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ASSESSMENT OF MAGNETIC FIELD EXPOSURE AND CURRENT DENSITY FROM ELECTRICAL SUBSTATIONS IN POTISKUM METROPOLIS, YOBE STATE, NORTH-EAST, NIGERIA

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ABSTRACT

This study was carried out to evaluate Extremely Low Frequency (ELF) Magnetic fields and associated current density across three (3) residential neighborhoods of electrical substations in Potiskum metropolis, with a view to assess the risk to public exposure among the residents. Three Hundred and Eighty-Four (384) data sets were collected 1 m above the ground using a Trifield meter facing four corners of the substations for each measurement at a radial distance of 3m, 6m, 9m and 12m away from the substations. The number of substations covered at each district are Potiskum West (6), Potiskum Central (10), and Potiskum Central (8), making a mean total of Twenty-Four (24) data sets. Data collected were evaluated using mathematical models given by Ahmad (2013), NIEHS (1998), ICNIRP (1998), Dong & Lu (2019), Canova et al. (2010), all assuming an ellipsoidal homogenous human body of isotropic conductivity at an EMF frequency of 50 Hz. The results indicate higher ELF magnetic field and current densities recorded at western, central and eastern districts are PWS_3 (0.22 μT), PCS_9 (0.45 μT) and PES_3 (0.33 μT), respectively. Findings from the study show that the average exposure levels of ELF magnetic field in Potiskum central (0.30 μT) is higher compared to Potiskum West (0.17 μT) and Potiskum East (0.22 μT) residential sites. A strong positive correlation was also observed between the Magnetic field and current densities at all substations. Overall results shows that ELF magnetic field exposure and associated current densities were within the threshold of public exposure as recommended by ICNIRP guidelines.

Keywords: ELF magnetic field, Magnetic field exposure, current density, electrical substation, ICNIRP guidelines

INTRODUCTION

An electrical substation is an integral part of an electricity generation, transmission and distribution system. They are installations where the voltages used with transmission lines are stepped down to lower voltages used through distribution lines. Similar to overhead power lines and electrical devices, a substation can be a source of Extremely Low Frequency (ELF) electromagnetic fields (Grahame, 2011). The Electromagnetic Fields (EMF) are found everywhere and therefore a source of exposure from natural and artificial sources. Natural sources of EMF include earth's EMF field due to thunderstorms, solar and cosmogenic activities (Ali and Cy, 2005). Anthropogenic sources of EMF include electrical power substations, transmission and distribution lines, in addition to uses of electrical devices and related appliances such as Television, mobile handsets, Laptops, etc. (Adnan *et al.,* 2012). The magnetic field is not easily attenuated and is generally assumed to be the source of any possible health hazard. When animal bodies are placed in a time-varying magnetic field (as opposed to remaining stationary in the earth's static magnetic field), currents are induced and flow through tissues. Exposure of humans and animals to external 60 Hz electric and magnetic field induces currents internally, and the density of these currents is non-uniform throughout the body (NAS, 1997) and can be a source concern within the bodies.

Every community utilizing electricity are connected to a substation, however, the capacity of the distribution substations varies, depending whether the target area is for residential or commercial purpose, which in each case, may expose the populace to high ELF magnetic field (Kovertz, 2000; Zakurazawa *et al.,* 2003; Tayebeh et al., 2012). Some detrimental health effects due to ELF magnetic fields exposure may include childhood leukemia, brain cancer, and sleep disturbances, among others (Draper *et al.,* 2005). Vercasalo (1993) evaluated a number of studies and reports an increased risk of leukemia for children and an increased risk of adult cancer due to residential exposure to ELF-EMF. Another study indicates a leukemia risk for adults living within a radius of 50 meters or less from power transmission lines are 33% more susceptible to the diseases compared to those living within a range of 50 m – 100 m from the lines (Abd-Allah *et al.,* 2000).

A study by Tayebeh *et al.,* (2012) and Mac-Gregor *et al.* (1994) reports that the presence of many substations amongst residential neighborhood and/or commercial areas may expose the people in these areas (including staff working in these stations) to high ELF magnetic field. According to Ng (2003), the ability of these fields to penetrate the human body, the sites of absorption and the subsequent health effects are very much frequency dependent. At a molecular level, the tissues in biological organism can be affected by the induced current, indicating that the ELF magnetic field can play an important role during chemical and biological reactions. It is well established that induced electric current can stimulate nerve and muscle tissue directly once the induced current density exceeds threshold values (Repacholi & Greenebaum, 1999; Bernhard, 1992; Tenforde, 1996). Previous studies (ICNIRP, 1998; Schmid *et al* 2013) indicates that a current density of 10 mA/m^2 can disrupts the regulation mechanism of the cell, protein synthesis, cell growth and differentiation, physiological phenomena, etc. of an organism.

