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Evaluating the Influence of Electromagnetic Fields on Electric Power Distribution Networks: A Focus on Capacitive Interactions

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ABSTRACT

The interaction of electromagnetic fields within electric power distribution networks, mainly through capacitive effects, presents a complex challenge with significant safety implications. Incidents of electrocution among power industry personnel and unauthorized individuals interacting with electrical infrastructure often stem from a lack of awareness or negligence toward fundamental electricity principles. These incidents typically occur during the commissioning of new installations, routine maintenance, system expansions, or the integration of network components. A common factor contributing to these accidents is the disregard for established safety standards, including statutory clearances, approach distances, and comprehensive network assessments. This analysis investigates a specific case in Lagos, where an individual suffered electrocution, to dissect the safety lapses encountered technically. By focusing on the electromagnetic field's impact, this study employs electrostatic techniques to understand the interaction dynamics in this incident. Our investigation is structured around three analytical angles based on empirical data collected from representative locations. The first angle considers how electric and magnetic fields affect human physiology, exploring the body's response when exposed to these forces. The second angle examines the interplay between the body's impedance and the electromagnetic field during direct contact scenarios, including the effectiveness of Personal Protective Equipment (PPE) and the potential for electrocution without direct contact. We aim to provide insights into the capacitive interactions within electric power distribution networks and their safety implications through detailed analysis involving charts, tables, and calculations grounded in established engineering principles. Our findings highlight the need to adhere to electrical safety protocols, proper network evaluation, and understand electromagnetic field effects to prevent future incidents. This study underscores the importance of capacitive effects in power distribution networks' safety and operational integrity, advocating for informed and cautious handling of electromagnetic field interactions.

Keywords: *Electric Fields, Magnetic Fields, Safety Standards, Capacitive Interactions, Electrostatic Techniques, Human Body Impedance, Personal Protective Equipment, Electrocution Prevention, Power Distribution Networks.*

I. INTRODUCTION

The pervasive presence of electromagnetic fields (EMFs) across various facets of modern life, from household appliances to vast electric power distribution networks, raises critical questions about their impact on human health and safety. This study delves into the complex interplay between EMFs and electric power distribution, particularly emphasizing capacitive interactions. Capacitive effects, a fundamental aspect of electromagnetic interactions within power networks, have profound implications for these systems' operational integrity and safety. These concerns are not unfounded, as instances of electrocution among power industry personnel and unintended contact by individuals highlight the potential risks associated with inadequate management of EMF exposure.

Recent incidents underscore the urgency of addressing these risks. For instance, electrocution cases in the power industry, often attributed to a disregard for established safety standards and protocols, signify a broader challenge within the sector (National Institute of Environmental Health Sciences, n.d.; World Health Organization, 2021). Moreover, the evolution of electric power systems, characterized by the integration of renewable energy sources and advancements in distribution technologies, necessitates a reevaluation of traditional safety and operational frameworks to accommodate the nuanced dynamics introduced by these developments (Energy Networks Association, n.d.; U.S. Environmental Protection Agency, n.d.).

Figure 1 provides a visual overview of the intricate relationship between electromagnetic fields (EMFs) and electric power distribution networks, emphasizing the significance of capacitive interactions. It highlights the critical aspects of public health concerns, safety protocols, and the evolution of power systems. This mindmap explores the balance between operational integrity and the necessity for effective EMF management strategies to ensure safety and efficiency.

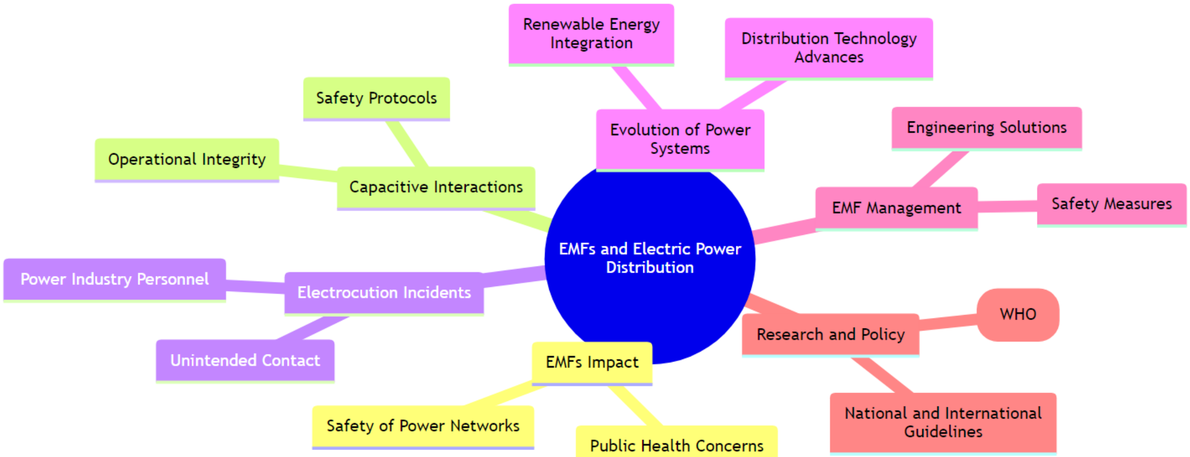

Figure 1: Electromagnetic Fields in Power Distribution: Navigating Safety, Health, and Technological Interactions

Figure 1 illustrates the multifaceted relationship between electromagnetic fields (EMFs) and electric power distribution, focusing on the pivotal role of capacitive interactions. It maps out the concerns for human health and operational safety within power networks, emphasizing the need for rigorous safety measures and advancements in distribution technology. The diagram also underscores ongoing research efforts and policy development to mitigate EMF exposure risks. Through a comprehensive analysis, this visual representation aids in understanding the complex dynamics that influence public health and the integrity of power distribution systems.

Recognizing the critical role of capacitive interactions in shaping the safety landscape of electric power distribution networks, this study aims to provide a comprehensive analysis based on empirical data and technical evaluations. By examining specific electrocution cases and employing electrostatic techniques to explore the effects of EMF on the human body, the research endeavors to bridge the gap between theoretical knowledge and practical application. This approach illuminates the physical and biological mechanisms and contributes to developing more effective safety measures and engineering solutions (National Cancer Institute, n.d.).

As the International EMF Project by the WHO and other research initiatives continue to assess the potential health effects of EMF exposure, the findings of this study are poised to add valuable insights to the ongoing discourse. Through a meticulous examination of capacitive interactions within electric power distribution networks, the research underscores the importance of informed, science-based strategies to mitigate risks and safeguard public health in an increasingly electrified world (World Health Organization, 2021).

The study of electromagnetic fields (EMFs) within electric power distribution networks is of paramount importance due to its direct implications for public health and safety. Electromagnetic fields, a fundamental aspect of our environment, are omnipresent, stemming from both natural phenomena and human-made sources, including power lines, appliances, and electronic devices. The World Health Organization (WHO) acknowledges EMFs as one of the most common and rapidly growing environmental influences, stressing the necessity for ongoing research and public health policy development to mitigate potential risks (World Health Organization, 2021).

