Investigating the Intensity and Extent of Magnetic Field Exposure in Transmission Switchyard of Hydropower Stations

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Abstract: - Occupational exposure to anthropogenic magnetic field at 50/60 Hz has attracted much attention recently with considerable apprehensions due to probable health hazards. The measurements of this magnetic field in the transmission switchyard of hydropower stations were performed in a segmented manner via a calibrated Extech 480826 Triple-Axis meter placed on a constructed stand with three observation heights (1.0, 1.5, and 1.8) metres corresponding to regions of waist, chest, and head for a standard normal human. The one-way ANOVA test in SPSS software with a *p*-value set at 0.05 demonstrated statistically significant differences in extremely low frequency (ELF) magnetic field exposure. The Tukey Simultaneous 95% CI significant differences were noted when the difference of mean for locations (Shiroro and Kainji switchyards) based on each observation height does not cross the zero-reference interval region. Whereas Jebba with Shiroro or Kainji switchyards were not significantly different. Furthermore, the Tukey Simultaneous 95% CI of two-way ANOVA shows that the difference of mean for heights: (1.0 m versus 1.5 m), (1.0 m versus 1.8 m), and (1.5 m versus 1.8 m) were statistically significant to ELF magnetic field exposure based on locations. The induced electric field and current density simulations using COMSOL Multiphysics for the highest mean magnetic field of uniform exposure in the switchyards show that the evaluated values were less than the stipulated basic restriction of 0.8 V/m and 10 mA/m^2 by ICNIRP standard. Therefore, this study has given an insight on the instant intensity, the extent of induction and the need for continuous monitoring as precautionary measures to safeguard occupational workforce from extreme and prolonged magnetic field exposure radiation in switchyards vicinity, and also some associated health hazards in the heights' region are discussed.

Key-Words: - Health hazards, Hydropower transmission switchyards, Magnetic field exposure, Observation heights, Occupational exposure and Zero-reference interval region.

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1 Introduction

The indispensability of electricity in society is greatly influenced by growth in human population, urbanisation and industrialisation. For these reasons, there are quest for reliable, low-cost and alternative means of electricity generation, [1], [2]. Hydropower offered this viable option of energy because water is nature's free gift, readily available and does not require fuel cost. Hence many nations are harnessing their technogenic potential for electricity generation and have become an integral part of energy sources, [3]. Other benefits derived from water for electricity generation are: nontoxic, usefulness in irrigation and aquatic farming, and has a longer lifespan when compared to other energy sources. Thus, dependable and serving as a fulcrum of industrialisation vis-à-vis economic prime mover and basis for improved living standards.

The generation, transmission, distribution and use of electricity is accompanied by the emission of electric and magnetic fields that pollute the environment, [4]. However, the magnetic field component has attracted research attention recently, [5], [6], [7], [8] since studies have revealed that it permeates skin effortlessly without hindrance [9], inducing electric field and current density in the biological tissues [10]. Hence, raising apprehensions on the environmental influence and occupational exposure safety, [11]. In view of these, the International Agency for Research on Cancers (IARC) has classified extremely low frequency (ELF) magnetic field as a likely human carcinogen (group 2B), [4] [7], [12], [13] whose prime source is electricity operated at 50/60 Hz, [9]. The World Health Organisation (WHO) an arm of the United Nations (UN) saddle with health has commissioned the International Commission on Non-Ionising Radiation Protection (ICNIRP), [14] to focus on assessing the level of health hazards associated with exposure. In view of the mandate, the ICNIRP has specified 10 mA/m^2 at frequencies from 4 Hz to 1 kHz and 0.8 V/m at frequency from 1 Hz to 3 kHz as respective values for induced current density and induced electric field for the electromagnetic fields radiated from high voltage facilities for occupational safety, [13]. The emitted technogenic fields are among the ubiquitous invisible environmental pollutions apart from the well-known pollutants in this modern era encountered daily by human beings, [15].

Transmission infrastructures in switchyard play a strategic role in society [14], and are one of the locations with high concentrations of electromagnetic fields pollutions [3], [7], which are functions of frequency, phase, magnitude and direction, [16]. These fields are emitted by operational equipment installed for the purpose of electrical energy generation, transmission, distribution and utilisation. In the process, they cause ionisation of air, emitting corona ions that get attached to several aerosol particles that pollute the earth's atmosphere, [17].

Published studies suggest professional groups such as utility workforce in hydro and thermal electrical plants [18] are exposed persistently to extreme ELF fields produced by infrastructures in the switchyard compared to ordinary workers in office environments whose intensity of field exposure is at the same levels as those found at home and public environments, [15], [19], [20]. However, the components of magnetic field have been discovered to move farther from its source, permeate virtually through all materials including human tissue. This might lead to increased risks of cancer and oxidative stress within the biological system than the electric field counterpart [7], [9], [16], because human tissue and air possess the same magnetic permeability property [1].

