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Assessment of Magnetic Field Effects and Estimation of Associated Current Density of Electrical Injection Substations in Kano Metropolis

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Abstract
The paper presents an assessment and estimation of human exposure to extremely-low-frequency (ELF) magnetic field generated in 33/11kV electrical injection substations equipment in Kano metropolis using the magnetic field model. The magnetic fields level were measured with the aid of hand-held "Trifield^{TM} 100XE Meter; frequency weighted" in different parts of the substations and the occupational exposure in a shift personnel was estimated by calculating the time weighted average exposure level (TWA) over the entire week and noting basically that the general public average exposure level to power frequency of 50 Hz is less than 2 mG (≡ 0.2 μT). The main objectives of this study are to assess the level of magnetic fields radiation in an injection substation and estimate induced current density level at the head region of the human body. Current density estimation at the head region was computed by using magnetic field model by assuming that the human body has a homogenous and isotropic conductivity and current path is circular. The result obtained was validated through comparison with the international guidelines and standards for safety occupational exposure set by the International Commission on Non-Ionising Radiation Protection (ICNIRP).
Keywords: Extremely Low Frequency (ELF), Electromagnetic Fields (EMF), Current Density, Magnetic field, Time Weighted Average (TWA), human body, physiology, radiation exposure, transmission lines.

1. Introduction

Electricity substations, like overhead power lines and electrical appliances in the home, are sources of extremely low frequency (ELF) electromagnetic fields (Grahame, 2011). Electromagnetic fields (EMFs) are all around us and in everyday life we are all exposed to EMFs from a variety of sources. The natural sources of EMF include a background electromagnetic field created by the earth, additional EMF created by thunderstorms, and solar and cosmic activity (Ali and Cy, 2005). However, besides natural electromagnetic fields, today human beings are mostly exposed to artificial electromagnetic fields due to progress in technology and outspread use of electrical devices (Adnan *et al.*, 2012). Electric power substations, transmission lines, distribution lines, industrial devices and electric appliances are some of the commonly known sources of ELF magnetic fields in the environment. Since many substations are surrounded by residential or commercial areas, people living near them and also personnel working in the substations may be exposed to high ELF magnetic field (Tayebeh *et al*., 2012).

Within all organisms are endogenous electric fields and currents that play a role in the complex mechanisms of physiological control such as neuromuscular activity, glandular secretion, cell-membrane function, and development, growth and repair of tissue (National Health and Medical Research Council NHMRC, 1989). Clinical experiments in all over the world have shown that different physiological processes including fertility, insemination, equilibrium of neuroendocrine and some cardio-respiratory systems may be affected by this environmental factor and lead to different abnormalities (Zahiroddin *et al.*, 2006). It is not surprising that, because of the role of electric fields and currents in so many basic physiological processes, questions arise concerning possible effects of artificially produced fields on biological systems (NHMRC, 1989).

Even in the absence of external EMFs, very small electrical currents are always present in the human body and are of the normal bodily functions (Cristina and Andres, 2010). There are three established basic coupling mechanisms through which time-varying electric and magnetic fields interact directly with living matter (ICNIRP, 1998).

- *Coupling to low-frequency electric fields*:- there is low energy absorption which leads to electric current, formation of electric dipoles and reorientation of electric dipoles already present in the tissue.
- *Coupling to low-frequency magnetic fields*:- there is low energy absorption which lead to induced electric fields and circulating electric current.
- *Absorption of energy from electromagnetic fields*:- there is significant absorption of energy and temperature increase which, results into highly non-uniform deposition and distribution of energy within the body.

Since we are interested in ELF magnetic field radiation, we restrict the present study to coupling with low-frequency magnetic fields.

The physical interaction of time-varying magnetic fields with the human body results in induced electric fields and circulating electric currents (ICNIRP, 1998). At low frequencies, when the displacement currents can be neglected, the magnetic and electric fields are decoupled (Cristina and Andres, 2010). The exact path and magnitude of the resulting current induced in any part of the body will depend on the electrical conductivity of the tissue (ICNIRP, 1998). Exposures to low-frequency EMFs result in negligible energy absorption. Consequently, there is no measurable temperature change in the human body (Cristina and Andres, 2010).