The significance of EMFs extends beyond their environmental presence, touching on critical aspects of modern infrastructure. The Energy Networks Association highlights the role of EMFs in the functionality of electric power distribution systems, emphasizing the need to understand their effects to ensure the operational integrity of these networks (Energy Networks Association, n.d.). Furthermore, the U.S. Environmental Protection Agency (EPA) elaborates on the nature of EMFs, distinguishing between ionizing and non-ionizing radiation and underscoring the complexity of their interactions with biological systems (U.S. Environmental Protection Agency, n.d.).

In public health, the National Institute of Environmental Health Sciences (NIEHS) contributes to the discourse by examining the potential health implications of EMF exposure. This includes investigations into how low-frequency, non-ionizing EMFs, typical of those emanating from power distribution networks, might influence human health (National Institute of Environmental Health Sciences, n.d.). Meanwhile, the National Cancer Institute (NCI) explores the contentious issue of EMFs and cancer, presenting a nuanced view of the scientific landscape that reflects the diversity of findings and interpretations within the field (National Cancer Institute, n.d.).

This study, positioned at the intersection of engineering, public health, and environmental science, seeks to contribute to the nuanced understanding of EMFs within electric power distribution networks. Focusing on capacitive interactions aims to unravel the complex dynamics that govern the safety and efficiency of these critical components of modern infrastructure. The exploration of capacitive effects, grounded in empirical data and technical evaluation, provides a lens through which to assess the implications of EMF exposure, offering insights that can inform policy and practice.

In light of the WHO's International EMF Project and the broader scientific community's efforts, this research aspires to add to the body of knowledge that supports informed decision-making and the development of effective strategies to address the challenges posed by EMFs in electric power distribution networks (World Health Organization, 2021).

II. LITERATURE REVIEW

The interaction between electromagnetic fields and human-made structures, particularly power lines, has been the subject of extensive research. Surainu (2009) provides valuable insights into the induced voltages by electric overhead power lines, emphasizing the significance of understanding these interactions to mitigate adverse effects on humans and the environment. Similarly, Musha (2015) discusses the potential of metamaterial structures within the human brain to explain advanced brain performance, suggesting a complex interplay between EMFs and biological systems.

The properties of materials used in electrical engineering, as discussed by Pascoe (1974), play a critical role in ensuring the safety and efficiency of power distribution networks. This foundational knowledge supports the development of safety standards and protective measures for individuals working near electromagnetic fields. The U.S. Department of Energy's (2013) handbook on electrical safety further underscores the importance of adhering to established guidelines to prevent accidents and ensure the well-being of workers.

Research on the tribological behaviour of human skin after tape stripping (Pailler-Mattei et al., 2011) contributes to a deeper understanding of how electromagnetic fields interact with human physiology. These findings are pivotal in assessing the safety risks associated with EMF exposure. Additionally, Audu (2016) addresses the frequent incidents of electrocution in Nigeria, highlighting the need for improved safety measures and awareness to mitigate these risks.

Studies by Usman and Usman (2015) on assessing magnetic field effects and estimating associated current density in electrical injection substations offer crucial data for evaluating power distribution networks' safety and operational integrity. This research aligns with the broader objectives of understanding EMFs' impact on infrastructure and human health.

Recent advancements have been made in understanding the role of spin qubits within photon-coupled microwave cavities. This research sheds light on the capacitive interactions between microwave cavities, each containing a single DQD qubit, offering a new perspective on quantum computing's interface with electromagnetic fields in power distribution networks (Spin Qubits in Photon-Coupled Microwave Cavities, 2023).

A significant study modelled nanoscale electric fields in microelectronics components, explored through operando electron holography. This research provides insights into how electric fields interact with objects and electromagnetic fields at the nanoscale, with implications for designing safer and more efficient power distribution systems (Modelling nanoscale fields in microelectronics components studied by operando electron holography, 2023).

The development of capacitive wearable devices for passive monitoring pressure information represents a breakthrough in leveraging electromagnetic fields for health and safety applications. This study demonstrates how wearable technology interacts with spatial electromagnetic fields, offering potential applications in monitoring the safety of personnel in power distribution networks (Wireless Wearable Devices for Passive Monitoring Pressure Information, 2023).

Research into an ultra-miniaturized, high efficiency implanted spiral antenna for leadless cardiac pacemakers highlights the potential for optimizing electromagnetic field interactions for medical devices. The study explores radiation resistance, inductance, and capacitance obtained from the circuit model, showcasing the antenna's interaction within the electromagnetic spectrum (An Ultra-Miniaturized High-Efficiency Implanted Spiral Antenna for Leadless Cardiac Pacemakers, 2023).

III. MATERIALS AND METHODS

As of 2023, the Nigerian Electricity Supply Industry (NESI) continues to address critical safety challenges, informed by past incidents and regulatory insights. A significant shift in strategy and approach towards electrical safety has been imperative, especially in light of historical data that underscored the urgency of reform. Reflecting on May 2022 to April 2023, the Nigerian Electricity Regulatory Commission (NERC) has observed a stark reminder of the importance of stringent safety measures within NESI. Despite efforts to enhance safety protocols, a concerning trend has been identified, with approximately 279 electrocutions and 88 injuries reported over the previous 12 months. This alarming statistic highlights a consistent issue with safety compliance among electricity distribution companies (DISCOs), manifesting in an average of nine deaths and seven injuries per month. Such figures have underscored the critical need for improved adherence to safety regulations to reverse this disturbing trend.

In response to these challenges, NESI, with oversight from NERC, has intensified its commitment to electrical safety by enforcing advanced safety protocols. Key among these has been the emphasis on de-energizing equipment for maintenance or repair unless such actions introduce greater hazards or are deemed impractical. A significant focus has been placed on equipping qualified electrical workers with comprehensive training, the latest protective equipment, and detailed work procedures. These measures are designed to safeguard against electrical shocks, burns, and other potential hazards, ensuring that work in electromagnetic field environments is conducted with the utmost safety.

To combat the non-conformance issues that have contributed to high rates of electrocutions and injuries, NESI, guided by NERC, has bolstered regulatory compliance measures. Enhanced oversight mechanisms have been established to ensure that all DISCOs adhere to the highest safety standards, aiming to cultivate a safety culture permeating the entire industry. Adopting innovative technologies plays a pivotal role in NESI's safety enhancement strategy. Remote monitoring systems, advanced circuit interrupters, and electromagnetic field mitigation technologies are among the tools deployed to minimize electrical work risks. Comprehensive educational and awareness programs have been launched to heighten understanding of the risks inherent in electromagnetic field environments. These initiatives aim to foster a proactive safety culture within NESI, emphasizing the importance of strict adherence to safety protocols among workers and management. As NESI progresses through 2023, the lessons drawn from May 2022 to April 2023 catalyze improved electrical safety standards. Through a concerted effort encompassing regulatory compliance, education, technological innovation, and enhanced safety protocols, NESI is committed to reducing the incidence of electrical accidents, ensuring a safer future for workers and the public within the Nigerian electricity sector.