In Nigeria, there are sparsity of studies conducted to assess the occupational intensity and extent of induction to ELF magnetic field exposure in transmission switchyards. Available works have centred on studying the fields' easement intensity along the right of way (ROW) of high-tension transmission lines, [16], [21], [22], [23]. Reference [21], used Trifield meter (model 100XE) to examined the electromagnetic fields pollution due to 132 kV and 330 kV transmission lines at Bauchi/Gombe area in Nigeria. Whereas, the health hazards analysis of exposure to electric and magnetic fields study around 11 kV, 33 kV, 132 kV and 330 kV high-tension lines in Kaduna metropolis with ELECTRO SMOG meter were performed in [16]. The measurements made, were at 10 m intervals from the base of the power lines to 100 m distance away. Reference [22] analysed the electric and magnetic fields of transmission lines emanating from four transmission stations at a horizontal distance of 10 m intervals up to a distance of 100 m by means of Electrosmog meter (Model TES-92). These aforementioned studies and others on fields radiated by electrical transmission lines in public domain around the easement of towers in the country have motivated occupational study of ELF magnetic field exposure in transmission switchyards of hydropower stations located in Niger state, north central Nigeria.

This article is continuance of the previous work in [24] of the same sites but in this present study, difference of mean for locations to instantaneous intensity of ELF magnetic field exposure based on the observation heights were examined and the statistically significant difference noted when the difference of mean for locations do not cross the zero-reference interval region. The induced electric field and current density of the highest mean ELF magnetic field exposure at the spot for each location were computed through COMSOL Multiphysics simulation.

This study aims at creating awareness for industry regulator and researchers to also focus on survey of ELF magnetic field intensity within switchyards vicinity as precautionary measures to safeguard occupational workforce from hazardous exposure.

2 Measurement Method

The study was carried out in the month of January, 2022 in three hydropower transmission switchyard generation plants located in Niger state, Nigeria as depict in Figure 1 (Appendix). The ELF magnetic field measurements were done with the aid of a calibrated handheld Extech 480826 triple-axis EMF meter with its external detachable probe sensor usually positioned on a constructed stand with three different observation heights of 1.0, 1.5 and 1.8 m, which represent standard regions of human such as the reproductive organs, pleural cavity and the brain respectively. These preferred heights are based on reports suggesting that excessive exposure beyond the occupational threshold limit of 1 mT is linked to probable health hazards such as reproductive, cardiovascular and neurological disorders, [5].

The records for the estimated average electricity consumption in the switchyard during measurement are stated in [24]. The Transmission Company of Nigeria (TCN) Shiroro sub-region granted approval and access to the facilities for the survey under the supervision of the personnel upon request.

The entire switchyards' measurements of the ELF magnetic field intensities at 50 Hz frequency were performed in a segmented format by placing the calibrated handheld meter sensor on the constructed stand. The resultant root mean square of the recorded magnetic field across the three axes evaluated for each observation height at the different spots of interest were noted.

The essence of the constructed stand was to guarantee measurements uniformity and accuracy at designated height at the various spots of interest in the switchyards. Same technique of measurement was applied throughout and duration of 60 seconds allowed before recording the value detected on the meter screen and subsequent change of sensor level across observation heights and spots to minimise errors due to fluctuation. The meter has an approximate sampling period of 0.4 s, flat frequency response with narrow frequency bandwidths of 30 – 300 Hz. The meter used conformed with the standard requirements set for instrumentation as stated in reference, [24].

The comparative analysis was performed via Tukey Simultaneous 95 % Confidence Interval (CI) for ELF magnetic field exposure based on heights for the difference of mean for locations using one-way ANOVA (version 23.0) in SPSS package with a *p*-value set at 0.05 as a statistically significant level. The induced electric field and current density were computed via COMSOL Multiphysics (version 5.5) software through simulation by subjecting the standard normal human to a uniform exposure of the highest mean ELF magnetic field recorded from the vicinity of switchyards.

2.1 Mathematical Model

Measuring the magnitude of electric field and current density induced within the biological system is difficult to achieve directly, [25]. But with mathematical model and the aid of COMSOL Multiphysics software, an approximate level of induction in an adult human can be evaluated.

This is done by the principle of quasi-static approximation with the assumption that the electric field is negligible and magnetic field is predominant in the environment with air as a perfect dielectric [25]. At ELF, the wavelength is large relative to the dimension of the human body [9], the relationship between the time-varying magnetic field and body induced electric field is expressed by time-harmonic Faraday's law, Ampère's law and Gauss's law for magnetism respectively as:

$$\nabla \times \vec{E} = -j\omega\vec{B} \quad (1)$$

$$\nabla \times \vec{H} = \mu\vec{J} \quad (2)$$

$$\nabla \cdot \vec{B} = 0 \quad (3)$$

where $\vec{E}$ (V/m) is the vector of electric field intensity, $\vec{B}$ (T) is the vector of magnetic flux density, $\vec{H}$ (A/m) is the vector of magnetic field intensity, ω (rad) is the angular frequency of incident field, $\vec{J}$ (A/m^2) is the conductive current density and μ (H/m) is the magnetic permeability.