At extremely low frequencies, the effects of the electric field and magnetic field on the human body can be studied. There are two scenarios for human exposure to low frequency fields, as follows: (Laissaoui *et al.*, 2013)

- *High voltage/low current systems* – the case of power lines high voltage and ultra high voltage is such that the effect of the electric field is predominant over the magnetic field. The coupling between the electric field and the human body causes the axial current density inside the body.
- *Low voltage/high current systems* - the case with most of electrical appliances, either domestic or industrial ones is such that the magnetic field is considered to be predominant. The coupling between the magnetic field and the human body is the cause of circular (closed loops) current density inside the human body.

At high frequencies that are above 100 kHz the displacement currents cannot be neglected, and the magnetic and electric fields are coupled. Exposure to EM radiation at these frequencies can lead to significant absorption of energy and consequently temperature increase (Cristina and Andres, 2010).

2. Formulation of Magnetic Field Model

Exposure to time-varying EMF results in internal body currents and energy absorption in tissues that depend on the coupling mechanisms and the frequency involved. The internal electric field and current density are related by Ohm's Law (ICNIRP, 1998):

$$\mathbf{J} = \sigma\mathbf{E} \qquad (1)$$

where σ is the conductivity. And from Faraday's law is usually given in the form

$$V_{emf} = -\frac{d\Phi}{dt} \qquad (2)$$

where $\Phi = \oint \boldsymbol{B}\bullet d\boldsymbol{A}$ is the magnetic flux through the circuit.

The emf for any closed path can be expressed as the line integral of $\boldsymbol{E}\bullet d\boldsymbol{l}$ over the path as (Serway and Jewett, 2003):

$$V_{emf} = \oint \boldsymbol{E}\bullet d\boldsymbol{l} \qquad (3)$$

A time-varying magnetic field vector $\boldsymbol{B}$ also creates an electric field $\boldsymbol{E}$ according to Faraday's law, (NIEHS, 1998)

$$\oint \boldsymbol{E}\bullet d\boldsymbol{l} = E(2\pi R) = -\frac{d\Phi}{dt} = -\pi R^2\frac{dB}{dt} \qquad (4)$$

where $E \equiv |\boldsymbol{E}|$, and $B \equiv |\boldsymbol{B}|$ are the respective magnitudes of vectors $\boldsymbol{E}$ and $\boldsymbol{B}$. Hence the induced emf in the loop (if $B = B_0 \cos\omega t$) is

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

where $A \equiv \pi R^2$ is the loop area. From equation (5) we see that the maximum emf has the value (Serway and Jewwet, 2003)

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

which occurs when $\omega t = 90^o$ $or\ 270^o$ and where $\omega = 2\pi f$. In other words, $V_{emf} \equiv V_{emf(max)}$ when the magnetic field is in the plane of the loop and the time rate of change of flux is a maximum. From equation (4) spatially uniform magnetic field will induce an electric field in the exposed body, according to Faraday's law, thus (Ahmad, 2013):

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

The time varying electric field varies sinusoidally as

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

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

$$E = \pi fRB \quad (9)$$

This relation is frequently employed in estimating induced electric fields in animal bodies and cell cultures but will give only approximate results because biological tissue is neither cylindrical nor electrically homogeneous (NIEHS, 1998).

For a pure sinusoidal field at frequency, f equation (1) becomes

$$J = \sigma\pi fRB \quad (10)$$

Equation (10) is referred to as the Magnetic Field Model (ICNIRP, 1998). In equations (1) to (10), the relevant symbols are:

J = current density (A/m^2)
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)
σ = tissue conductivity (S/m)
f = 50 Hz ELF magnetic field (Hz)
B = magnetic flux density (T)

3. Analysis of Magnetic Field Exposure

In ICNIRP, (1998) it has been reported that a set of basic restrictions and reference levels exist based on the best available scientific data in order to ensure a high level of protection against exposure to electromagnetic fields. The analysis of the magnetic field exposure may be divided into the following two parts:

A. Occupational Exposure Limitations

The occupationally exposed population consists of adults who are generally exposed under known conditions and are trained to be aware of potential risk and to take appropriate precautions (Belrose Residential, 2013). The tolerance limit of $1\ mT$ was set.

