 mT) with an accuracy better than (±2%) of reading or (±0.005 μT) and typical (±1%) of reading or (±0.003 μT).

Table 1
The main data of the 220/66 kV substation

Item	Value
Substation area (busbars area)	150 m × 110 m
Number of ingoing 220 kV power lines	2 lines with 4 circuits
Number of subconductors per phase for 220 kV lines	2
Ingoing 220 kV power line height	12 m
Number of 220 kV busbar	2
220 kV busbars height	9 m
Number of transformers and ratings	4 (each with 125 MV A)
Transformer height	12 m
Number of 66 kV busbars	2
66 kV busbars height	5 m
Number of outgoing 66 kV power lines	4 lines with 8 circuits
Number of subconductors per phase for 66 kV lines	1
Outgoing 66 kV lines exit height	5 m
Suspension height (lower phase)	8 m

3.1. *Under 220 kV busbar*

Fig. 2 presents the measured magnetic field along the longitudinal direction under 220 kV busbar. The magnetic field is varying over the path reaching its maximum value of about 12.14 μT. The magnetic field profile has four peaks which are almost in front of the feeders connected to the four transformers.

3.2. *Near transformers*

Fig. 3 presents the measured magnetic field directly under the center phase of each transformer feeder at a distance of 2 m from the each transformer side formulated in a longitudinal direction. The centers of the four transformers are positioned longitudinally at 50 m, 66.67 m, 83.33 m and 100 m, respectively starting from a vertical lateral plan passing through the origin ‘O’. The maximum magnetic field is about 3.8 μT, occurred in front of transformer number 4 (T4).

3.3. *Under 66 kV busbar*

Fig. 4 presents the measured magnetic field along the longitudinal direction under 66 kV busbar. The magnetic field measurement is starting from the point at which the 66 kV busbar is starting (about 42 m from the reference point with respect to 220 kV busbar). The magnetic field is varying over the path reaching its maximum value of about 23 μT. As in the case under 220 kV busbar, the magnetic field profile has four peaks, which are almost in front of the feeders connected

Table 2
The 220/66 kV substation loads during the measurements

Time (h)	220 kV lines							
	L1				L2			
	L11		L12		L21		L22	
	MW	Amp.	MW	Amp.	MW	Amp.	MW	Amp.
10 a.m.	110	360.8	110	360.8	29	95.1	29	95.1
12 a.m.	115	377.3	115	377.3	30	98.4	30	98.4
	66 kV lines							
	L1 and L3				L2 and L4			
	L11		L12		L21		L22	
	MW	Amp.	MW	Amp.	MW	Amp.	MW	Amp.
10 a.m.	42	459.3	38	415.5	37	404.6	37	404.6
12 a.m.	37	404.6	42	459.3	23	251.5	23	251.5
	L31		L32		L41		L42	
	MW	Amp.	MW	Amp.	MW	Amp.	MW	Amp.
10 a.m.	39	426.5	35	382.7	25	273.4	25	273.4
12 a.m.	46	502.9	40	437.4	39	426.5	39	426.5
	Transformers							
	T1 (MW)		T2 (MW)		T3 (MW)		T4 (MW)	
10 a.m.	70		69		69		70	
12 a.m.	73		69		69		73	

Note: The currents are based on an actual average power factor of 0.8.

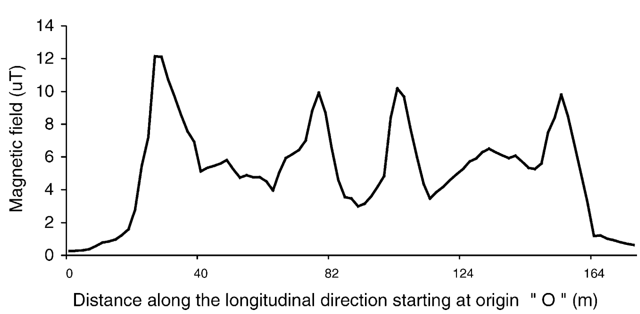

Fig. 2. The measured magnetic field along longitudinal direction under 220 kV busbar.