The magnetic vector potential, $\vec{B}$ is expressed as [25]:

$$\vec{B} = \nabla \times \vec{A} \quad (4)$$

which is a direct consequence of the magnetic Gauss's law. Solving equations (1) and (4) gives,

$$\nabla \times \vec{E} = -\nabla \times j\omega\vec{A}. \quad (5)$$

Thus,

$$\nabla \times \left(\vec{E} + j\omega\vec{A}\right) = 0 \quad (6)$$

But, the curl of the gradient of any scalar field vanishes, that is $\nabla \times \nabla\phi = 0$. Hence,

$$\nabla \times \left(\vec{E} + j\omega\vec{A}\right) = -\nabla \times \nabla\phi \quad (7)$$

and the electric field is then expressed as:

$$\vec{E} = -(j\omega\vec{A} + \nabla\phi) \quad (8)$$

where ϕ is the scalar potential resulting from static electric field and $\vec{A}$ is the vector potential due to alternating electric field, [25]. The $\nabla\phi$ in equation (8) demonstrates that magnetic field represent gradient of scalar potential, [26].

The electric field induced in the tissue, setup eddy currents. Thus, the conduction current density may be expressed as:

$$\vec{J} = -\sigma(j\omega\vec{A} + \nabla\phi) \qquad (9)$$

where σ is the conductivity of the human tissue [27]. By taking the divergence of equation (9) with LHS vanishing, one obtains the magnetic field exposure form as:

$$-\nabla\cdot\sigma\left(j\omega\vec{A} + \nabla\phi\right) = 0 \qquad (10)$$

Therefore, the ELF magnetic field equation (10) is the governing equation for the air and the tissues interface.

3 Results

The perimeter of the transmission switchyard is always a function of the installed capacity of the equipment in the hydropower stations. So, the number of recorded ELF magnetic field spots are unequal across the switchyards. Jebba, Kainji and Shiroro transmission switchyards have 164, 170 and 183 respectively as the number of spots from the survey.

The plots in Figure 2, Figure 3 and Figure 4 are the results of comparative analyses based on observation heights with significant differences ($\alpha = 0.05$) for ELF magnetic field exposure observed when the difference of mean for locations does not cross the zero-reference interval region.

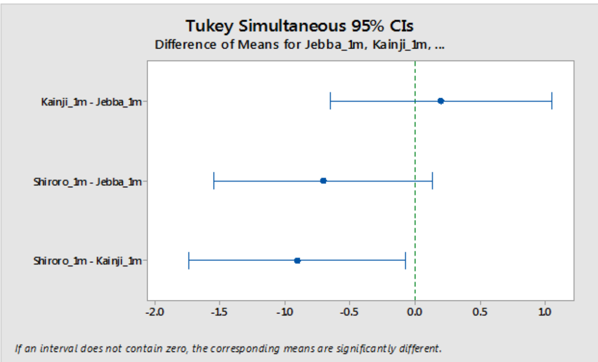

Fig. 2: Tukey 95% CI of Height at 1.0 m of Difference of Mean for Locations
Source: created by the authors

Figure 2 shows that the difference of mean for locations (Shiroro and Kainji switchyards) based on height 1.0 m is significant to ELF magnetic field exposure. Meanwhile, at the same observation height there were no statistically significant differences observed between Jebba with Kainji or Shiroro transmission switchyards because the difference of mean for locations crossed the zero-reference region interval.

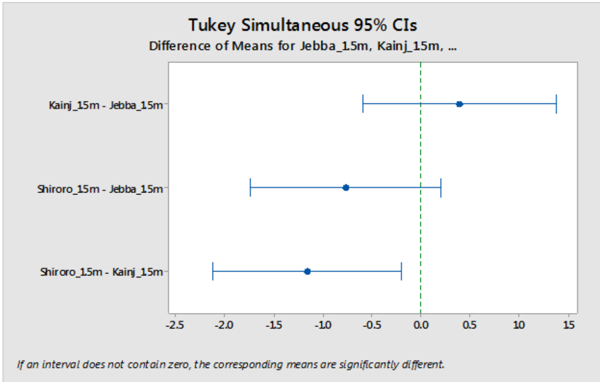

Fig. 3: Tukey 95% CI of Height at 1.5 m of Difference of Mean for Locations
Source: created by the authors

Figure 3 shows that Jebba with Kainji or Shiroro transmission switchyards at Tukey 95% CIs test are not significantly different from ELF magnetic field exposure at height 1.5 m because of the difference of mean for locations that crossed the zero-reference interval region, whereas based on the same observation height the difference of mean for locations (Shiroro and Kainji transmission switchyards) is significant in exposure.

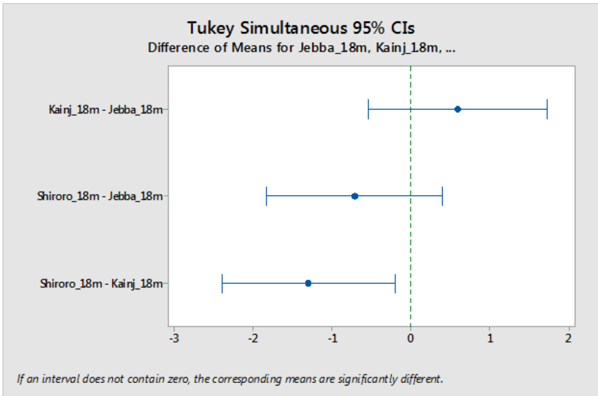

Fig. 4: Tukey 95% CI of Height at 1.8 m of Difference of Mean for Locations
Source: created by the authors

Figure 4 reveals a significant difference for ELF magnetic field exposure based on a height 1.8 m of the difference of mean for locations (Shiroro and Kainji transmission switchyards), whereas at the same observation height, Jebba with Kainji or Shiroro transmission switchyards whose differences of mean for locations cross the zero-reference interval region are not statistically significant.