Reference Level: occupational and public exposure

Frequency range of both ELF magnetic field and current density are shown in Table 1.

The aim of this study is to assess the magnitudes of Extremely Low Frequency (ELF) Magnetic fields in the residential neighborhood of electrical substations in Potiskum metropolis to which the members of the population are exposed. The results would be used to evaluate the impact of associated current density to people residing around the vicinity of those substations. Final results would be compared with standard values recommended by International scientific and regulatory agencies, and also a baseline reference data for future studies and monitoring.

Table 1: Reference Level for ELF Magnetic field and current Density for occupational and public exposure (Havas, 2000; ICNIRP, 1998; NAS, 1997)

ELF Magnetic Field		
	Frequency range (Hz)	*Magnetic flux density (T)*
Occupational exposure	1 Hz -8 Hz	0.2/f
	8 Hz – 25 Hz	2.5 × 10-2/f
	25 Hz – 300 Hz	1 × 10-3
	300 Hz – 3 kHz	0.3/f
	3 kHz – 100 MHz	1 × 10-4
General public exposure	1 Hz -8 Hz	4×10-2/f2
	8 Hz – 25 Hz	5 × 10-3/f
	25 Hz – 300 Hz	2 × 10-4
	50 Hz – 400 kHz	2 × 10-4
	300 Hz – 3 kHz	5 × 10-2/f
	3 kHz – 100 MHz	2.7 × 10-5
Current Density		
	Frequency range (Hz)	*Current Density (Head and Trunk) (mA/m2)*
Occupational exposure	Up to 1 Hz	40
	1 - 4 Hz	40/f
	4 Hz – 1 kHz	10
	1 – 100 kHz	f/100
	100 kHz – 10 MHz	f/100
	10 MHz – 10 GHz	na
General public exposure	Up to 1 Hz	8
	1 - 4 Hz	8/f
	4 Hz – 1 kHz	2
	1 – 100 kHz	f/500
	100 kHz – 10 MHz	f/500
	10 MHz – 10 GHz	na

MODELLING FORMATION OF EM FIELD

Exposure to time-varying EMF results in internal body currents and energy absorption in tissues, and these depend on the coupling mechanisms and the frequency involved. The internal electric field *E* and current density *J* are related by Ohm's Law in equation (1) as reported by (Kovačević *et al.* 2022).

$$J\sigma E \tag{1}$$

where σ is the conductivity. From Faraday's law, equation (1) can be expressed as:

$$V_{emf} = \frac{-d\Phi}{dt} \tag{2}$$

where the term $\Phi = (\oint B.d/A)$ is the magnetic flux per unit area flowing through the circuit. The *EMF* for any closed path can be expressed as the line integral of *E.dl* over the path as given by Serway & Jewett (2005) and shown in equation (3):

$$V_{emf} = \oint E.dl \tag{3}$$

Also, the time-varying magnetic field vector *B* also creates an electric field *E* according to Faraday's law as shown below (NIEHS, 1998):

$$\oint E.dl = E(2\pi R) = \frac{-d\Phi}{dt} = -\pi R^2 \frac{dB}{dt} \tag{4}$$

where $E \equiv \vee E \vee$, and $B = B \vee$ are the respective magnitudes of vectors *E* and *B*. Hence if $B = B_o Cos\omega t$, then the induced *emf* in the loop for the induction of the current in the human body is

$$V_{emf} =- AB\frac{d}{dt}(cos\omega t) = AB\omega sin\omega t \quad (5)$$

where $A = \pi R^2$ is the loop area from equation (4), and thus the maximum *emf* according to Serway & Jewwet (2003) can be expressed as

$$V_{emf} = V_{emf}(max) = AB_0\omega \quad (6)$$

Equation (5) is valid when $\omega t = 90° \; or \; 270°$ and $\omega = 2\pi f$ while the term V_{emf} is maximum when the magnetic field is in the plane of the loop and the time rate of change of flux is a maximum. The uniform magnetic field *B* above will induce an electric field *E* in the exposed body given by (Ahmad, 2013):

$$E = \frac{-R}{2}\left[\frac{dB}{dt}\right] \quad (7)$$

The time varying electric field varies in sinusoidal form as

$$E = \omega B_0\left[\frac{R}{2}\right] sin\omega t \quad (8)$$

In the simplest model of an equivalent circular loop corresponding to a given human body contour, the induced electric field is expresses as:

$$E = \sigma\pi f RB \quad (9)$$

Equation (9) is frequently employed in estimating induced electric fields in animal bodies and cell cultures, however, results obtained are only approximations because biological tissue is neither cylindrical nor electrically homogeneous (NIEHS, 1998). For a pure sinusoidal *EM* field at frequency *f*, equation (9) becomes

