Nigerian Journal of Physics (NJP)

ISSN: 1595-0611

Volume 32(2), June 2023

Determination of on-the-Spot Occupational Elf Magnetic Field Levels in Hydro-Electric Power Transmission Switchyards

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ABSTRACT

The study determined the level of spot ELF magnetic fields generated in switchyards of the Hydro-electric power located in Niger state, Nigeria using the same measurement procedures. Extech 480826 Triple-Axis EMF metre was used for data capturing to assess the intensity of emitted ELF magnetic field. The external probe of Extech 480826 Triple-Axis metre was then mounted on specially constructed stand with three different reference heights that support the sensor in fixed position for field detection and recording at a spot. The stand was usually placed at accessible, permissible and safe locations in segmented manner within the switchyard. The on-the-spot occupational exposure was computed as the mean of the measurements from the three different reference heights of 1.0, 1.5 and 1.8 m above ground level. The mean values of 6.1780 µT was obtained in switchyard of Kainji Hydro-electric power station, 5.7843 µT was obtained for Jebba Hydro-electric power station switchyard while 5.0555 µT was obtained for Shiroro Hydro-electric power station switchyard as their on-the-spot occupational exposure. When the group differences were assessed using Dunnett's T3 Post Hoc Multiple Comparison test, Kainji switchyard was observed to have significant difference of (p = .027) with Shiroro switchyard, while nonsignificant difference of (p = .606) was observed with Jebba. Switchyards of Shiroro and Jebba show nonsignificant difference of (p = .259). The surveyed and analysed results of the study have revealed that on-the-spot occupational ELF magnetic fields level emitted in the switchyards are not the same within the switchyard and there exist variation from one switchyard to another even though operated at the same frequency of 50 Hz and voltage level of 330 kV.

Keywords:
ELF magnetic fields,
Extech 480826 Triple-Axis EMF metre,
Hydro-electric power station,
On-the-spot occupational exposure,
Transmission Switchyard.

INTRODUCTION

Of all known sources of energy: heat, mechanical, chemical and electrical; electricity is the most convenient for use in the economy. And of several means of generation of electricity, energy obtained from water (Hydro-electric power) is one of the cheapest sources of power available to mankind. Energy source from hydro-plant has now becomes an integral part of electricity generation that is contributing to modern life style, especially beneficial in health care service delivery, transportation services and fast industrial revolution because water, which is a free gift of nature is cheap, thus no fuel cost is incurred.

The professional commitment of personnel working in the transmission switchyards (Kokoruš *et al.*, 2014), of hydro power stations make them to be frequently exposed to high level of electromagnetic fields (EMFs) produced in the atmosphere of switchyard environment during the process of generation, transmission and distribution of electricity (Ocheni *et al.*, 2023). The transmission switchyards facilities mostly operate on continuous and uninterrupted basis, and emit fields in the vicinities that pollute the atmosphere. The workforces are unexpectedly exposed to these electropollution especially extremely low frequency (ELF) magnetic field that cannot be easily screened. When human body that is nonmagnetic encountered ELF magnetic field exposure, it caused no perturbation, therefore, making the field to penetrate partially owing to attenuation of the tissues because the permeability of the tissue is the same as that of air (Bakker *et al.*, 2012; Ocheni and Genesis, 2020). These have motivated researchers to study the general public and occupational exposure to ELF electric and magnetic fields (Ghnimi *et al*., 2016), due to serious concerns expressed about biological interactions and the potential negative health effects on human as a result of the prevalence of excessive and prolonged exposure in the environment (Korpinen *et al*., 2011; Ztoupis *et al*., 2013). Successive investigation by scientific experts on ELF related to electric fields have revealed that it has no substantive health issues at levels generally encountered by members of the public but however, recommended further research on the possible health effects of exposure associated with magnetic fields (Kim *et al*., 2013), in the occupational environment. This led to ELF magnetic field being tagged and classification in “Group 2B” as possible carcinogenic (Ocheni *et al*., 2023). In response to the apprehension, World Health Organisation (WHO) through the International EMF project has established the International Commission on Non-Ionising Radiation Protection (ICNIRP) to monitor and evaluate the likely biological effects and health risks associated with ELF magnetic field exposure, and update the public periodically (Haque *et al*., 2016).