In summary, the Tukey Simultaneous 95% CIs for one-way ANOVA have revealed that significant differences to magnetic field exposure based on each observation height occurred between transmission switchyards when the difference of mean for locations do not cross the zero-reference interval region but nonsignificant if otherwise.

Furthermore, Figure 5 illustrates the two-way ANOVA performed on the ELF magnetic field by considering two factors: locations and observation heights. The Tukey 95% CI based on locations for ELF magnetic field exposure of the difference of mean for observation heights revealed significant differences of exposure for locations ($P < 0.001$); heights ($P < 0.001$) and nonsignificant difference of locations with heights ($P = 0.964$). Thus, null hypothesis stands rejected for locations with heights.

The Tukey 95% CI plot shows that the difference of mean for height (1.0 m versus 1.5 m); (1.0 m versus 1.8 m); and (1.5 m versus 1.8 m) are significantly different for ELF magnetic field exposure based on locations because none of the mean heights crossed the zero-reference interval region. These show that there exist differences in ELF magnetic field exposure experienced at the regions of waist, chest and head in the switchyards for a standard normal human.

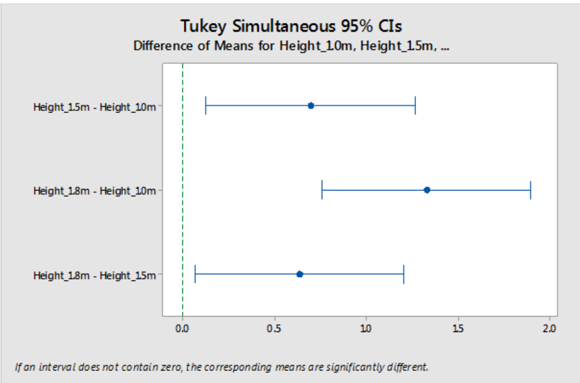

Fig. 5: 95% CI of Locations of the Difference of Mean for Observation Heights
Source: created by the authors

The evaluation of induced electric field and current density for ELF magnetic field exposure is of great interest due to probable health hazards. It was performed using COMSOL Multiphysics software via the AC/DC module. Problems analysis in COMSOL is resolved by the finite element method. The 2-D human model used in the study was assumed to have a constant head radius of 0.1 m, body radius of 0.3 m and body height of 1.8 m, relative permeability (μ_r) of 1 H/m, relative permittivity (ε_r) for all organs of 2×10^7 F/m, and conductivity of skin as 0.04 S/m, [25].

The complete mesh of 2D human surface structure was discretised into 807 linear triangular domain elements consisting of 159 boundary elements.

Figure 6, Figure 7 and Figure 8 represent the 2D standard normal human structure simulations distribution of induced electric field and current density subjected to a homogeneous exposure of highest mean magnetic field recorded in 330 kV Jebba, Kainji and Shiroro transmission switchyards respectively.

The evaluations in Figure 6, Figure 7 and Figure 8, show that the maximum induced electric field and current density occurred in Shiroro transmission switchyard with respective values of $55 \times 10^{-12}\, V/m$ and $35 \times 10^{-13}\, A/m^2$ but, the values are much less than the ICNIRP set basic restriction values of 0.8 V/m and 10 mA/m^2 that can lead to health hazards.

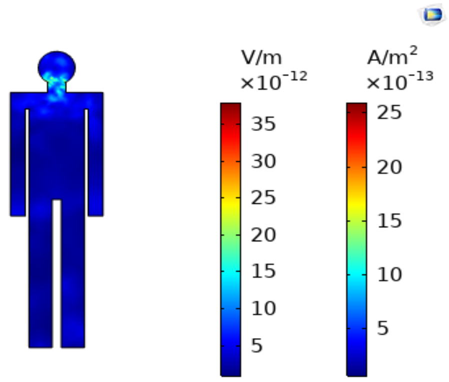

Fig. 6: Jebba Switchyard Induced Electric field and Current Density Simulation
Source: created by the authors

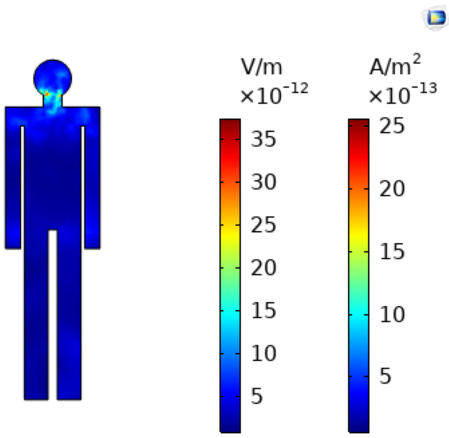

Fig. 7: Kainji Switchyard Induced Electric field and Current Density Simulation
Source: created by the authors