B. General Public Exposure Limitations

The general public comprise individuals of all ages and of varying health status, and may include particularly susceptible groups or individuals. In many cases, members of the public are unaware of their exposure to EMF (ICNIRP, 1998). While these limits are not breached by individual man-made sources, additive effects must also be considered, as we shall see (Alex, 2013). The tolerance limits of 200 μT was set. Tables 1 and 2 contain the ICNIRP reference levels for occupational and general public exposure to time-varying magnetic fields and current density.

Table 1: ICNIRP Reference levels for Magnetic Fields Exposure (Source: ICNIRP, 1998) Note: 1 µT ≡ 10 *mG*, f is frequency in Hz and all values are in rms.

Exposure	Frequency range	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	$4\times10^{-2}/f^2$
	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}

From the ICNIRP table the maximum Magnetic field exposure limit for general public at the power frequency of 50 *Hz* is 200 μT while occupational exposure is 1000 μT.

Table 2: ICNIRP Reference levels for Current Density Exposure (Source: ICNIRP, 1998)

Exposure	*Frequency range*	*Current density for head and trunk (mA/m^2) (rms)*
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	------
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	------

4. Materials and Methods

Fifteen 33/11 kV electrical power injection substations were surveyed in the study area. All the electrical substations surveyed have different ratings and numbers of electrical transformers installed depending on the number of feeders connected to them. The feeders range from one up to seven connected to transformers via circuit breakers.

Field measurements of magnetic field level in 300 test points across the fifteen 33/11 kV electrical injection substations were taken at an interval of 1.5 m starting from the foot of each switchyard up to a distance of 30 m in all of the 33/11 kV electrical injection substations. A peg was used to demarcate the interval by the use of measuring tape. The magnetic fields at each substation were measured with the aid of hand-held device. As per the standard procedure for measurements of 50 Hz magnetic fields for assessment of human exposure all measurements were made at 1 m above the ground level (Khaled *et al.*, 2009). The average current densities over all locations are presented in Table 3.

Table 3: Average Current Densities over all locations. (In the estimation of induced current density in the head region, at extremely low frequency, tissue conductivities, σ, are of the order of 0.2 S/m while an average radius *R* of 0.075m of the induction loop are assumed for the head.)

Distance (m)	**Mean Current Density for all locations in ($\mu A/m^2$)**	**Standard Deviation ($\mu A/m^2$)**
1.5	14.20	9.38
3.0	4.32	4.30
4.5	1.65	1.57
6.0	0.92	0.83
7.5	0.70	0.55
9.0	0.57	0.39
10.5	0.49	0.32
12.0	0.43	0.26
13.5	0.38	0.25
15.0	0.35	0.20
16.5	0.30	0.15
18.0	0.28	0.15
19.5	0.22	0.14
21.0	0.19	0.12
22.5	0.16	0.10
24.0	0.14	0.10
25.5	0.11	0.07
27.0	0.10	0.06
28.5	0.08	0.06
30.0	0.07	0.05

5. Results and Discussion

The average estimated induced current density in the human head region using magnetic field model derived from Faraday's law of induction assuming the human body is circular over the 300 test points is as presented in

Table 3. Of all the Injection Substations surveyed, only ten representing 66.7% of the stations were in full operation (i.e all the installed transformers are functional) while the remaining five representing 33.3% have one transformer knock off for repair purpose (i.e not functional). Note that highly rated transformers are expected to radiate much more magnetic fields around it than low rating transformers because of the current carrying capacity.

There were fluctuations encountered in some substations during the measurements of magnetic fields level as one progresses in distance away from the source of fields. These fluctuations are due to the complexity of the power geometry and of the conductor's arrangements in substations. Some of these fluctuations arise due to nearby telecom masts while others are due to concealed cables underneath the ground being run from the switchyard to the control room or from the control room to the feeders.