3.1 Work on High-Voltage Systems in Electromagnetic Field Environments

The operation and maintenance of high-voltage equipment and power systems are critical tasks that necessitate rigorous safety protocols to protect workers from inherent dangers. These activities must only be undertaken by qualified and authorized individuals, ensuring adherence to established safe work procedures as mandated by the Nigerian Electricity Regulatory Commission (NERC). The guidelines for conducting work on such systems are detailed within the Nigerian Electricity Health and Safety Standards (Section 2) and the Occupational Health and Safety Regulation, Part 19. Key to these procedures is the process of isolation and lockout, which workers must follow according to the directives provided by their employer and the owner of the power system. The consequences of accidents involving high voltages are often dire, leading to severe injuries or fatalities. The passage of electric current through the human body can cause significant internal damage due to heat generation. In extreme cases, the severity of entry and exit wounds necessitates the amputation of limbs.

Additionally, there is a risk that the electrical current could induce cardiac arrest. Electrical workers often find themselves close to energized components, where the risk of power arcs is a constant threat. Physical contact with an energized conductor is not a prerequisite for receiving an electrical shock.

Qualified electrical workers must be cognizant of the established final flash boundary distance and the shock protection distances, ensuring that individuals without protection are prevented from entering areas within these critical distances. The shock protection distance represents the minimum safe distance from a live part within which only a "Qualified Person" is permitted to work. Our study investigates various recent electrocution incidents, aiming to analyze these events in the context of relevant safety standards. By identifying areas where violations occurred, we intend to propose practical solutions designed to prevent the recurrence of such incidents. This analysis is pivotal in enhancing the safety protocols associated with work on high-voltage systems within electromagnetic field environments, thereby safeguarding the well-being of electrical workers and mitigating the risks associated with these operations.

3.2 HV/LV Overhead Network Configurations and Safety Implications

In electrical power distribution, H.V. (High Voltage) and LV (Low Voltage) overhead network configurations present unique challenges and hazards, often underestimated by workers and inadvertently ignored by unauthorized individuals, such as vandals. The rush to complete tasks and a possible lack of proper training or awareness contribute to the oversight of critical safety considerations inherent to these configurations.

3.2.1 Recognizing the Hazards

Successfully navigating the complexities of a dual-voltage network requires a multifaceted approach to safety and hazard recognition:

1. **Comprehensive Analysis of Network Interconnections**: Before undertaking any work, it is essential to conduct a detailed examination of the network's interconnecting circuits and interlocks. This analysis is crucial for identifying specific risks associated with the network in question and implementing strategies to mitigate the danger of electrocution. Such an approach ensures that workers are fully aware of the potential hazards and are prepared to address them effectively.
2. **Adherence to Safety Precautions and Statutory Requirements**: Working with electrical distribution equipment demands strict compliance with all relevant safety protocols and statutory

regulations designed to eliminate electrical hazards. This entails taking every necessary precaution unique to the type of electrical distribution network serviced. These measures are not merely recommendations but are mandated practices that safeguard workers from the risks associated with HV/LV overhead configurations.

Addressing the safety challenges of HV/LV overhead networks necessitates a commitment to thorough preparation, education, and adherence to established safety standards. By recognizing and respecting the hazards associated with these configurations, workers can significantly reduce the risk of injury or death. Our analysis highlights the importance of safety in managing HV/LV overhead network configurations, advocating for enhanced training programs and the strict implementation of safety protocols to protect those who work close to these potentially dangerous electrical systems.

3.2.2 Case Study Report: Electrocution Incident Involving Ikeja Electric Worker

It was reported that an Ikeja Electric worker, identified only as Tunde, was hospitalized following a fall from a pole on Palace Way, Abule, Arepo, in the Obafemi Owode Local Government Area of Ogun State. The incident occurred in the early hours of Monday when Tunde and his colleagues were dispatched to disconnect the power supply in the community.

The equipment in question was a Low Voltage (LV) electric cable at the distribution substation in the area. From the configuration of the task - disconnecting an LV cable from a utility pole - it is understood that this was a routine operation conducted by the power distribution company's maintenance team. The geographical location of the incident is in a residential area known for its dense population and frequent maintenance activities by Ikeja Electric.

The sequence of events leading to the accident can be summarized as follows: a) Tunde had initially disconnected the wire from the pole, following standard safety procedures to isolate the section of the network being worked on. b) Despite the initial disconnection, Tunde was instructed by his supervisor, the new marketer, to climb the pole again and physically remove the wire, increasing the risk of an accident due to the proximity of the energized environment. c) While attempting to remove the cable, the pole unexpectedly uprooted and fell, causing Tunde to suffer severe injuries as he was still attached to the pole.

The incident resulted in Tunde sustaining significant injuries to his face, with reports of blood loss from his mouth and nostrils. Eyewitnesses described a chaotic scene, with initial fears that Tunde had been electrocuted. It was later confirmed that the injuries were due to the fall and not an electrical shock.

Fig 2: Unexpected Peril: A Utility Worker's Fall During Routine Maintenance in Abule, Arepo.

Image Credit: https://punchng.com/lagos-electricity-worker-falls-from-pole-while-disconnecting-community/

This case study highlights the dangers associated with work on electrical distribution networks, mainly when deviations from standard safety protocols occur. It underscores the importance of strict adherence to safety measures and the need for comprehensive training and supervision to prevent similar incidents in the future.

3.2.3 Evaluation and Analysis of Electromagnetic Fields in Power Distribution

In power distribution, circuits at a higher-voltage distribution level often supply power to multiple lower-voltage distribution circuits via transformers. A critical safety concern arises when the higher-voltage circuit is de-energized, but the lower-voltage circuits remain energized through alternative sources. This scenario can inadvertently energize the supposedly de-energized higher voltage circuit. Our analysis assumes that the transformer's Low Voltage (LV) side is completely isolated by the High Voltage (H.V.) drop-out fuses.

A notable risk emerges when de-energized conductors become re-energized through electrostatic or electromagnetic induction from nearby energized conductors. This presents a significant hazard, primarily when workers may conduct maintenance or repairs on high or low-voltage lines near other energized lines, increasing the risk of electrocution.

Figure 3 visually represents the structure of a power distribution network, showing the flow from high-voltage lines through distribution transformers to low-voltage lines. It highlights vital components like safety devices and proximity hazards, illustrating the critical elements in ensuring electrical safety and efficiency.