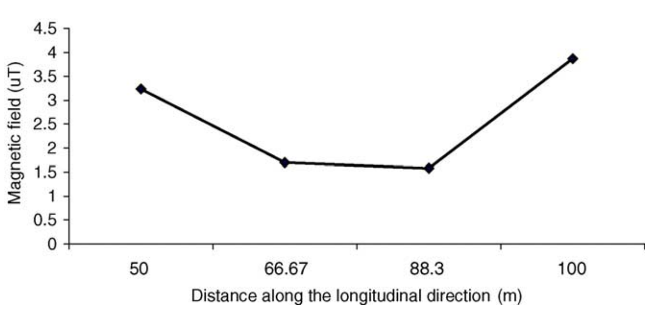

Fig. 3. The measured magnetic field near the transformers.

to the four transformers. Compared to 220 kV busbar side, the higher magnetic field values are obtained at the 66 kV busbar side due to the higher currents and lower conductors heights in the latter case.

3.4. At other places

Table 3 presents the measured magnetic field values under the ingoing feeders of 220 kV at 15 m far from the busbar.

Table 4 presents the measured magnetic values under the outgoing feeders of 66 kV at 15 m far from the 66 kV busbars.

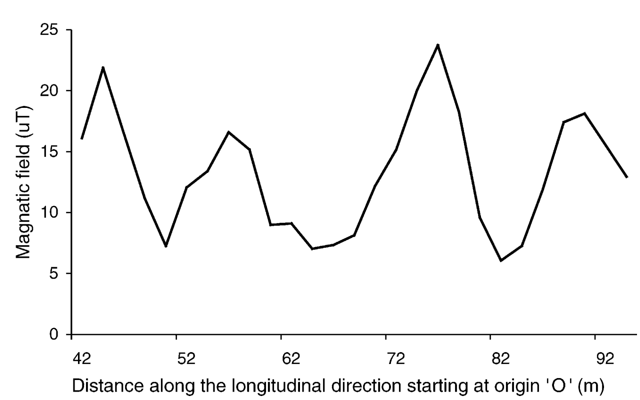

Fig. 4. The measured magnetic field along longitudinal direction under 66 kV busbar.

Table 3
The measured magnetic field under the ingoimg feeders of 220 kV

Position	Magnetic field (μT)	
	L1	L2
Under the inner circuit center	2.523	2.613
Under the tower center	1.671	1.847
Under the outer circuit center	2.018	2.869

The measurements direction begins from the tower 4 position. The magnetic field is reaching its maximum value of about 5.1 μT under the tower number 4 (Tower 4) position.

Table 5 presents the measured magnetic field values at different locations inside the control room (located at the second floor at 4 m height level from the ground): at the 220 kV busbar side, at the control room center and at the 66 kV busbar side. The highest magnetic field values is about 6.7 μT located at the 220 kV side.

4. Induced electric fields and current densities inside the human body due to substation magnetic fields

4.1. Human body simulation

To determine the electric fields and currents that are induced inside a human body standing at different locations in the 220/66 kV substation, the human body is simulated as a prolate spheroid (with a height of 2a and width of 2b). Since the induced electric field is proportional to the path radius in simple term, therefore the outer edges (with maximum path radius) of the exposed model are considered in this study since they are supposed to have the highest level of induction. The human height is taken in the Y-direction while the width is taken in the X–Z plane.

According to Faraday's law, a changing magnetic field produces an internal electric field with the body (and consequently a flow of induced current density) as follow [6]:

$$\bar{E}_{mx} = j\omega\left(\frac{zB_y}{2} - \frac{kyB_z}{1+k}\right) \tag{1}$$

$$\bar{E}_{my} = j\left(\frac{\omega}{1+k}\right)(xB_z - zB_x) \tag{2}$$

$$\bar{E}_{mz} = j\omega\left(\frac{kyB_x}{1+k} - \frac{xB_y}{2}\right) \tag{3}$$

Table 5
The measured magnetic field inside the control room

Position	Magnetic field (μT)
220 kV side	6.694
Room center	6.014
66 kV side	4.274

$$E_m = \sqrt{E_{mx}^2 + E_{my}^2 + E_{mz}^2} \tag{4}$$

where E_m is the internal induced electric field; E_{mx}, E_{my} and E_{mz} are the three components of the internal induced electric field; B_x, B_y and B_z are the three components of the external magnetic field; $k = (b/a)^2$ and ω is the angular frequency of the alternating external magnetic field.