The ELF electric field and magnetic field components with a frequency range of 0 to 300 Hz (Rathebe *et al*., 2018), generated by power system are usually decoupled (Morega and Machedon, 2004), due to the quasi-static nature of electromagnetic field (Costea *et al*., 2014; Halgamuge *et al*., 2011), and therefore studied separately. The ELF magnetic fields are emitted into the atmosphere by electrical infrastructures during the process of generation, transmission, distribution and utilisation of electricity. This generated field assertion is supported by Oersted's experiments, which stated that magnetic fields are emitted in the vicinity of conductors carrying current and also validated by Maxwell that conductor with alternating current flowing through also have components of electric field and magnetic field emission around it (Sudarti *et al*., 2018).

The operating frequency of electrical infrastructure in Nigeria is 50 Hz. The electropollution emitted at ELF by electrical power infrastructures into the atmosphere are latest known addition to environmental pollution which have drawn research interest and regarded as constituting threat to normal lives (Bahaodini *et al*., 2015; Vergallo and Dini, 2018), therefore posed as one of the biggest problems of the twenty first century (Adekunle *et al*., 2015; Al-Faqeeh *et al*., 2015). Despite the fact that the investigations on harm caused by electropollution is still open to question because of conflicting results from researchers on its negative effect on human beings (Redlarski *et al*., 2015).

Since data pertaining to occupational exposure to ELF fields are scarce in Nigeria, especially transmission switchyards that serve as transit network for electricity. It is appropriate to perform a comprehensive measurements of ELF magnetic field to evaluate the on-the-spot occupational exposure in the existing 330 kV switchyards of hydro-electric power stations. The results obtained from this research would create more awareness on the level of ELF magnetic field emitted into the atmosphere and expected to provide further insight for future study pertaining to ELF magnetic fields level in other switchyards of generating plants of the same specifications in the country.

MATERIALS AND METHODS

Study Areas

There are three operational hydropower plants in Niger state, north central Nigeria: Kainji, Jebba and Shiroro hydro-electric power stations. Kainji hydro-electric power station (Latitude 9.861044ºN, 4.613103ºE) has eight turbines with installed capacity of 760 MW, Jebba hydro-electric power station (Latitude 9.168045ºN and Longitude 4.821214ºE) has six turbines with installed capacity of 578 MW and Shiroro hydro-electric power station (Latitude 9972474ºN and Longitude 6.830333ºE) has four turbines with installed capacity of 600 MW.

Figure 1 presents the map of Niger state, Nigeria showing the exact locations of the three study areas where research was conducted.