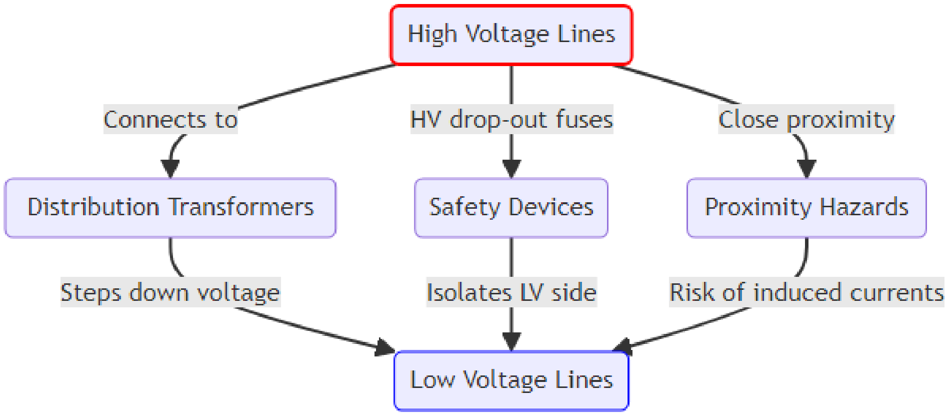

Fig 3: HV/LV Line Configurations. Flow Diagram by Author

Figure 3 depicts high voltage (H.V.) lines connecting to distribution transformers, which step down the voltage to low voltage (LV) lines for distribution. Safety devices, such as H.V. drop-out fuses, are shown to isolate the LV side when H.V. lines are de-energized. Proximity hazards illustrate the risk of electromagnetic induction where H.V. and LV lines run close, highlighting potential induced currents and emphasizing safety considerations in power distribution networks.

At the medium and high voltage levels, violating the approach clearance limit can lead to electrocution due to electrostatic or electromagnetic induction. This phenomenon underlines two primary mechanisms through which electromagnetic induction can pose a risk of electrocution:

1. **Electric Field Induced Currents**: The power frequency electric field can induce eddy currents within the body and charges on its surface. This effect directly results from the body's exposure to the electric field, which can lead to dangerous currents passing through the body, potentially resulting in electrocution.

2. **Magnetic Induction**: The body can also experience currents induced by the magnetic field, typically strongest near the body's periphery and weakest at the centre. This variation in induced current intensity across the body's cross-section further illustrates the complex interaction between electromagnetic fields and the human body. This underscores the necessity for stringent safety measures when working near energized electrical lines.

Analyzing electromagnetic fields in power distribution highlights the inherent risks of working close to energized electrical infrastructure. Understanding the mechanisms of electrostatic and electromagnetic induction is crucial for implementing effective safety protocols and protective measures to prevent electrocution incidents among electrical workers.

Figure 4 illustrates the complex interactions between a human body and electromagnetic fields near an electric line. It depicts the direct electric field lines targeting the human body and the magnetic field's induced voltage, highlighting the principles of electromagnetic induction and direct field impact. The visualization is an educational tool to understand the safety considerations in environments with high electromagnetic activity.

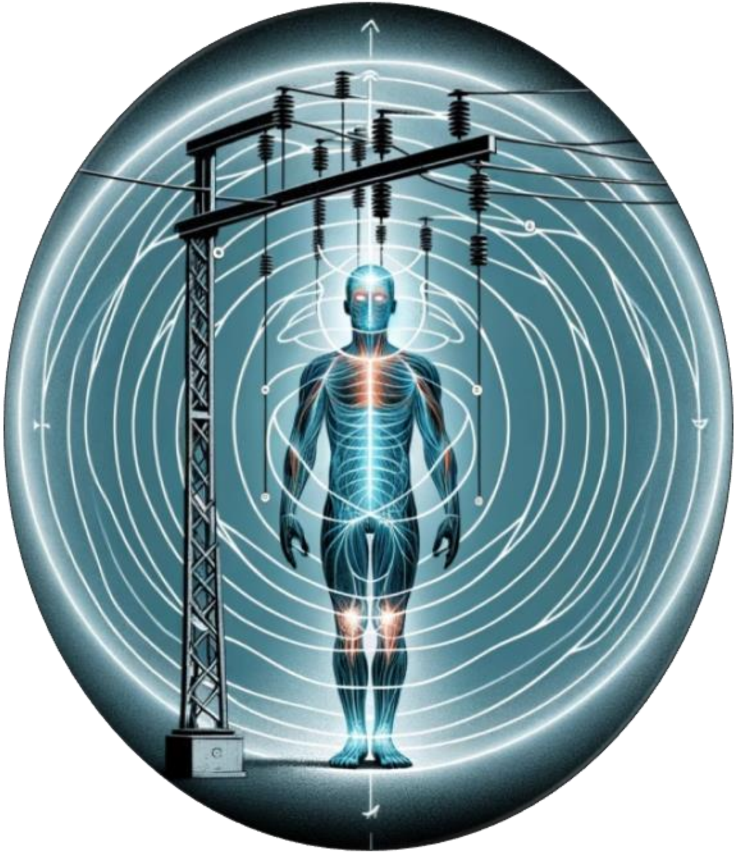

Fig 4: Electromagnetic Field Induction and Direct Electric Field Interaction in Human Body Proximity to Electric Line. Diagram by Author

Figure 4 illustration showcasing the interaction between electromagnetic fields and a human body near an electric line has been generated. It visually represents the direct electric field lines connecting to the human body and the magnetic field around the electric line, inducing voltage within the human body.

The effects of electromagnetic fields (EMFs) on the human body can be summarized and adapted as follows:

- EMFs induce voltages in human tissues, leading to currents due to the body's conductivity.
- The impact of magnetic fields on human tissues can vary, being beneficial or harmful based on their nature.

- Factors such as the source's characteristics, proximity to the source, environmental conditions, and individual differences in body composition influence the magnitude of induced surface charges and internal currents.
- Insulation from the ground can cause individuals near overhead transmission lines to accumulate an electrostatic field, leading to discharge currents when grounded. However, these are typically weaker than the body's natural currents.
- The threshold for human perception of electromagnetic fields is around 15kV/m RMS.

The human body acts as an antenna within electromagnetic fields, unknowingly interacting with them due to the inherent conductivity of human tissues. EMFs are generated by both electric currents and voltages, influencing the body in complex ways. The Nigerian Electricity Supply and Installation Standards Regulations (NESIS) 2015, specifically in section 3.6.1(c), outlines critical clearance guidelines for conductors of different circuits at crossing points. This includes the minimum clearance distance plus the maximum design sag of the lower circuit's conductor at the crossing point. For Nigeria's 33/11/0.415KV power distribution systems, specific values mentioned in Table 3.6.1, particularly in Columns 6, 7, and Row 5, are pertinent.