The electric current density $\bar{J}$, produced by the internal field may be expressed as:

$$\bar{J} = \sigma \bar{E}_m \tag{5}$$

where σ is the electrical conductivity of the human body tissues (S/m).

4.2. Results of magnetic induction

4.2.1. Theoretical case—exposure to 1 μT magnetic field

Initially, the electric fields and current densities inside the human body are evaluated due to the exposure to a magnetic field of 1 μT taking into consideration the effect of the human body size and the incident angle of the externally applied magnetic field. An average conductivity of 0.04 S/m for the human body tissues is used [7].

4.2.1.1. Effect of the human size. To investigate the effect of the human size on the magnetically induced electric fields and current densities inside the human body, three height levels of 1.7 m, 1.8 m and 1.9 m (i.e., a = 0.85 m, 0.9 m and 0.95 m), in addition to three widths of 0.3 m, 0.4 m and 0.5 m (i.e. b = 0.15 m, 0.2 m and 0.25 m) are employed. The human is assumed to be exposed to 1 μT applied vertically over the human head.

Fig. 5 presents the internal induced electric fields and the corresponding induced electric current densities at the outer edge along the human height of 1.7 m with different human widths.

For different widths, the maximum values of induced internal electric fields and current densities occur at and are proportional to the human's mid-height. The maximum induced

Table 4
The measured magnetic field under the outgoing feeders of 66 kV

Position	Magnetic field (μT)		
	Under center phase for first circuit	Under the line center	Under center phase for second circuit
Line 1	4.53	4.38	3.84
Line 2	2.57	3.46	4.30
Line 3	3.92	3.15	2.06
Line 4	5.12	5.13	4.77

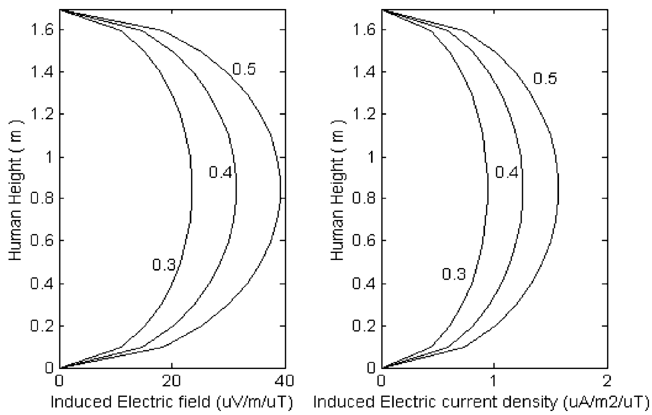

Fig. 5. The internal induced electric fields and current densities for different human widths (2*b*) at human height 1.7 m.

electric fields and current densities are (23.51 μV/m/μT, 0.94 μA/m^2/μT), (31.346 μV/m/μT, 1.254 μA/m^2/μT) and (39.183 μV/m/μT, 1.567 μA/m^2/μT) for width 0.3 m, 0.4 m and 0.5 m, respectively.

Fig. 6 presents the internal induced electric fields and the corresponding induced electric current densities at the outer edge along the human height of 1.8 m with different human widths.

For different widths, the maximum values of induced internal electric fields and current densities occur at and are proportional to the human's mid height. The maximum induced electric fields and current densities are (23.55 μV/m/μT, 0.94 μA/m^2/μT), (31.4 μV/m/μT, 1.256 μA/m^2/μT) and (39.25 μV/m/μT, 1.57 μA/m^2/μT) for the widths 0.3 m, 0.4 m and 0.5 m, respectively.

Fig. 7 presents the internal induced electric fields and the corresponding induced electric current densities at the outer edge along the human height of 1.9 m with different human widths.