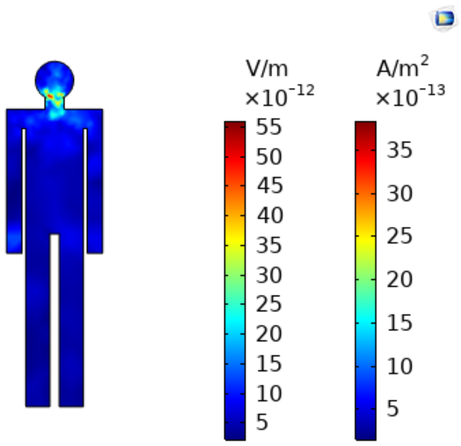

Fig. 8: Shiroro Switchyard Induced Electric field and Current Density Simulation [Source: created by the authors]

The simulations revealed the relative concentration of the induced electric field and current density at the upper body part, mostly at the neck region. This region's level of vulnerability is due to its smaller cross-sectional size and closeness to the field source, and consistent with the assertion in [27] and [28].

4 Discussion

The corresponding instant highest recorded ELF magnetic field in transmission switchyards at height 1.0, 1.5 and 1.8 m from Jebba are 13.18 μT, 16.40 μT and 19.49 μT; Kainji are 11.00 μT, 12.63 μT and 15.26 μT, and Shiroro are 21.32 μT, 23.73 μT and 26.48 μT respectively. These measured values from the locations are 1.95 %, 1.53 % and 2.65 % of the occupational exposure limit. Thus, significantly low in comparison to the 1 mT as the occupational exposure threshold specified by ICNIRP.

Similar study in [12] assessed the health risk associated with magnetic field exposure in five switchyards of three electrical substations from two states of Southeast, Nigeria using the TENMARS (model TM-191) magnetic field meter. The highest value of 15.04 μT obtained from the middle of the switchyard in Alaoji 330 kV substation was within the range of values of the present study obtained from Jebba and Kainji 330 kV transmission switchyards.

Studies have unveiled that persons exposed to ELF magnetic fields exhibit potential health hazards, [11]. So, the possible effects of ELF magnetic field induction in transmission switchyards might be quite different from those in other environments due to the strength and extent of exposure, [9]. These have raised disquiet about the occupational safety of switchyards' workforce and the resulting possible health hazards associated with exposure, and induction arising owing to proximity and frequent encounter with high-intensity fields from electrical equipment during routine activities.

Extreme, frequent and prolonged exposure to ELF magnetic field have been reported to cause physiological and psychological effects on interaction with sensitive organs in the body.

The direct interaction with the internal human brain vital signals produces measurable changes in brain electrical activity influencing the motor coordination, sensory perception, cognitive activities, visual processing, overproduction of oxidative stress indices and exhaustion that may interfere with quality of sleep and, is an underlining cause of stress, [9], [10], [19], [29]. Reference [30] examined the effects of chronic exposure to ELF magnetic field at 3000 μT for an hour at 60 Hz on the human brain and noticed activity changes in a specific region when monitored with magnetic resonance imaging. Also, a cross-sectional study among shift and non-shift workers in a combined cycle power plant exposed to extremely low frequency electric and magnetic fields was performed in [5]; increased stress was linked with exposure to ELF electromagnetic fields. This suggests that care must be taken to avoid lengthy and extreme exposure of the head where the nervous system is located to guard against neurological effects among the workforce, [31]. Since the bioelectric properties of the nervous system make it more vulnerable to the influence of the ELF magnetic field, [9].

Pleural cavity located at the chest wall aids optimal functioning of the lung during breathing, [32]. The ELF magnetic field from high voltage lines causes ionisation of air emitting corona ions that get attached to several aerosol particles that pollute the air and are deposited in the lungs, [17]. The chronic exposure of the pleural cavity to the polluted air in the atmosphere has been suggested to influence the risk of lung cancer, asthma, inflammation, oxidative stress and alteration in the immune system, [32]. The principal causes of these effects are changes in melatonin secretion as a result of exposure to ELF magnetic fields. Since melatonin is an antioxidant and a scavenger of free radicals, the level of this hormone declines due to exposure, [9].

Studies also suggested that the prevalence cases of infertility among adults is linked to occupational exposure to ELF magnetic field and the hazard can affect the levels of reproductive regulating hormones. Male reproductive system can be more sensitive and vulnerable to exposure to increased temperature that might lead to a reduction in testosterone levels, thereby affecting the sexual cells and sexual desire, [33], [34]. Studies in [8], [9], [35] reported that reproductive systems are susceptible to influence of ELF magnetic field especially the infertility potential in male by decreasing human sperm parameters such as motility, viability, inducing pathological changes in sperm and testes morphology. This in turn affects the quality of genetic materials and inability to retort to its original form and therefore, contribute to the well-being of baby during pregnancy. However, in some instance, it may result to high risk of miscarriage during pregnacy.

5 Conclusion

The intensity of the ELF magnetic field emitted by electrical infrastructures in transmission switchyard have been investigated through measurements, the exposure comparative analyses of difference of mean for locations to determine the statistically significant differences based on observation heights performed, the extent of induced electric field and current density evaluated through simulation and, the related health hazards from literature studies discussed.