Figure 5 demonstrates a typical High Voltage/Low Voltage (HV/LV) pole configuration in Nigeria, reflecting scenarios similar to those under analysis. Adhering to statutory clearance limits is essential for avoiding electromagnetic field interferences. The incident described might involve a victim who attempted to vandalize a de-energized low-voltage network, highlighting the risks associated with double-circuit overhead power lines comprising active and passive circuits. This situation underscores the importance of assessing induced voltages from active circuits into disconnected ones, given the potential for electromagnetic field-induced disturbances at the low frequency of 50 Hz common to overhead power transport and distribution lines. Such disturbances can adversely affect the operation of electrical equipment and have biological impacts on organisms near these lines.

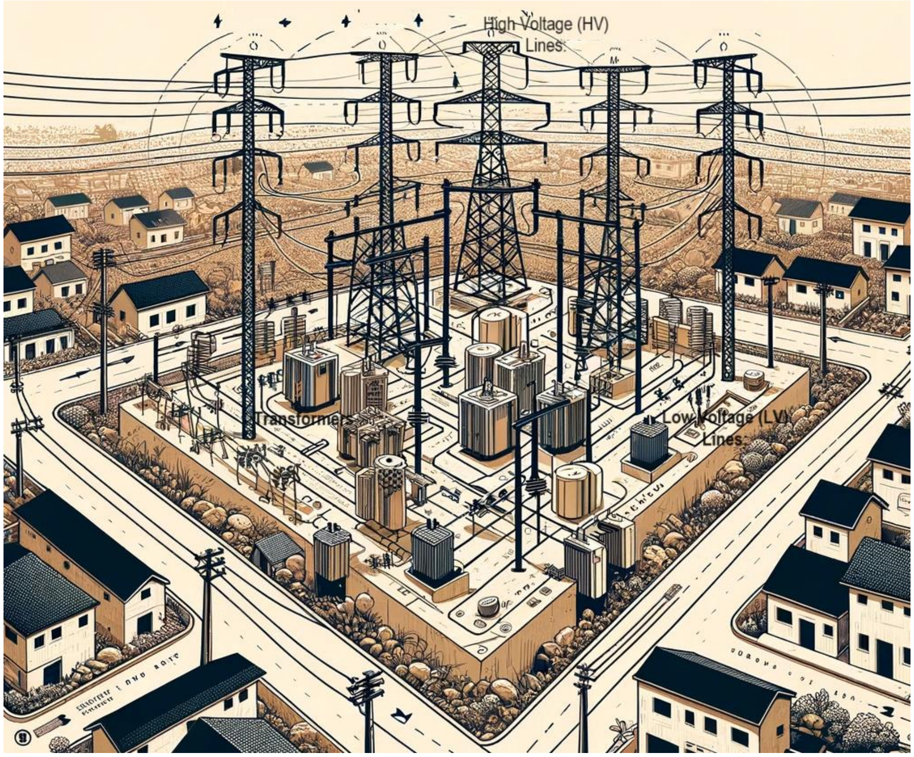

Figure 5: Typical HV/LV Power Line Configuration in Nigeria: Safety and Structure Overview. Diagram by Author

Electromagnetic disturbances are known to exert two types of influences on nearby objects and electric lines: electric influences stemming from capacitive couplings between phase conductors of three-phase overhead power lines and nearby entities and magnetic influences due to inductive couplings between the conductors' loops and the Earth. Understanding the electromagnetic parameters, particularly those related to voltages induced in capacitive couplings and magnetic effects, is crucial for developing strategies to mitigate unwanted impacts and enhance the safety of personnel working near power lines. Electromagnetic coupling, whether capacitive or inductive, affects the values of induced voltages, which depend on the geometry of the electrical lines and the loads they carry. The focus is on capacitive couplings responsible for induced voltages that can lead to electrocution incidents. In cases of capacitive coupling, a double-circuit electric line forms a complex set of capacitors due to potential differences between active circuit phases and between active and passive circuit conductors insulated from the ground. Figure 6 illustrates the Electric Field influence point and the simplified capacitor set formed in such scenarios, relevant to understanding the risks individuals face in contact with passive phases.

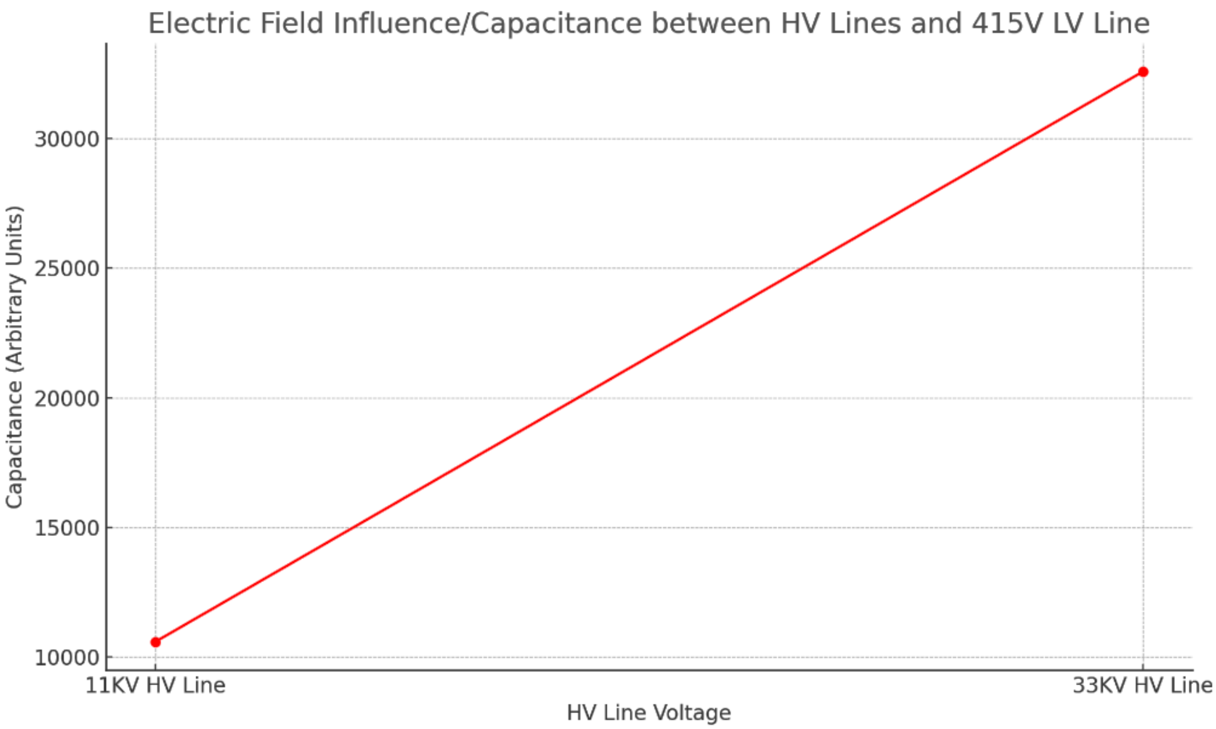

Figure 6: Comparative Analysis of Electric Field Influence/Capacitance Across H.V. to LV Line Configurations. Diagram by Author

Figure 6, line graph represents the electric field influence/capacitance between High Voltage (H.V.) lines (11KV and 33KV) and a 415V Low Voltage (LV) line. The capacitance or electric field influence is illustrated in arbitrary units, showcasing the relationship as the voltage level of the H.V. line changes. The electrocution incident under analysis likely occurred due to the victim's contact with one of the low voltage (LV) lines, specifically assumed to be the Red Phase. Given the human body's electromagnetic properties, bridging the gap between an LV line and another conductive point can facilitate a current flow sufficient for electrocution, as depicted in Figure 7.