For different widths, the maximum values of induced internal electric fields and current densities occur at and are proportional to the human's mid height. The maximum induced electric fields and current densities are (23.55 μV/m/μT,

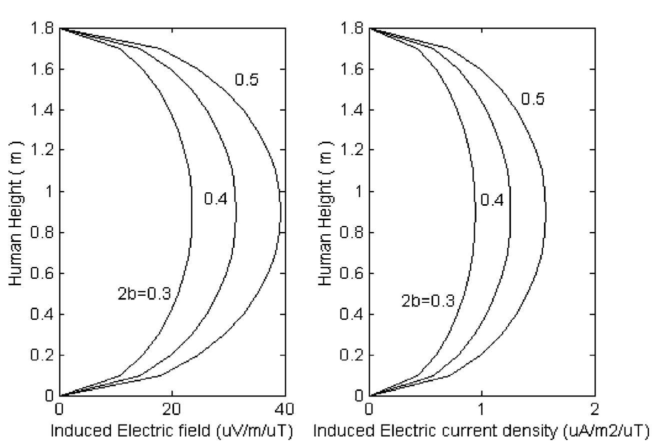

Fig. 6. The internal induced electric fields and current densities for different human widths (2*b*) at human height 1.8 m.

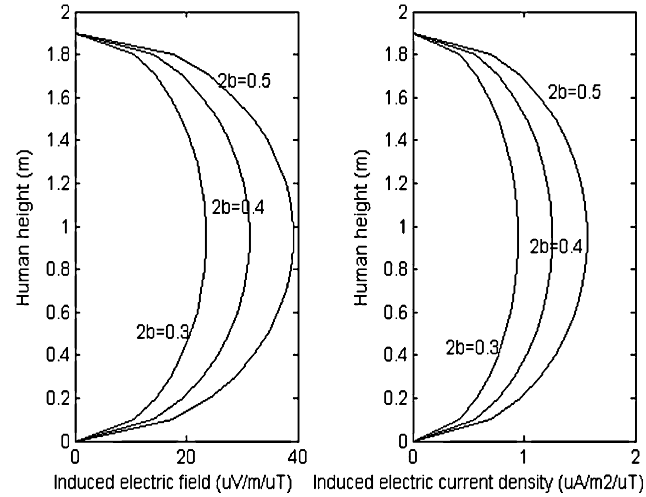

Fig. 7. The internal induced electric fields and the corresponding induced electric current densities at the outer edge along the human height of 1.9 m with different human widths. For different widths, the maximum values of induced internal electric fields and current densities occur at and proportional to the human's mid height. The maximum induced electric fields and current densities are (23.518 μV/m/μT, 0.94 μA/m^2/μT), (31.357 μV/m/μT, 1.284 μA/m^2/μT) and (39.196 μV/m/μT, 1.567 μA/m^2/μT) for the widths 0.3 m, 0.4 m and 0.5 m, respectively.

0.94 μA/m^2/μT), (31.4 μV/m/μT, 1.256 μA/m^2/μT) and (39.25 μV/m/μT, 1.57 μA/m^2/μT) for the widths 0.3 m, 0.4 m and 0.5 m, respectively.

Table 6 summarizes the maximum induction values with varying human size. The maximum induced electric field and current density occur at the highest human width with each case of human height.

4.2.1.2. Effects of the incident angle. To account for the effect of the incident angle of the applied external magnetic field, the human is exposed to 1 μT with different incident angles (0° "horizontal", 30°, 45° and 90° "vertical") at a human height of 1.8 m and width of 0.4 m. Fig. 8 presents

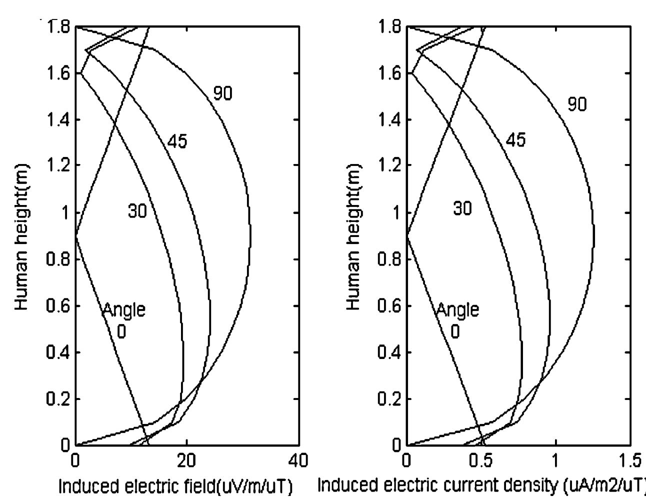

Fig. 8. The internal induced electric fields and current densities for different incident angles.