The findings show ELF magnetic field distribution in switchyards varies in values with respect to heights, spots, locations and hence, the induction on human. The region of the head at height $1.8\,m$ was found to experience highest ELF magnetic field exposure with maximum recorded value in Shiroro switchyard at duration of the survey compared to other observation heights and locations. This value though far less than the occupational reference level of $1\,mT$ set by ICNIRP for personnel safety. Furthermore, the induced electric field and current density of $55\,pV/m$ and $350\,pA/m^2$ are the respective values obtained from the simulation in the same location. These values when compared to the basic restriction threshold of 0.8 V/m and 10 mA/m^2 by ICNIRP are insignificant to cause any adverse health hazards.

These values recorded in this study at the time of the survey are not assurance of safety vicinity for workforce because there are instantaneous spot measured values of ELF magnetic field exposure in switchyards. However, it has uncovered existence of radiated field in the environment, highlighted potential future threats, and the need to prioritise close and continuous monitoring of magnetic field levels for the occupational safety of the workforce. Therefore, further study is recommended to be performed using a data logging meter for hourly values of fields in the switchyards to obtain comprehensive records of radiation in the environment.

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References:

[1] T. Meriouma, S. A. Bessedik and R. Djekidel, "Modelling of Electric and Magnetic Field Induction under Overhead Power Line Using Improved Simulation Techniques," *European Journal of Electrical Engineering,* vol. 23, no. 4, p. 289–299, 2021. doi: 10.18280/ejee.230402.

[2] A. O. Sougui and M. Mohd-Jenu, "Measurement and Analysis of Magnetic Field Radiation near 132 kV Power Lines," in *2014 IEEE Asia-Pacific Conference on Applied Electromagnetics (APACE)*, Johor Bahru, Malaysia, 2014 , May 18–21. doi: 10.1109/APACE.2014.7043781.

[3] A. U. U. Ocheni, A. S. Moses, O. D. Oyedum and M. N. Nwohu, "Determination of On-the-spot Occupational ELF Magnetic Field Levels in Hydro-electric Power Transmission Switchyards," *Nigerian Journal of Physics (NJP),* vol. 32, no. 2, p. 72–79, 2023.

[4] M. Bonato, E. Chiaramello, M. Parazzini, P. Gajšek and P. Ravazzani, "Extremely Low Frequency Electric and Magnetic Fields Exposure: Survey of Recent Findings," *IEEE Journal of Electromagnetics, RF, and Microwaves in Medicine and Biology,* vol. 7, no. 3, p. 216–228, 2023. doi: 10.1109/JERM.2023.3268555.

[5] S. E. Abarghoee, G. H. Halvani, F. Kargar-Shouroki, H. Mihanpour and F. Madadizadeh, "Job Stress among Workers Exposed to Extremely Low Frequency Electric and Magnetic Fields in a Combined Cycle Power Plant," *Journal of Environmental Health and Sustainable Development (JEHSD),* vol. 7, no. 2, p. 1614–1622, 2022.

doi: 10.18502/jehsd.v7i2.9785.

[6] T. O. Ale and A. Adeyemi, "Electricity Demand Pattern and Supply Availability on Nigeria Grid System," *Journal of Applied Science & Process Engineering,* vol. 9, no. 1, p. 1042–1053, 2022. doi: 10.33736/jaspe.4264.2022.

[7] M. Sahu, S. Behera and B. Chattopadhyay, "The Influence of Electromagnetic Field Pollution on Human Health: A Systematic Review," *Siriraj Medical Journal (SMJ),* vol. 73, no. 7, p. 485–492, 2021. doi: 10.33192/Smj.2021.63.

[8] H. Tian, H. Zhu, C. Gao, M. Shi, D. Yang, M. Jin, F. Wang and X. Sui, "System-Level Biological Effects of Extremely Low-Frequency Electromagnetic Fields: An in vivo Experimental Review," *Frontiers in Neuroscience,* vol. 17, p. 1247021, 2023. doi: 10.3389/fnins.2023.1247021.

[9] O. D. Oyedum, M. N. Nwohu, A. U. U. Ocheni and A. S. Moses, "Bio-Interaction Mechanism of Occupational Extremely Low-Frequency Magnetic Field and its Potential Effects on Human," *Journal of Applied Science & Process Engineering,,* vol. 11, no. 1, p. 49–59, 2024. doi: 10.33736/jaspe.6346.2024.

[10] M. Bidi, "Biological Risk Assessment of High-Voltage Transmission Lines on Worker's Health of Electric Society," *Polska Akademia Nauk (PAN),* vol. 69, no. 1, p. 57–68, 2020. doi: 10.24425/aee.2020.131758.

[11] R. Beltrán, E. Chamorro, C. Quinator and J. Toaza, "Evaluation of Low Frequency Electrical and Magnetic Fields in a Electrical Transmission Substation," *WSEAS Transactions on Electronics,* vol. 15, p. 77–87, 2024. doi: 10.37394/232017.2024.15.10.