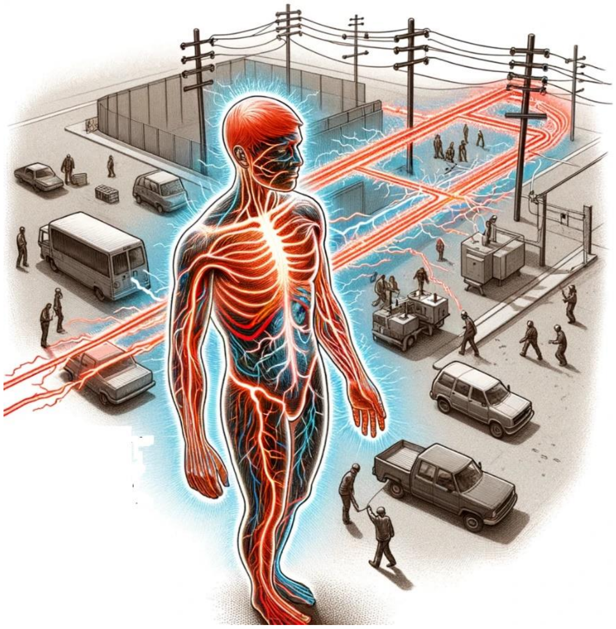

Figure 7: Impact of Electromagnetic Induction on a Person. Diagram by Author

Figure 7 illustrates an electrocution incident involving contact with a low voltage (LV) line, specifically the Red Phase, has been created. It shows the human body acting as a conductor, bridging the gap between the LV line and another conductive point, leading to a dangerous current flow.

To quantify the inductive effects of this incident, we reference the equivalent circuit depicted in Figure 9. This circuit is an electrical representation of the scenarios illustrated in Figures 7 and 8. Points O and O′ are designated as hypothetical contact points with a non-conductive medium, namely the concrete pole and metallic cross-arm, respectively, for H.V. and LV connections. Point P represents a conceptual earth return terminal for the circuit.

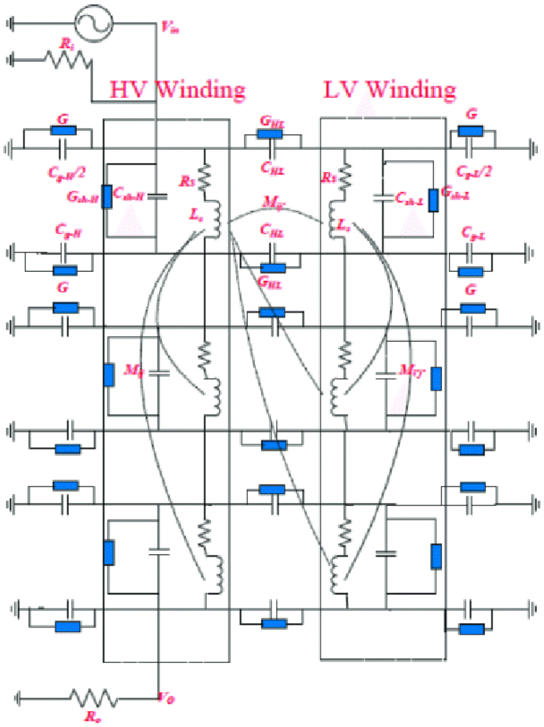

Figure 8: Capacitance Distribution between High Voltage and Low Voltage Lines

The scenario suggests the victim, of average height between 1.5 to 1.6 meters, penetrated the gap between the Medium Voltage (MV) line and the LV network, effectively reducing the safety clearance by approximately 0.8 meters. The current from the active H.V. line acts as the initiating current across the capacitive network's impedance, further analyzed in the optimized equivalent circuit shown in Figure 11 and its corresponding impedance network in Figure 12.

This analysis underscores the complex interactions between phase-to-phase and line-to-line couplings and the significant risk of inadequate clearances in electrical network configurations.

The Delta-star transformation is a mathematical technique used to simplify the analysis of electrical circuits by converting a delta (Δ) configuration into a star (Y) configuration or vice versa. This transformation was applied to the High Voltage (H.V.)/Low Voltage (LV) capacitive couplings depicted in Figure 9. As a result of this transformation, the impedance network was reconfigured, establishing a new impedance network, as illustrated in Figure 10. The process allows for a more straightforward analysis of the circuit's behaviour by converting the complex capacitive couplings between H.V. and LV lines into a form that is easier to manage and understand within electrical network analysis.

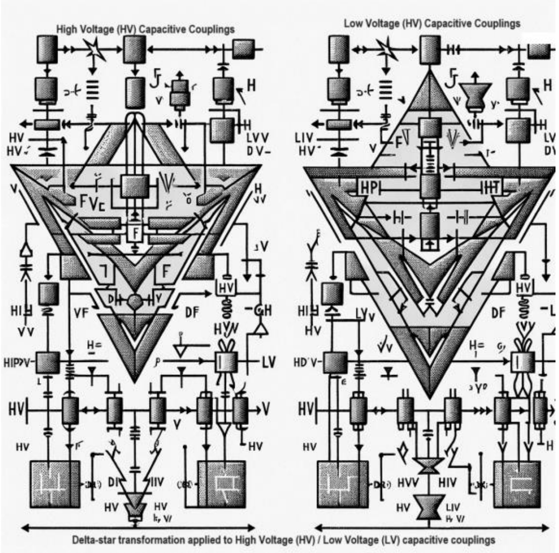

Figure 9: Delta Configuration of HV/LV Capacitive Couplings Before Transformation