A value of 0.4 μT has been set as the exposure limit to TWA power frequency magnetic field (Belrose Residential, 2013). From the calculated data for magnetic field (TWA), it therefore implies that long time exposure to magnetic field radiation at approximate distance of 10 meters from the switchyard may be classified as a possible carcinogen (IARC, 2002). The results obtained indicate that the induced current density values computed by use of magnetic field model at the head region of the body varies from $0.05\ \mu A/m^2\ \mu A$ (0.2 mG) at a distance of 30 m to $23.57\ \mu A/m^2$ (100mG) at a distance of 1.5 m.

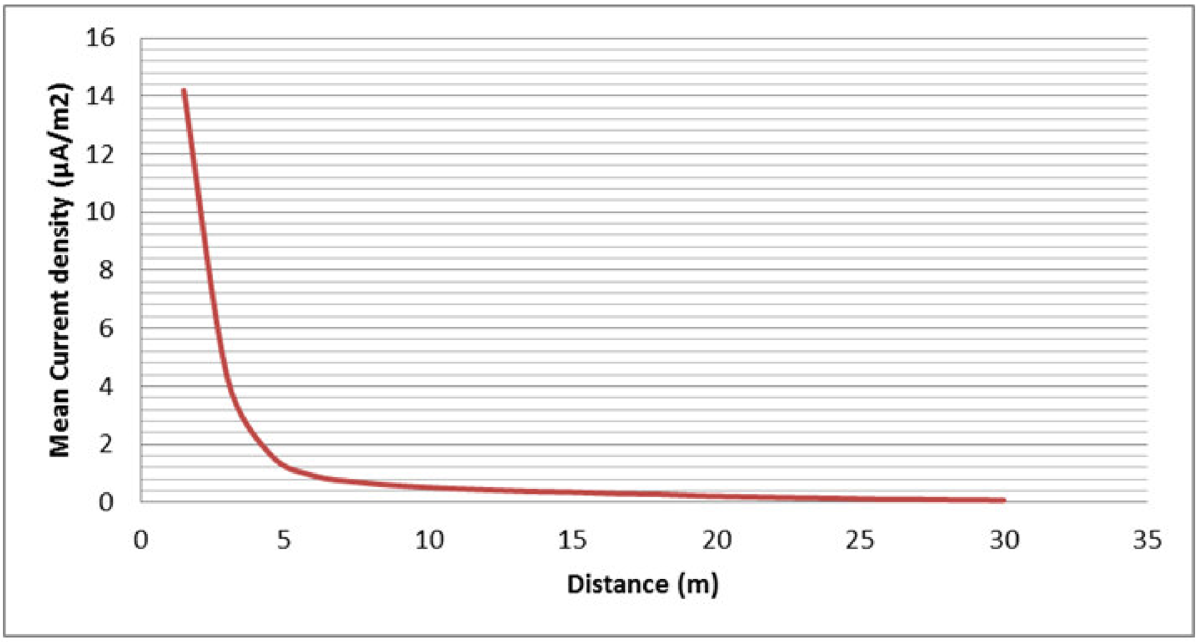

Figure 1: Plot of Mean Current Density versus Distance Locations. Table 3 gives the data used. (See text for more explanations)

Figure 1 indicates the relation of the average mean current densities versus distance plotted using Table 3. The chart shows that the current density decreases exponentially with distance. That is at distance, x = 0, the induced current density, J_{max} is maximum and for x > 0, the current density decreases exponentially.

7. Conclusions

The induced current densities around the head region for 300 test points for fifteen 33/11 kV Injection substations have being computed; 20 test points were used for each substation. The maximum induced current density in the head region from the survey was found to be $23.57\ \mu A/m^2$ at a distance of 1.5 m away from the switchyard at one location tagged as S4 while the value of $1.18\ \mu A/m^2$ was the minimum value at the same distance from the source of the fields.

The maximum computed value for induced current density for the head region was found to be far less than the recommended reference value of $10\ mA/m^2$ set by ICNIRP. Therefore, the level of magnetic fields in 33/11/kV Injection substations around Kano city based on this computation may not pose any known environmental health risk to the substation personnel. However, more research work is recommended.

There is no convincing scientific evidence of the adverse health effect to the power frequency magnetic fields exposure. Therefore further research based on epidemiological studies, experimental biology, volunteer studies and Dosimetry may provide further verification of the current results.

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