[12] I. J. Njoku, C. E. Orji, E. C. Mbamala, U. M. Ukewuihe, C. P. Onyenegecha and O. Orji, "Assessing the Health Risk due to Exposure to Non-Ionizing Radiation in the Form of Magnetic Field from Electrical Power Substations," *Journal of Applied Sciences,* vol. 22, no. 4, p. 187–195, 2022. doi: 10.3923/jas.2022.187.195.

[13] ICNIRP, International Commission on Non-Ionizing Radiation Protection, "ICNIRP Guidelines for Limiting Exposure to Time- varying Electric and Magnetic Fields (1Hz – 100 kHz)," *Health Physics,* vol. 99, no. 6, p. 818–836, 2010. doi: 10.1097/HP.0b013e3181f06c86.

[14] F. R. Rojas, G. Guerra and S. Rivera, "High Gradient Magnetic Fields Generated in Events on the 230 kV Electric Power Transmission Infrastructure: Human Exposure Analysis and Risk," *WSEAS Transactions on Circuits and Systems,* vol. 23, p. 212–222, 2024. doi: 10.37394/23201.2024.23.22.

[15] F. G. D. Thulu, D. Tembo, R. Nyirongo, P. J. C. Mzaza, A. Kamfosi and U. Mawenda, "Electromagnetic Frequency Pollution in Malawi: A Case of Electric Field and Magnetic Flux Density Pollution in South Africa," *International Journal of Environmental Research and Public Health,* vol. 20, no. 5, p. 4413, 2023. doi: 10.3390/ijerph20054413.

[16] J. E. Nwoke, M. Y. Onimisi, S. A. Jonah and R. A. Tafida, "Measurement and Analysis of Health Effects due to Exposure to Non-ionizing Radiation from High Tension Cables around Kaduna Metropolis, North West, Nigeria," *American Journal of Condensed Matter Physics,* vol. 7, no. 3, p. 73–80, 2017. doi: 10.5923/j.ajcmp.20170703.03.

[17] A. Balaji, "Effect of High Voltage Transmission Lines on Human Health, Plant Life, and Animal Activity," *International Research Journal of Engineering and Technology (IRJET),* vol. 2, no. 3, p. 441–446, 2015.

[18] A. Jevtić, V. Stanković, S. Glišović and E. Jovanović, "Environmental Impact of Substations: A Short Review," *Ecological Engineering and Environmental Protection,* no. 2, p. 5–11, 2024. doi: 10.32006/eeep.2024.2.0511.

[19] M. H. Bagheri, N. Khanjani, M. H. Ebrahimi, S. H. Mousavi and F. Nazarkhani, "Investigating the Effects of Exposure to Extremely Low Frequency Electromagnetic Fields on Job Burnout Syndrome and the Severity of Depression: The Role of Oxidative Stress," *Journal of Occupational Health,* vol. 62, no. 1, p. e12136, 2020. doi: 10.1002/1348-9585.12136.

[20] R. Stam, "The Revised Electromagnetic Fields Directive and Worker Exposure in Environments with High Magnetic Flux Densities," *Annal of Occupational Hygiene,* vol. 58, no. 5, p. 529–541, 2014. doi: 10.1093/annhyg/meu-010.

[21] O. Aliyu, I. Maina and H. Ali, "Analysis of Electromagnetic Pollution due to High Voltage Transmission Lines," *Journal of Energy*

Technologies and Policy, vol. 2, no. 7, p. 1–10, 2012.

[22] H. Ali, R. O. Olatunbosun, A. A. Ibiyemi and A. O. Awodugba, "Analysis of Electromagnetic Radiation for Four Different Transmission Power Stations Areas of Nigeria," *FUDMA Journal of Sciences (FJS),* vol. 2, no. 1, p. 48–53, 2018.

[23] J. J. Popoola, M. R. Adua and E. S. Itodo, "Assessment of Possible Health Risks Potential of Electromagnetic Fields from High Voltage Power Transmission Lines in Akure, Nigeria," *Journal of Applied Science & Process Engineering,* vol. 8, no. 1, p. 684–699, 2021. doi: 10.33736jaspe.v8i1.

[24] A. S. Moses, A. U. U. Ocheni, N. M. Nwohu and O. D. Oyedum, "Analysing and Profiling the Magnetic Field Levels in 330 kV Transmission Stations Switchyard," *Andalasian International Journal of Applied Science, Engineering, and Technology (AIJASET),* vol. 4, no. 2, p. 115–124, 2024. doi: 10.25077/aijaset.v4i2.143.

[25] A. Siriwitpreecha and P. Rattanadecho, "Numerical Analysis of Biological Effects on Several Organs inside Human Body Exposed to Electric Field from 500 kV OHTLs," *Songklanakarin Journal of Science and Technology (SJST),* vol. 41, no. 3, p. 649–657, 2019.

[26] W. Greiner, Classical Electrodynamics, New York, USA: Springer-Verlag, New York, Inc., 1998, [Online]. https://homepages.dias.ie/ydri/Greiner.pdf (Accessed Date: January 24, 2025).