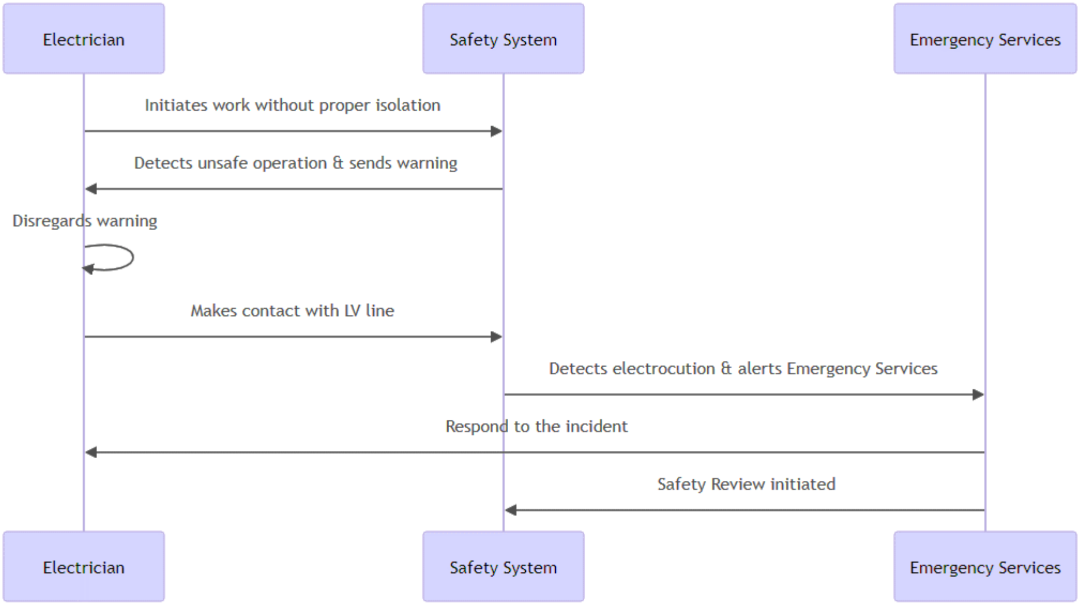

Figure 10: Sequence diagram illustrating the electrocution incident analysis:

1. For the partial capacitances between phases:

$$\frac{C_{ij} = 2\ln\left(\frac{d_{ij}}{l}\right)}{2\pi\varepsilon} \quad (1)$$

2. For the partial capacitances between phases and ground:

$$\frac{C_{ig} = 2\ln\left(\frac{2hi}{r}\right)}{2\pi\varepsilon} \quad (2)$$

Where:

- C_{ij} is the capacitance between phase i and phase j.
- C_{ig} is the capacitance between phase i and ground.
- l is the length of the line taken into account.
- d_{ij} is the distance between phase conductors i and j.
- r is the radius of the phase conductor (assuming =150 mm2a=150 mm2 for both H.V. and LV).
- hi is the height of conductor i above ground.
- ϵ is the permittivity of the medium.
- ln f_0 denotes the natural logarithm.

These equations provide a simplified linear representation of the capacitance calculations involved in electric circuit analysis, considering the lines' geometric dimensions and the conductors' physical properties.

Table 1 shows the minimum clearances required for electric lines at different voltage levels.

Voltage	**Normal Equivalent Span**	**Phase to Phase clearance**	**Phase to Structures / Earth clearance**
400 volts	45 meters	200 mm	25 mm
3300 volts	45 meters	400 mm	130 mm
6600 volts	45 meters	600 mm	180 mm
11000 volts	90 meters	700 mm	300 mm
33000 volts	90 meters	1200 mm	600 mm
66000 volts	190 meters	1800 mm	1200 mm
132000 volts	210 meters	2400 mm	2400 mm
330000 volts	450 meters	500 mm	
750000 volts			

Referring to Table 1, which is also depicted in a closer dimension in Figure 11 below, considering an 11 kV power supply

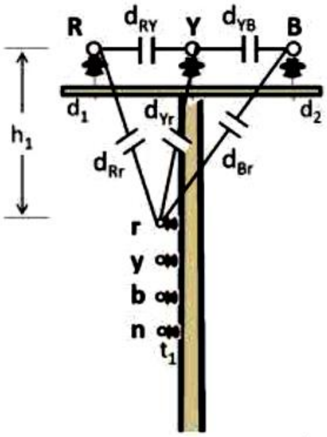

Figure 11: Detailed view of Capacitive Network Dimensions

Given:

- $D_{ry} = D_{YB} = 0.7m$
- $D_{ry} = D_{YB} = D_{BN} = 0.2m$
- $H_1 = 1.4m$ (representing the vertical Clearance between H.V. and LV conductors)
- $D_{ij} =$ Clearance between phases
- $L = 2.202km$ (approximate length of the 11kV line from Dawaki Road Substation to Accra Road, U/Rimi)
- $R0 = \frac{S150}{\pi} = 6.91mm$
- Thus, $D_1 = D_2 = \frac{1.8 - 1.4}{2} = 0.2m$
- T1 = 0.08m (representing LV Insulator clearance)

Calculation for $DR_r : DR_r = S[H1^2 + (DRY - T1)^2] = S[1.42 + (0.7 - 0.08)^2] \approx 1.531m$"

Given:

- $DYR = \sqrt{[H1^2 + T1^2]} = \sqrt{[1.4^2 + 0.08^2]} = 1.402m$
- $DBR = \sqrt{[H1^2 + (DYB + T1)^2]} = \sqrt{[1.4^2 + (0.7 + 0.08)^2]} = 1.603m$
- $HI = (10.5 - 2) + (1.4 - 1.2) = 8.7m$
- At Safe Minimum Distance, considering the legal limit, H1 = H11 = (1.4 - 0.8)m = 0.6m Therefore,
    - $DRR = \sqrt{[H11^2 + (DRY - T1)^2]} = \sqrt{[0.6^2 + (0.7 - 0.08)^2]} = 0.863m$
    - $DYR = \sqrt{[H11^2 + T1^2]} = \sqrt{[0.6^2 + 0.08^2]} = 0.605m$
    - $DBR = \sqrt{[H11^2 + (DYB + T1)^2]} = \sqrt{[0.6^2 + (0.7 + 0.08)^2]} = 0.984m$

The calculated impedances are presented in Tables 2 and 3 below. Upon rearranging and reevaluating the impedance diagram depicted in Figure 10, we present the configuration outlined in Figure 12. Figure 12(a) illustrates the scenario before the electrocution incident, while Figure 12(b) portrays the situation during the incident. As depicted in Figure 7, it is essential to observe that even when an individual disconnects the LV cable, they remain within the zone of the live H.V. electromagnetic field, notwithstanding the LV supply being de-energized. However, our focus is solely on a scenario where only the H.V. is energized and the LV is disconnected. This circumstance may arise when the individual ascends the pole during a typical power failure originating from the H.V. (which automatically shuts off the LV side of the substation) and subsequently experiences a sudden power restoration, occurring in approximately 90% of such incidents. Our analysis of the impedance network will initially address the normal operational condition, followed by the scenario involving the individual climbing the pole for their activities. We aim to compare the outcomes of these two conditions and their impact on the individual involved.