$$J = \sigma\pi f RB \quad (10)$$

Equation (10) is referred to as the Magnetic Field Model (ICNIRP, 1998), where J = current density *(A/m²)*, E = induced electric field strength (*V/m*), R = radius of the loop for induction of the current *(m)*, usually several cm up to 20 cm (for trunk) and 7.5 cm (for head) and $\sigma = 0.2$ *(S/m)* as average tissue conductivity ((Dong and Lu, 2019; Canova *et. al*., 2010), frequency f = 50 *Hz* and B = magnetic flux density (*T*). Equation (10) assumes an ellipsoidal homogenous body of isotropic conductivity.

MATERIALS AND METHODS

Sampling

For the purpose of this study, Potiskum Metropolitan is divided into eastern, central and eastern residential districts consisting a total twenty of four (24) electrical distribution substations were selected due to their relatively high population density. The districts hosting the substations consist consists a total of six (6) wards distributed as follows: *Potiskum East* (Yerimaram Ward, Dogo Nini Ward), *Potiskum Central* (Bolewa A Ward, Bolewa B Ward,) and *Potiskum West* (Hausawa Asibiti Ward, Bare Bari Bauya Laile Ward). The number of substations across the districts are: eight (8) substations in Potiskum West, six (6) substations in Potiskum Central and ten (10) substations in Potiskum East. The residential areas in the neighborhood of the stations were coded to ensure that no exposure data are wrongly allocated to some measurement spots and the following were adopted: Potiskum West (PW_{S1} - PW_{S6}), Potiskum Central (PC_{S1} - PC_{S10}), and Potiskum Central (PE_{S1} - PE_{S8}), making a mean total of Twenty Four (24) data sets crunched from a total of Three Hundred and Eighty Four (384) data set from substations across the districts.

SPECIAL ISSUE
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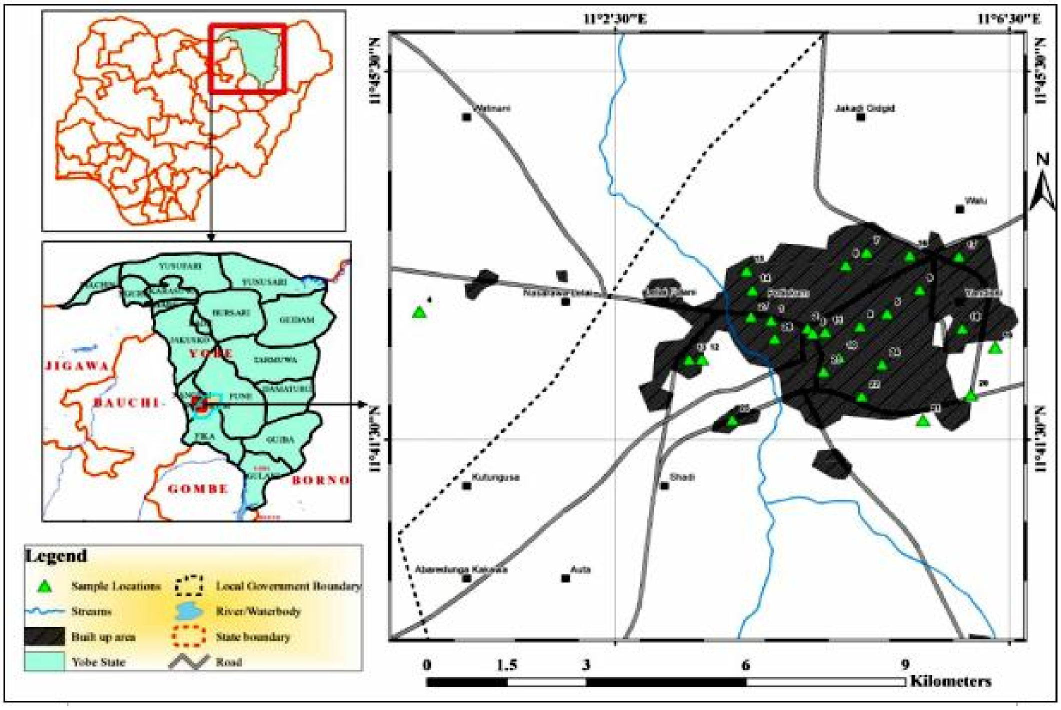

Figure 1: Map of Potiskum metropolitan showing sample's locations for this study.