Table 6
Maximum electric fields and current densities at different human size

Human height (m)	Human width (m)	Maximum electric field (μV/m/μT)	Maximum electric current density (μA/m²/μT)
1.7	0.3	23.51	0.94
	0.4	31.35	1.25
	0.5	39.18	1.57
1.8	0.3	23.55	0.94
	0.4	31.4	1.26
	0.5	39.25	1.57
1.9	0.3	23.52	0.94
	0.4	31.36	1.25
	0.5	39.20	1.57

the internal induced electric fields and the corresponding induced current densities at the outer edge along the human height with different incident angles.

The maximum induced internal electric fields and current densities increase as the incident angle increases from 0° (i.e., horizontal) to 90° (i.e., vertical). While the maximum induced electric fields and current densities occur the human mid height, they tend to occur at the lower body sections as the incident angle decreases. So that through the next sections, the 90° (vertical) incident angle will be considered since it gives the maximum induction.

4.2.2. Typical case—exposure to substation magnetic

In this case, the human body is exposed to magnetic field values equal to those measured at different positions inside the substation under study. The human height and width are 1.8 and 0.4 m, respectively.

4.2.2.1. Exposure to the maximum magnetic values. This condition corresponds to the maximum magnetic fields measured at different locations in the substation. Fig. 9 provides the internal induced electrical fields and current densities inside the human body at different positions inside the substation corresponding to the maximum magnetic field values resulted from the measurements.

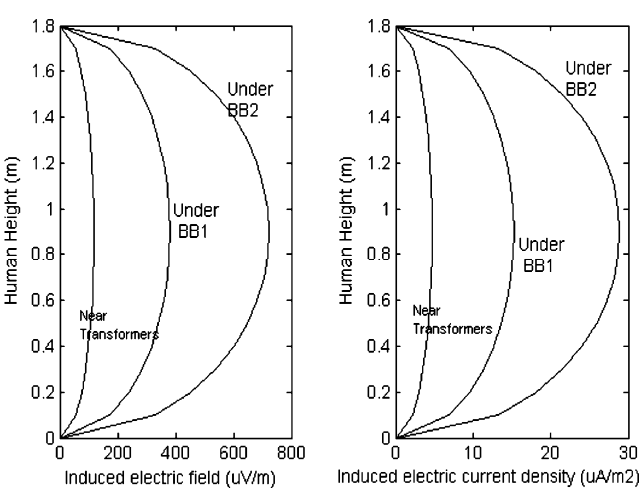

Fig. 9. The internal induced electric fields and current densities at different positions inside the substation due to the measured maximum magnetic field values.

The maximum induced electric fields and currents are about (120 μV/m, 4.8 μA/m^2) near the transformers, (381 μV/m, 15.25 μA/m^2) under 220 kV busbar (BB1) and (722 μV/m, 18.89 μA/m^2) under 66 kV busbar (BB2), respectively.

4.2.2.2. Exposure to average magnetic values. This condition corresponds to the average magnetic fields measured at different locations in the substation. Fig. 10 provides the internal induced electrical fields and current densities inside the human body at different positions inside the substation corresponding to the average magnetic field values resulted from the measurements.

The maximum induced electric fields and currents are about (81.6 μV/m, 3.27 μA/m^2) near the transformers, (160.1 μV/m, 6.42 μA/m^2) under 220 kV busbar (BB1) and (417.6 μV/m, 16.7 μA/m^2) under 66 kV busbar (BB2), respectively.

Fig. 11 shows the comparative average to maximum induced current densities over the human height as depicted from Figs. 9 and 10.

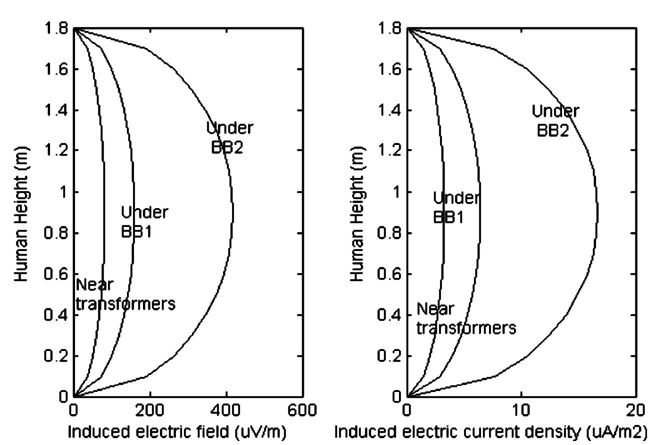

Fig. 10. The internal induced electric fields and current densities at different positions inside the substation due to the measured average magnetic field values.