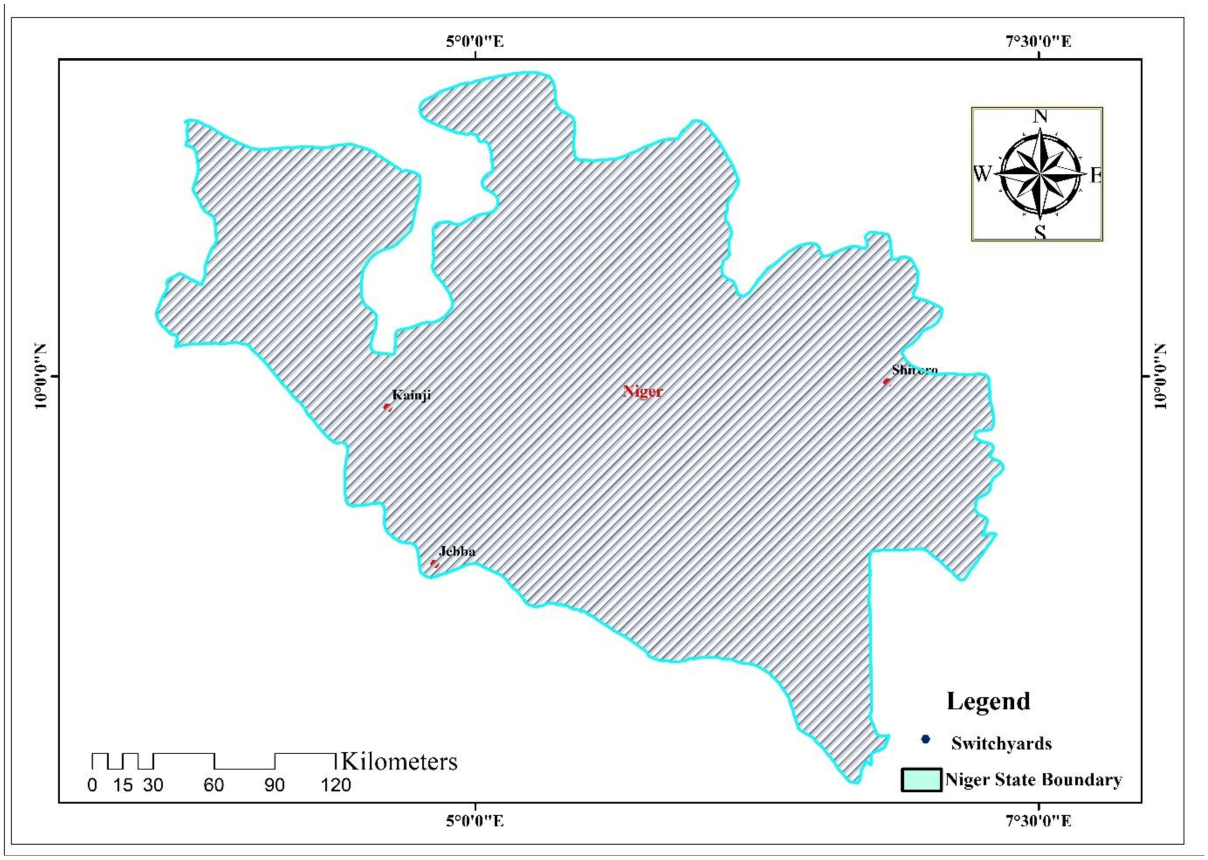

Figure 1: Map of the Study Area

The generated electricity by hydro-plant is evacuated from the sites via 330 kV transmission switchyards located in the vicinity of the hydro-electric power generating stations.

The permission to carry out measurements survey of ELF magnetic field in the 330 kV transmission switchyards was seek for and request granted by the management of Transmission Company of Nigeria (TCN) Shiroro sub-region.

Measurement Procedure

Measurement of ELF magnetic fields data at the switchyards were performed using Extech 480826 Triple-Axis EMF metre manufactured by Extech Instruments that measures in the frequency bandwidth of 30 to 300 Hz range with sampling time of approximately 0.4 s. The metre measures the root means square ELF magnetic field in each of the three orthogonal directions and displayed on the screen, and resultant value evaluated through the equation:

$$\mathrm{B}_{\mathrm{rms}} = \sqrt{\mathrm{B}_x^2 + \mathrm{B}_y^2 + \mathrm{B}_z^2} \qquad (1)$$

The instrument has three modes of selection with corresponding basic accuracy as 20 µT (4 %), 200 µT (5 %) and 2000 µT (10 %), and calibrated to flat frequency response. Spot measurement technique was employed for data acquisition at three observation heights. The mean stationary measurements at position were then computed to account for the on-the-spot occupational exposure condition of the field strengths at the selected spots personnel might be exposed to at an instant of time. The measurement was performed in accordance with the guideline stipulated in Institute of Electrical and Electronics Engineers (IEEE) Standards and results obtained compared with the reference standard set by ICNIRP.

Measurement of ELF magnetic fields in switchyards are harmful task due to complexity of the grid, where different loads are supplied with different sizes of conductor carrying-current (Alghamdi, 2019). Therefore, the momentarily measurements were performed at the accessible, permissible and safe locations in switchyard in segmented manner because of the multifaceted nature of the environment and using the exact procedure of detection at each spot in the three surveyed switchyards to assist in comparison of results. Since weather conditions can affect the results, the exposure measurement was done at specific atmospheric conditions of operating temperature and relative humidity ranges, between the hours of 10 am to 4 pm on sunny day as specified on manufacturer user's guide.

ELF Magnetic field laws

Biot-Savart's law and Ampere's circuit laws are referred to as magnetostatics law and applicable in the analyses of ELF magnetic fields sources emitted by electrical infrastructures in the switchyards (Habiballah *et al.*, 2003). However, for analysis of symmetrical current distributions around conductors, Ampere's circuit law is applicable while for analysing the strength of the magnetic field at a distance from the source, Biot-Savart law is applied (Ocheni *et al.*, 2023). Due to the complex networks in switchyard, interconnections of installed equipment are normally accomplished via overhead and underground connections.