Field measurement

The assessment of magnetic field exposure was made through a measurement survey carried out among the residential sites close to the substations using the Trifield TM100XE Meter. The device is gaussmeter, electric field meter, radio field strength meter in a single unit. When measuring electromagnetic fields (EMFs), the primary concern is usually magnetic fields, and detects the three types of electromagnetic pollution: AC magnetic fields, AC electric fields, and radio/microwaves. It can be used to measures AC magnetic fields such as from overhead power lines or improperly grounded equipment and can also locate wiring in walls, in addition to major Radio Frequency (RF)/microwave sources such as leakage from microwave ovens, or the field near cell towers. The device is designed to measure extremely low frequency (ELF) magnetic fields ranging from 40 *Hz* – 100 *kHz* and magnetic field of up to 100 *mG* with an accuracy of ± 20% (Michael, 2010). Other materials used for data collection include measuring tape and a Log book. The data was collected with the device held at a distance of 1 m above the ground to ensure that any emissions from underground cables do not affect the readings on the meter. Measurements was carried out with the device facing Four (4) corners of each substations for each measured ELF reading, making a total of three hundred and eighty four (384) data sets at a radial distance interims of 3m, 6m, 9m and 12m.

Data analysis

The date set were evaluated from a total of $n = 384$ distance measurements using microsoft Spreadsheet. A total set of Twenty-Four (24) mean ELF reading were obtained, which represent the levels of ELF magnetic fields in the three regions of Potiskum Metropolitan. The results were tabulated, graphically presented and the exposure levels of the magnetic fields were compared across the three residential environments.

RESULTS AND DISCUSSION

Extremely Low Frequency (ELF) Magnetic Field

Results from this study are the outcome of assessment of residential exposure in different parts of Potiskum metropolis. Table 2 is the mean results of magnetic fields due to electrical substations at Potiskum West, while Table 3 and Table 4 show results from Potiskum Central and Potiskum East, respectively.

Table 2: Mean magnetic field from Potiskum West residential sites at various substations.

Substations	*3m*	*6m*	*9m*	*12m*	*Mean*
PW_{S1}	0.47	0.15	0.05	0.02	0.17
PW_{S2}	0.44	0.12	0.03	0.00	0.15
PW_{S3}	0.62	0.18	0.06	0.03	0.22
PW_{S4}	0.48	0.13	0.05	0.01	0.17
PW_{S5}	0.38	0.12	0.04	0.00	0.14
PW_{S6}	0.50	0.15	0.06	0.02	0.18

Table 3: Mean magnetic field from Potiskum Central residential sites at various substations.

Substations	*3m*	*6m*	*9m*	*12m*	*Mean*
PC_{S1}	0.48	0.13	0.05	0.01	0.17
PC_{S2}	0.38	0.12	0.04	0.00	0.14
PC_{S3}	0.72	0.15	0.05	0.00	0.23
PC_{S4}	0.79	0.26	0.11	0.05	0.30
PC_{S5}	0.81	0.26	0.04	0.01	0.28
PCS6	0.64	0.18	0.08	0.03	0.23
PC_{S7}	0.54	0.14	0.04	0.00	0.18
PC_{S8}	0.93	0.37	0.26	0.06	0.41
PC_{S9}	1.28	0.41	0.09	0.03	0.45
PCS_{10}	0.60	0.24	0.05	0.00	0.22

Table 4: Mean magnetic field from Potiskum East residential sites at various substations.

Substations	*3m*	*6m*	*9m*	*12m*	*Mean*
PE_{S1}	0.36	0.10	0.03	0.00	0.12
PE_{S2}	0.48	0.12	0.05	0.02	0.17
PE_{S3}	0.88	0.28	0.12	0.04	0.33
PE_{S4}	0.60	0.19	0.05	0.02	0.22
PE_{S5}	0.68	0.20	0.08	0.02	0.25
PE_{S6}	0.43	0.12	0.04	0.01	0.15
PE_{S7}	0.59	0.18	0.06	0.01	0.21
PE_{S8}	0.50	0.14	0.03	0.00	0.17

The magnetic field from Potiskum West shows the following results from Six (6) substations: PW_{S1} (0.17 μT), PW_{S2} (0.15 μT), PW_{S3} (0.22 μT) PW_{S4} (0.17 μT), PW_{S5} (0.14 μT) and PW_{S6} (0.18 μT) with a minimum and maximum of 0.14 μT and 0.22 μT from PW_{S5} and PW_{S3}, respectively.

Similarly, results from Potiskum central residential district in Table 3 indicates a minimum and maximum mean magnetic field of 0.14 μT and 0.45 μT recorded at stations PC_{S2} and PC_{S9}, respectively. This implies that people residing in the neighborhood of PC_{S9} were being exposed to maximum magnetic field relative to those at other Nine (9) stations, which according to Tayebeh *et al., (2012)*, residents in the neighborhood of the station (PC_{S9}) are potentially at higher risk due to this exposure (NAS, 1997).