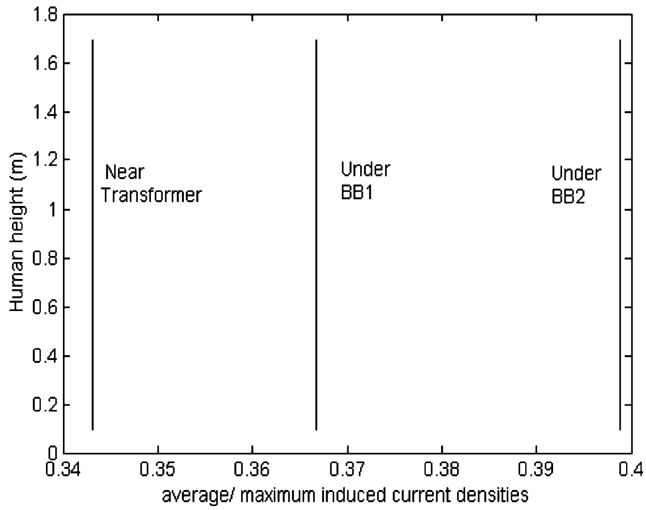

Fig. 11. Comparative average to maximum induced current density over the human height at different locations in the substation.

It is shown that the average to maximum induced current densities are about 0.37, 0.4 and 0.34 over the human height as the human position changes from BB1 (220 kV), BB2 (66 kV) and near the transformers, respectively.

5. Conclusion

The following remarks can be highlighted from the present work:

- The maximum global magnetic field measured inside the 220/66 kV substation under normal load conditions is about 23 μT and occur under the 66 kV busbar.
- The magnetic field profiles under substation busbars show peaks values at those locations where the feeders are connected to the busbars.
- The human is exposed to the higher electric field and current induced inside his body as his height and/or his width increases. The maximum induced electric field or current is increased by 45% as the human body width increases from 0.15 to 0.25 m.
- The maximum induced electric field is about 722 μV/m and the maximum internal induced current density is about 28 $\mu A/m^2$.

The average to maximum induced current is about 0.37, 0.4 and 0.34 over the human height as the human position changes from BB1 (220 kV), BB2 (66 kV) and near the transformers, respectively.

References

[1] P.S. Wong, A. Sastre, Simultaneous AC and DC magnetic field measurement in residential areas: implication for resonance theories of biological effects, IEEE Trans. Power Deliv. 10 (4) (1995).

[2] R.G. Olsen, R.G. Paul, R. Wong, Characteristics of low frequency electric and magnetic fields in the vicinity of electric power lines, IEEE Trans. Power Deliv. 7 (4) (1992).

[3] H. Anis, et al., Measurements of ELF magnetic field levels in Egypt, in: First Regional Meeting for the Continent of Africa, CIGRE, Cairo, Egypt, September, 1997.

[4] A.S. Farag, et al., Magnetic Field Measurement and Management in and Around Substations in Saudi Arabia, CIGRE, Paris, 1998 (Session).

[5] D.C Renew, J.C. Male, B.J. Maddock, Power–frequency magnetic fields: measurement and exposure assessment, GIGRE, Paper 36–105, Paris, 1990.

[6] J.F. Deford, O.P. Gandhi, Impedance method to calculate currents induced in biological bodies exposed to quasi-static electromagnetic fields, IEEE Trans. Electromagn. Compat. EC-27 (3) (1985) 168–173.

[7] M.A. Abd-Allah, Sh.A. Mahmoud, H.I. Anis, Interaction of Envirnomental ELF Electromagntic Fields with Living Bodies, Electric Machines and Power Systems, vol. 28, Taylor & Francis, 2000, pp. 301–312.