For an overhead lines, the symmetrical magnetic fields generated by current distribution around the conductor can be analysed by Ampere's circuit law (Sadiku, 1989):

$$B = \frac{\mu_o I}{2\pi r} \qquad (2)$$

where B is the magnetic field, I is the current flow through the long-conductor, μ_o is the permeability of free space and $2\pi r$ is the circumference of the magnetic field makes with current through a long-conductor. Since magnetic field produced by a conductor forms concentric circle, by application of Pythagoras theorem, the value of r which is the distance from the current source can be written as:

$$r = (x^2 + y^2)^{1/2} \qquad (3)$$

and equation (1) yields,

$$\vec{B} = \frac{\mu_o I}{2\pi (x^2+y^2)^{1/2}} \qquad (4)$$

Magnetic field is a vector quantity with vertical and horizontal components, and θ is the angle between B_x and B (Belhadj *et al.*, 2008). Therefore, the components are expressed as:

$$B_x = -B\sin\theta \qquad (5)$$

$$B_y = B\cos\theta \qquad (6)$$

The minus sign on B_x term is because of the coordinate convention. The magnetic field with both horizontal and vertical components at a point can be evaluated as in equations (7 and 8):

$$B_x = -\frac{\mu_o I_o}{2\pi\sqrt{x^2+y^2}}\sin\theta = \frac{-\mu_o I_o y}{2\pi(x^2+y^2)} \qquad (7)$$

$$B_y = \frac{\mu_o I_o}{2\pi\sqrt{x^2+y^2}}\cos\theta = \frac{\mu_o I_o x}{2\pi(x^2+y^2)} \qquad (8)$$

where,

$$\cos\theta = \frac{x}{r} = \frac{x}{\sqrt{x^2+y^2}} \qquad (9)$$

$$\sin\theta = \frac{y}{r} = \frac{y}{\sqrt{x^2+y^2}} \qquad (10)$$

Equations (7 and 8) represent calculated field from a single current. The resultant vertical and horizontal components of magnetic field is vectorially added as:

$$B = \sqrt{B_x^2 + B_y^2} \qquad (11)$$

The superposition of individual conductor contributions to current flows is used to evaluate the magnetic flux density at each point of space (Muharemovic *et al.* 2012). For multiple conductors of the same phase angle, the resultant magnetic field is expressed as (Kocatepe *et al.*, 2014):

$$B = \sqrt{(B_{xi})^2 + (B_{yi})^2} \qquad (12)$$

where the horizontal component, B_{xi} and vertical component, B_{yi} are expressed as:

$$B_{xi} = \sum_{i=0}^{n} -\frac{\mu}{2\pi} I_i \left[\frac{y_k - y_i}{r_{ik}^2}\right] \qquad (13)$$

$$B_{yi} = \sum_{i=0}^{n} \frac{\mu}{2\pi} I_i \left[\frac{x_k - x_i}{r_{ik}^2}\right] \qquad (14)$$

and r_{ik} is the distance between the conductor and the point of measurement expressed as,

$$r_{ik} = \sqrt{(x_k - x_i)^2 + (y_k - y_i)^2} \qquad (15)$$

For magnetic fields generated by multiple conductors of different phase angles, three-dimensional components generally have different phase-angles from each other, so that their vector sum (total magnetic field) rotates in a plane, describing an ellipse, at the same frequency as the source currents (Hayashi *et al.*, 1992). When three conductors are placed 120° apart and the whole rotated in a uniform magnetic field, a three-phase supply is generated (Bird, 2003). By this consideration current-carrying conductors in three-phase system with a phase difference of 120° (Ali *et al.*, 2016) is expressed as:

$$I_R = I\angle 0^o;\ I_B = I\angle 120^o;\ I_Y = I\angle -120^o \qquad (16)$$

Individual component of magnetic field has an in-phase $(B_{x(in)}, B_{y(in)})$ and an out-phase $(B_{x(out)}, B_{y(out)})$ components. For multiple cables the x and y components of fields are expressed as:

$$B_x = \sqrt{\left\{\sum_{i=1}^{n} B_{x(in)_i}\right\}^2 + \left\{\sum_{i=1}^{n} B_{x(out)_i}\right\}^2} \qquad (17)$$

$$B_y = \sqrt{\left\{\sum_{i=1}^{n} B_{y(in)_i}\right\}^2 + \left\{\sum_{i=1}^{n} B_{y(out)_i}\right\}^2} \qquad (18)$$