Table 4 is a result from the eastern part, showing a minimum and maximum magnetic exposure of 0.12 μT and 0.33 μT at PE_{S1} and PE_{S30}, respectively. Similarly, a magnitude of 0.33 μT, 0.22 μT, *0.25* μT were recorded at stations PE_{S3}, PE_{S4} and PE_{S5}, respectively. In general, the magnetic field exposure in the eastern residential district across the stations varies in the following ascending order: $PE_{S1} < PE_{S6} < PE_{S2,S8}, < PE_{S7} < PE_{S4} < PE_{S5} < PE_{S3}$ at 0.12 μT < 0.15 μT < 0.17 μT < 0.21 μT < 0.22 μT < 0.33 μT, respectively. Figure 2 shows the total magnetic field measured across the three residential districts and their individual contribution.

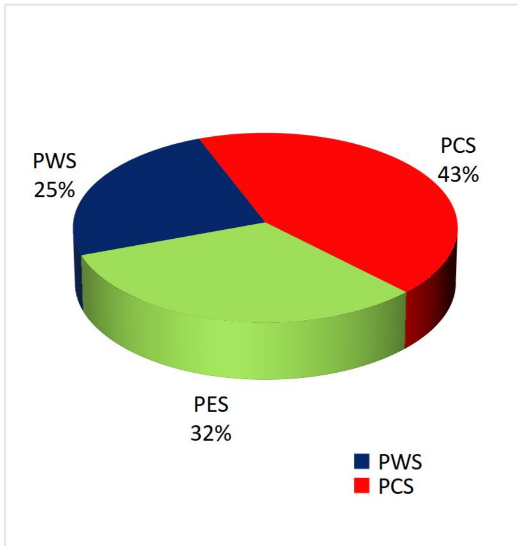

Figure 2: Contribution of mean magnetic field by substations from Western, Central and Eastern residential districts of Potiskum metropolis.

Analysis of the results indicates that power stations from eastern district contributes 32% to the total magnetic field within the metropolis, while those from central and western parts are put at 43% and 25%, respectively. The relatively higher exposure at the central part may not be unconnected to the higher number of electrical substation located there; about 10 in number compared to western and eastern parts that have 6 and 8 stations, respectively. Consequently, higher current densities are expected from the central district due to the higher exposure level in area. In general, evaluated results of the magnetic field are all below the reference value for public exposure, which is 0.1 μT.

Current Density

The current densities J associated with the ELF magnetic field B are given in Table 5, Table 6 and Table 7. A total summary of the results showing minimum, maximum, and mean values for Western, Central and Eastern residential districts of Potiskum metropolis are also given in Table 8.

SPECIAL ISSUE
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Table 5: Mean ELF and Current densities for head and trunk regions from Potiskum West.

Substations	ELF B (μT)	J_{head} (A/m^2)	J_{trunk} (A/m^2)
PW_{S1}	0.17	0.41	1.08
PW_{S2}	0.15	0.35	0.93
PW_{S3}	0.22	0.52	1.40
PW_{S4}	0.17	0.39	1.05
PW_{S5}	0.14	0.32	0.85
PW_{S6}	0.18	0.43	1.15

Table 6: Mean ELF and Current densities for head and trunk regions from Potiskum Central

Substations	ELF B (μT)	J_{head} (A/m^2)	J_{trunk} (A/m^2)
PC_{S1}	0.17	0.39	1.05
PC_{S2}	0.14	0.32	0.85
PC_{S3}	0.23	0.54	1.45
PC_{S4}	0.30	0.71	1.90
PCS5	0.28	0.66	1.76
PC_{S6}	0.23	0.55	1.46
PC_{S7}	0.18	0.42	1.13
PC_{S8}	0.41	0.95	2.55
PC_{S9}	0.45	1.07	2.84
PCS_{10}	0.22	0.52	1.40

Table 7: Mean ELF and Current densities for head and trunk regions from Potiskum East

Substations	ELF B (μT)	J_{head} (A/m^2)	J_{trunk} (A/m^2)
PE_{S1}	0.12	0.29	0.77
PE_{S2}	0.17	0.39	1.05
PE_{S3}	0.33	0.78	2.07
PE_{S4}	0.22	0.51	1.35
PE_{S5}	0.25	0.58	1.54
PE_{S6}	0.15	0.35	0.94
PE_{S7}	0.21	0.49	1.32
PE_{S8}	0.17	0.39	1.05

Figures 3, 4 and 5 show results from western, central and eastern districts of Potiskum as derived from Tables 2, 3 and 4, respectively.