[27] A. Laissaoui, B. Nekhoul, K. Kerroum, K. K. Drissi and D. Poljak, "On the Rotationally-Cylindrical Model of the Human Body Exposed to ELF Electric Field," *Progress in Electromagnetics Research M,* vol. 29, p. 165–179, 2013. doi: 10.2528/PIERM13012812.

[28] A. Hossam-Eldin, K. Youssef and H. Karawia, "Study and Evaluation of Induced Current in Human Body from Exposure to Electromagnetic Fields at low Frequency," in *Paper presented at the 20th International Conference and Exhibition on Electricity Distribution (CIRED 2009)*, Prague, Czech Republic, 2009, June 8 - 11. doi: 10.1049/cp.2009.0528.

[29] R. Eskandani and M. I. Zibaii, "Unveiling the Biological Effects of Radio-Frequency and Extremely-Low Frequency Electromagnetic Fields on the Central Nervous System Performance," *BioImpacts,* vol. 14, no. 4, p. 30064, 2024. doi: 10.34172/bi.2023.30064.

[30] A. Legros, J. Modolo, S. Brown, J. Roberston and A. W. Thomas, "Effects of a 60 Hz Magnetic Field Exposure up to 3000 μT on Human Brain Activation as Measured by Functional Magnetic Resonance Imaging," *PLoS One,* vol. 10, no. 7, p. 1–27: e0132024 , 2015. doi: 10.1371/journal.pone.0132024.

[31] N. T. Dolchinkova and B. E. Karaivanova-Dolchinkov, "Impact of Types of Electromagnetic Radiation on Living Nature," in *Proceedings of the 14th International Scientific and Practical Conference*, Rezekne, Latvia, 2023. doi: 10.17770/etr2023.

[32] R. M. Sarimov, D. A. Serov and S. V. Gudkov, "Biological Effects of Magnetic Storms and ELF Magnetic Fields," *Biology,* vol. 12, no. 12, p. 1506, 2023. doi: 10.3390/biology12121506.

[33] S. Suri, S. F. Dehghan, A. S. Sahlabadi, S. K. Ardakani, N. Moradi, M. Rahmati and F. R. Tehrani, "Relationship between Exposure to Extremely Low-Frequency (ELF) Magnetic Field and the Level of some Reproductive Hormones among Power Plant Workers," *Journal of Occupational Health,* vol. 62, p. e12173, 2020. doi: 10.1002/1348-9585.12173.

[34] S. Verma, A. Gupta and B. Kumar, "Interaction of Radiofrequency Radiation with Bological Systems: A Comprehensive update on Recent Challenges," *Defence Life Science Journal,* vol. 4, no. 2, p. 83–90, 2019. doi: 10.14429/dlsj.4.13383.

[35] A. S. Adah, D. I. Adah, K. T. Biobaku and A. B. Adeyemi, "Effects of Electromagnetic Radiations on the Male Reproductive System," *Anatomy Journal of Africa,* vol. 7, no. 1, p. 1152–1161, 2018. doi: 10.4314/aja.v7i1.169488.

APPENDIX

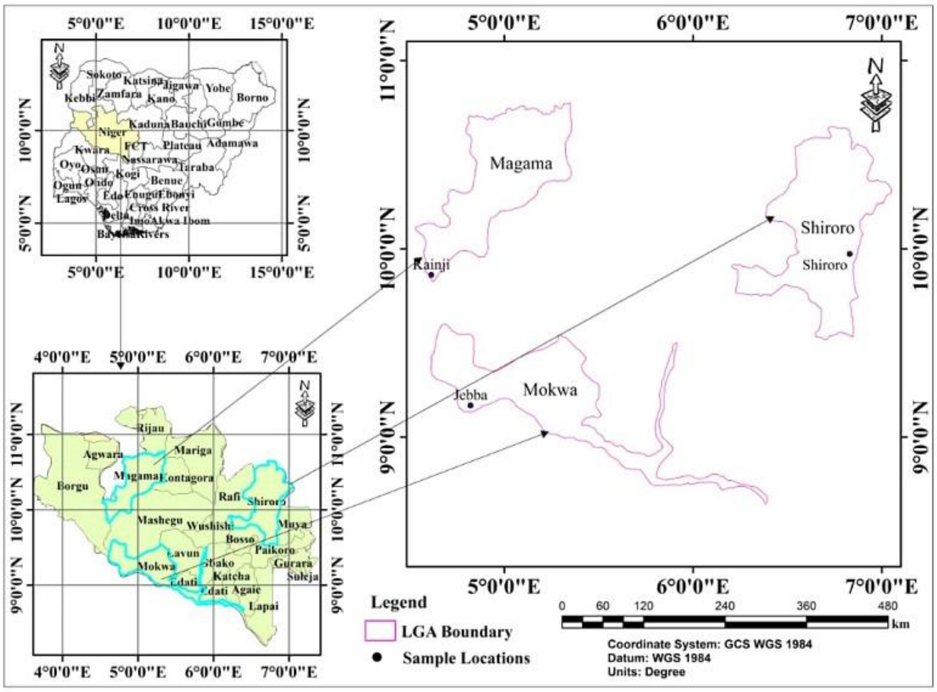

Fig. 1: Maps showing the coordinates of the study locations
Source: created by the authors

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