The entirety contributions from the line currents for the magnetic field is given as (Belhadj *et al.*, 2008):

$$B = \sqrt{B_x^2 + B_y^2} \qquad (19)$$

These analyses were based on the assumption that the conductors carrying-current of infinite length are arranged parallel to each other but horizontal to a ground level.

On the other hand, for buried cables underneath in switchyard, the conductors carrying-current produce magnetic fields around them but the conductive shields under their insulators screened the electric fields from reaching outside the cables (Ahmadi *et al.*, 2010; Kocatepe *et al.* 2014). Therefore, there are negligible electric field and predominant magnetic field in the atmosphere of the environment.

By analytical application of Biot-Savart's law of equation (20) to buried cables, magnetic fields from underneath sources can be arrived at (Vujević *et al*, 2009).

$$B = \frac{1}{10^7}\int \frac{I d\vec{l}\times\hat{r}}{r^2} \qquad (20)$$

where I is the line current, dl is a differential element of the conductor in the direction of current, r is the distance between an observation point and a source point and $\hat{r}$ is a distance vector. The magnetic field density for horizontal and vertical components at an observation point produced by buried three-phase cable due to the current from multiple cables can be expressed as (Djekidel *et al*., 2016):

$$B_{xi} = \sum_{i=1}^{n} -\frac{\mu}{2\pi} I_i \left[\frac{y_i+y_j}{r_{ij}^2}\right] \qquad (21)$$

$$B_{yi} = \sum_{i=1}^{n} \frac{\mu}{2\pi} I_i \left[\frac{x_i-x_j}{r_{ij}^2}\right] \qquad (22)$$

where the coordinates of three-phase conductors are x_i and y_i, the coordinates of observation point are x_j and y_j while the distance from the current source to observation point is r, defined as:

$$r_{ij} = \sqrt{(x_i - x_j)^2 + (y_i - y_j)^2} \qquad (23)$$

Therefore, the total magnetic flux density produced by the three-phase underground cable at observed point can be expressed as:

$$B = \sqrt{B_{xi}^2 + B_{yi}^2} \qquad (24)$$

Equations (20 and 24) are presumed as contributions from overhead lines and buried underground cables sources respectively for magnetic field at any spot in space within the vicinity of the switchyard.

RESULTS AND DISCUSSION

A sum total of 517 computed on-the-spot occupational ELF magnetic fields data were assessed and analysed across the three surveyed switchyards of hydro-electric power stations. Due to variation in the sizes of the switchyards, the obtained data from each location are unequal. The obtained data were subjected to One-way analysis of variance (ANOVA) with significant different set at 0.05 level to observe the significant differences in occurrence of the on-the-spot occupational exposure between the stations.

Table 1 presents the One-way ANOVA descriptive statistics, Test of homogeneity of variance, Robust tests of equality of means and Group differences using Dunnett T3 Multiple comparisons test for the on-the-spot occupational exposure levels of ELF magnetic fields analyses for 330 kV transmission switchyards of hydro-electric power stations.

Table 1: Analysed Results

			Test of Homogeneity of Variance		**Robust tests of Equality of Means**	
Hydro Switchyard	**Mean µT**	**Std. Deviation**	**Levene Statistics**	**Sig.**	**Welch Statistics**	**Sig.**
Kainji	6.1780	3.18878	16.443	.000	3.426	.034
Jebba	5.7843	3.28311				
Shiroro	5.0555	4.76172				

Group Differences

Hydro Switchyards		**Mean Difference**	**Sig.**	**95% Confidence Interval Lower Bound**	**Upper Bound**
Kainji	Shiroro	1.12254*	.027	.0939	2.1512
Jebba	Shiroro	.72886	.259	-.3161	1.7738
Kainji	Jebba	.39367	.606	-.4565	1.2438

Kainji switchyard (*N* = 170, *M* = 6.1780, *SD* = 3.18878) was observed to has the highest means of on-the-spot occupational exposure fields, but the value was still relatively close to Jebba switchyard (*N* = 164, *M* =5.7843, *SD* = 3.28311) compared to that of Shiroro switchyard (*N* = 183, *M* = 5.0555, *SD* = 4.76172).