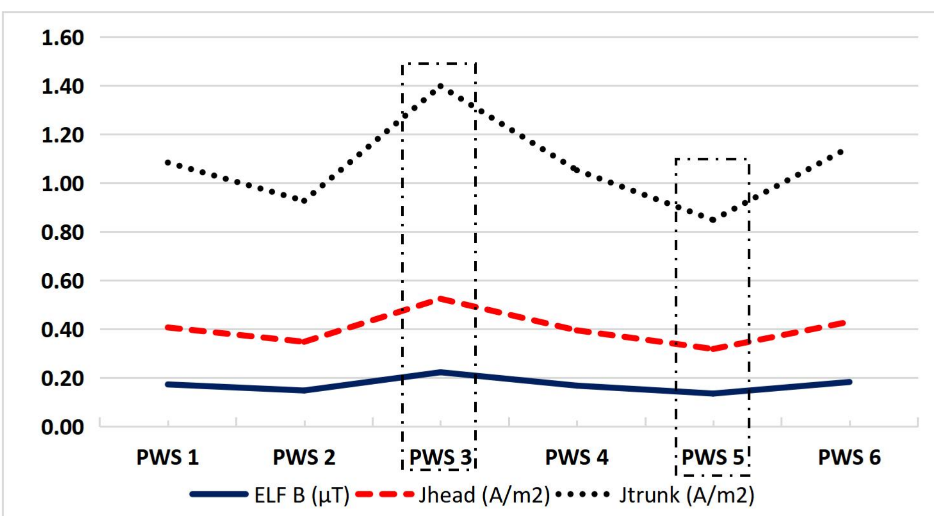

Figure 3: Variation of magnetic field from Six (6) substations at Potiskum West

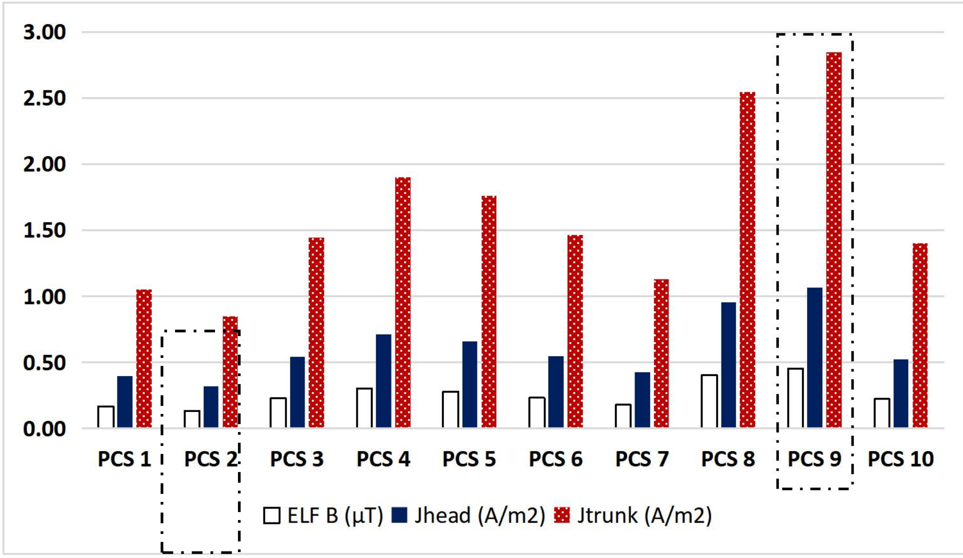

Figure 4: Variation of magnetic field from Ten (10) substations at Potiskum Central.

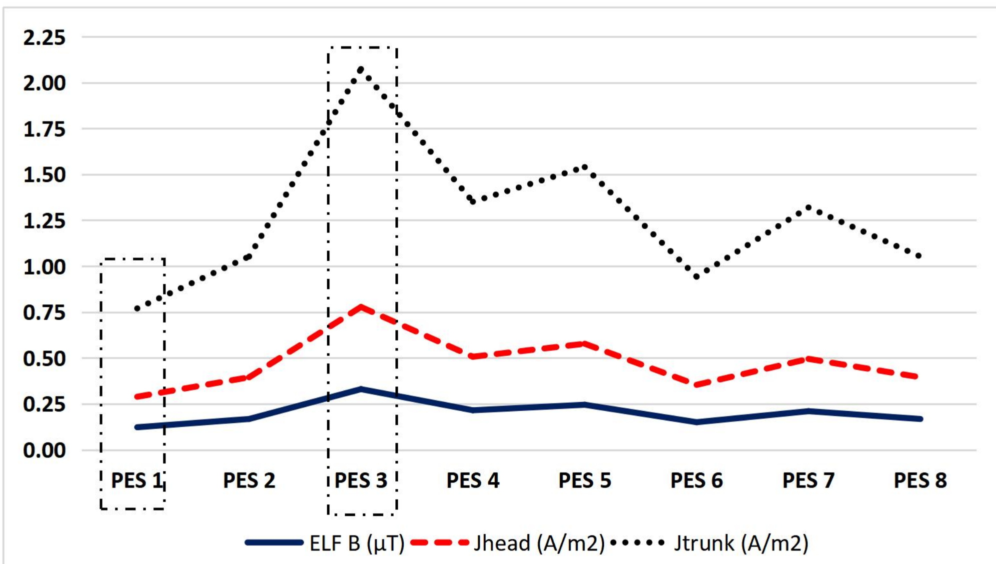

Figure 5: Variation of magnetic field from Eight (8) substations at Potiskum East.

From Fig.3 (Potiskum West), the minimum and maximum Current densities for head (0.32 A/m^2 and 0.52 A/m^2) and trunk (0.85 A/m^2 and 1.40 A/m^2) at (PS$_5$ and PS$_3$) are indicated by the dotted rectangles, respectively. Also, results from central Potiskum shows a maximum ELF and current densities for head (1.07 A/m^2) and trunk (2.84 A/m^2) recorded at station PCS$_9$. In the case of eastern residential district (Fig.5), stations PE$_3$ recorded the maximum current densities for head (0.78 A/m^2) and trunk (2.07 Am^2), while PE$_1$ recorded the minimum densities for head and trunk at 0.29 Am^2 and 0.77 Am^2, respectively.

A summary of the overall mean ELF and current densities for both head and trunk are shown in Table 8. Results from all the three districts are below the reference level of 2 *mA/m^2* for public exposure and thus within the exposure threshold recommended by quality control agencies (ICNIRP, 1998; Havas, 2000). Fig.6 shows the showing the mean ELF and current densities for both head and trunks across the three districts of the metropolis and result of both parameters from central Potiskum were found to be higher than those recorded from the western and eastern district.

Table 7: Total mean ELF and Current densities for head and trunk regions from all stations across western, central and eastern residential areas of Potiskum metropolis.

Substations		ELF B (μT)	J_{head} (A/m^2)	J_{trunk} (A/m^2)
PWS	Min.	0.14	0.32	0.85
	Max.	0.22	0.52	1.40
	mean	*0.17*	*0.40*	*1.08*
PCS	Min.	0.14	0.32	0.85
	Max.	0.45	1.07	2.84
	mean	*0.30*	*0.70*	*1.86*
PES	Min.	0.12	0.29	0.77
	Max.	0.33	0.78	2.07
	mean	*0.22*	*0.52*	*1.38*

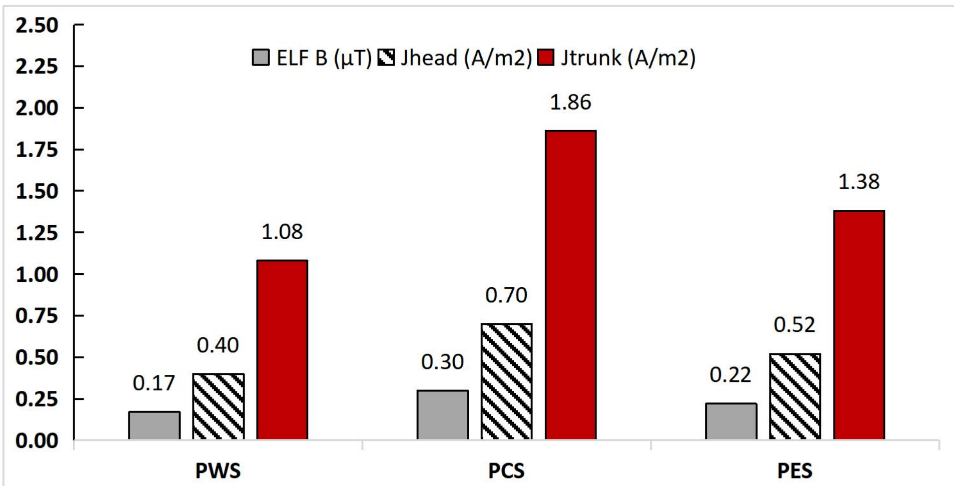

Figure 6: Total mean ELF and Current densities for head and trunk regions from all stations across western, central and eastern residential areas of Potiskum metropolis.

Figure 7 shows the magnitudes of the magnetic field at different distance interims. It can be observed that the magnetic field is inversely proportional to distance, obeying the inverse square law such that when the distance of measurement r increases, the corresponding field decreases by a factor of $1/r^2$. Results from the figure implies that the farther away the inhabitants are from the electrical substations, the safer they are from any illness potentially arising from EMF exposure and the corresponding current densities at those stations (WHO, 2007). This fact is supported by Fig. 8, which indicates a strong positive correlation ($R=1$) between measured magnetic field and current density for all measurements at these substations. Thus any increase in magnetic field leads to an increase the current density and vice-versa (Thuróczy, 2008).