The Levene's statistic for Homogeneity of variances revealed statistically significant differences of (*F*(2, 514) = 16.433, $p < .001$), therefore, assumption for Homogeneity of variance have being violated. So, the null hypothesis "there is no significant differences in the on-the-spot occupational exposure to ELF magnetic field levels in switchyards of hydro-electric power stations" stand rejected. Since the Homogeneity of variance was significant, so equal variance was not assumed. To further assess the significant differences, Welch-Robust test of equality of means was employed to analysed the significant level since it is robust to violation of Homogeneity of variances

The Welch One-way ANOVA revealed statistically significant differences of (*F*(2, 339.196) = 3.426, $p < .034$) between switchyards exposure. To determine the specific switchyards that differs, Multiple comparison using Dunnett T3 Post Hoc tests since equal variances were not assumed for the three switchyards. Kainji switchyard demonstrated statistically significant difference of ($p = .027$) when compared to Shiroro switchyard, however nonsignificant differences were observed between Jebba switchyard with both Kainji and Shiroro switchyards as shown in Table 1.

Public and occupational exposure assessment to ELF magnetic fields exposure have been carried out by researchers of recent. Rathebe *et al.* (2018) evaluate 30 public residential areas across three metropolitan municipality. The ELF magnetic field measurements were collected at the distances of 3 m, 6 m and 9 m outside electrical substations using a Trifield meter model XE 100. The results demonstrated nonsignificant differences among 15 residential areas and six residential areas whereas, significant differences were observed between three residential areas guidelines. Kenji *et al*. (2011) carried out an international cooperative study to measure the levels of electric field and magnetic field produced within and near 23 power facilities in seven countries with system voltage in the range of 110 to 500 kV employing identical procedures for data capturing. For spot technique, Furukawa's electric field metre and Enertech's magnetic flux density metre were used to performed measurements of the field at every 1 metre interval along two straight paths orthogonal to each other and for continuous technique EFM-309 electric field strength metre and EMDEX-II magnetic flux metre were fixed at waist and shoulder of volunteer who record data as he walks around the locations. The maximum magnetic field of 21 µT recorded in their survey was closed to the maximum value of 23.85 µT observed in this research, however these values are still far below the recommended occupational level of 1,000 µT stipulated by ICNIRP.

Medical research has suggested that exposure to magnetic fields above safe limits can have a significant detrimental effect on health (Fernandez and Patrick, 2021) and might result to dangerous effects on human beings in close proximity (Audu, 2018). Recent epidemiological studies have shown that time weighted average (TWA) occupational exposure to ELF magnetic fields above 0.4 µT is associated with a small increase in the absolute risk of leukaemia (Joseph *et al*., 2009). To curtail the effects that might probably arise, there is need for frequent monitoring of fields level within the switchyards of generation, transmission and distribution stations in Nigeria.

CONCLUSION

The performed study compared the on-the-spot occupational exposure between the switchyards and assessed whether the emitted ELF magnetic fields by the electrical facilities in the switchyards of hydro-power plants are within the permissible standards occupational level. The one-way ANOVA analyses demonstrated significant and non-significant differences between switchyards. However, comparison of measured ELF magnetic fields values with established set standard for occupational exposure show that the maximum value of 23.85 µT was far below the reference limit of 1,000 µT set by ICNIRP. These results do not validate that the vicinities are entirely safe and ELF magnetic fields are harmless to the operators since it was an instant evaluation. It is the researchers' opinion that constant monitoring undertaken to determine the time-weight-average (TWA) exposure, and occupational ethics adhered to always in accordance with standards laid down rules by IEEE.

Acknowledgment

The authors wish to appreciate the management of Transmission Company of Nigeria (TCN) for granting the approval and permission to use their premises and the contributory roles played by the staff in directing and guiding the term during the survey.

Conflict of interest

The authors declared that there exists no conflicting interest.

Sources of Funding

none

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