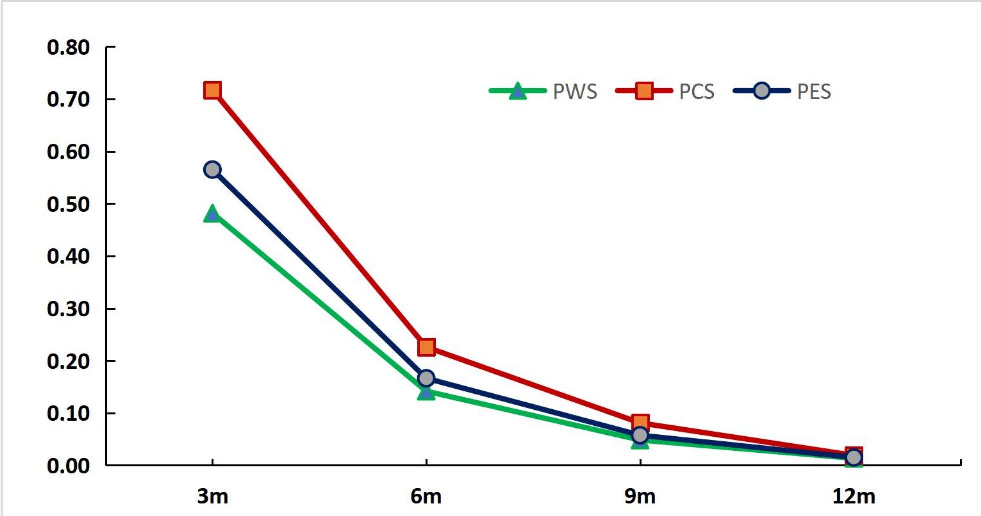

Figure 7: Variation of measured magnetic field as a function of distance at the western, central and eastern Potiskum metropolis.

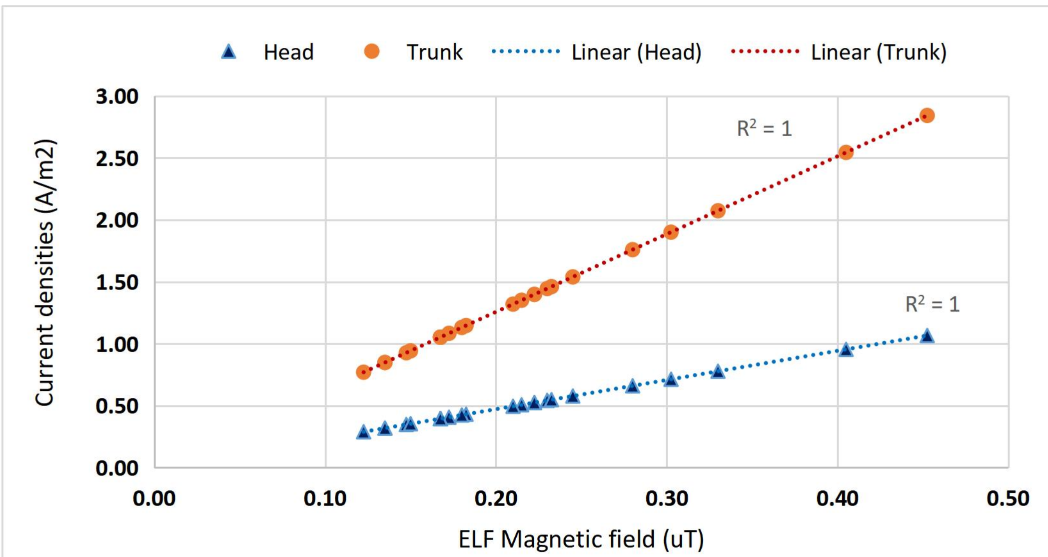

Figure 8: Correlation between ELF and current densities for head and trunk regions of the human body.

CONCLUSION

Result of the study show that the mean exposure levels of ELF magnetic field measured in Potiskum central (0.29 μT) are higher compared to Potiskum West (0.18 μT) and Potiskum East (0.21 μT) residential sites. Higher current densities were also recorded at the trunk region relative to the head regions across the three residential areas as follows: central district (head: 0.70, trunk: 1.86) A/m^2, relative to the western district (head: 0.40, trunk: 1.08) A/m^2 and eastern district (head: 0.52, trunk: 1.38) A/m^2. Overall results shows that ELF magnetic field exposure and associated current densities are within the threshold of public exposure as recommended by ICNIRP guidelines.

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