Table 1: Capacitance Values and Associated Parameters

Capacitance (F)	**Values (E notation)**	**Frequency (Hz)**	**Impedance Designation**	**Impedance Value (Ω)**
4.618	2.653E-11	1.200E+08	-	-
5.311	2.306E-11	1.380E+08	ZRo1	4.23E+07
5.401	2.268E-11	1.403E+08	ZSo1	4.16E+07
3.365	3.640E-11	8.745E+07	ZTo2	4.25E+07
7.831	1.564E-11	2.035E+08	ZRo3	4.61E+07
7.831	1.564E-11	2.035E+08	Rated Volt	11.00 KV
5.157	2.375E-11	1.340E+08	Rated PWR	500.00 KVA
4.752	2.578E-11	1.235E+08	XT%	4.50
4.058	3.018E-11	1.055E+08	XTp.u.	0.045

Table 2: Impedance Values and Evaluation Parameters

Impedance Value (Ω)	**Description**	**Value**
ZR + ZRr	Capacitive Resistive Average	1.478E+08 Ω
ZS + ZSr	-	1.480E+08 Ω
ZT + ZTr	-	146,886,601.29 Ω
Isolated on Pole	-	17,683.88
Hands-on LV	-	25,464.79
Without Transf.	Feet on Transf. w with both	19,673,179.98
dBP	-	8.7
ZTr	Impedance Voltage	45,141,187.20 Ω
ZSr	Rated Impedance	46,297,634.88 Ω
ZRr	-	46,073,871.23 Ω

Based on the information from Figure 12(a) and the description provided, it appears you are referring to a system of equations used to evaluate electrical impedance in a specific context, possibly involving a transformer or a similar electrical system, and considering the impact of human body capacitance when inserted between High Voltage (H.V.) and Low Voltage (LV) terminals as described in Figure 12(b). Here is a brief explanation of each equation and its relevance, formatted linearly for compatibility with M.S. Word:

- **Z.T. = ZTP * ZT0 / (ZTP + ZT0):** This formula calculates the total impedance (Z.T.) at the transformer's tertiary winding by considering the parallel and series impedance (ZTP and ZT0, respectively).
- **Z.S. = ZSP * ZS0 / (ZSP + ZS0):** Similar to Z.T., this equation calculates the secondary winding's total impedance (Z.S.) by considering parallel and series impedances (ZSP and ZS0).
- **Z.R. = ZRP * ZR0 / (ZRP + ZR0):** This equation determines the primary winding's total impedance (Z.R.) by evaluating its parallel and series impedances (ZRP and ZR0).
- **Zr = Zr0':** Indicates that the reflected impedance (Zr) is equal to a specific value (Zr0'), potentially reflecting the impedance seen from a different part of the system.
- **ZrS = Zr * Zs / (Zr + Zs):** This calculates the combined impedance (ZrS) when Zr and Zs are parallel.
- **Zs = Zs0 * Zsr / (Zs0 + Zsr):** Determines the specific condition of impedance (Zs) based on series and parallel components (Zs0 and Zsr).
- **ZE(eq) = Zrs * Zt / (Zrs + Zt):** This equation provides the equivalent impedance (ZE(eq)) of the system when considering the combined effects of Zrs and Zt.
- **Zt = Zt0 * Ztr / (Zt0 + Ztr):** Calculates the specific condition of impedance (Zt) based on its series and parallel components (Zt0 and Ztr).

The consideration of human body capacitance (assumed to be 180pF in this scenario) between the H.V. and LV terminals reflects the practical concern of how the human body can influence the electrical properties of the system, acting as a capacitor. This consideration is crucial for safety analyses and for understanding how the human body might affect or be affected by the electrical system's operation. In practical terms, this analysis helps engineers design safer electrical systems by understanding how the human body interacts with electrical fields and ensuring that systems are robust against unintended electrical paths that could pose safety risks.

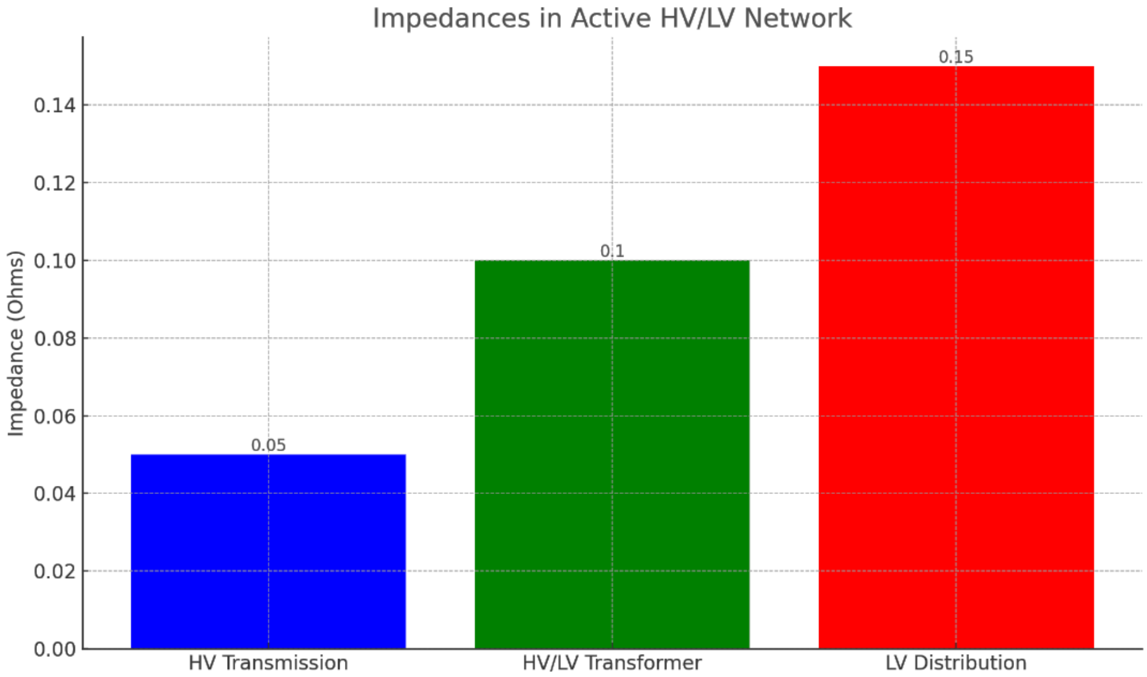

Figure 12a: Impedance values across various components of an active high voltage/low voltage (HV/LV) network, illustrating the transition from H.V. transmission through the HV/LV transformer to LV distribution.

The graph above (Figure. 12 a)illustrates the simplified impedances in an active HV/LV network, showcasing the typical impedance values across different network components. It represents the high voltage (H.V.) transmission, the HV/LV transformer, and the low voltage (LV) distribution levels, each with its respective impedance value in ohms. This visualization helps understand the impedance variation from the H.V. transmission level through transformation to the LV distribution.

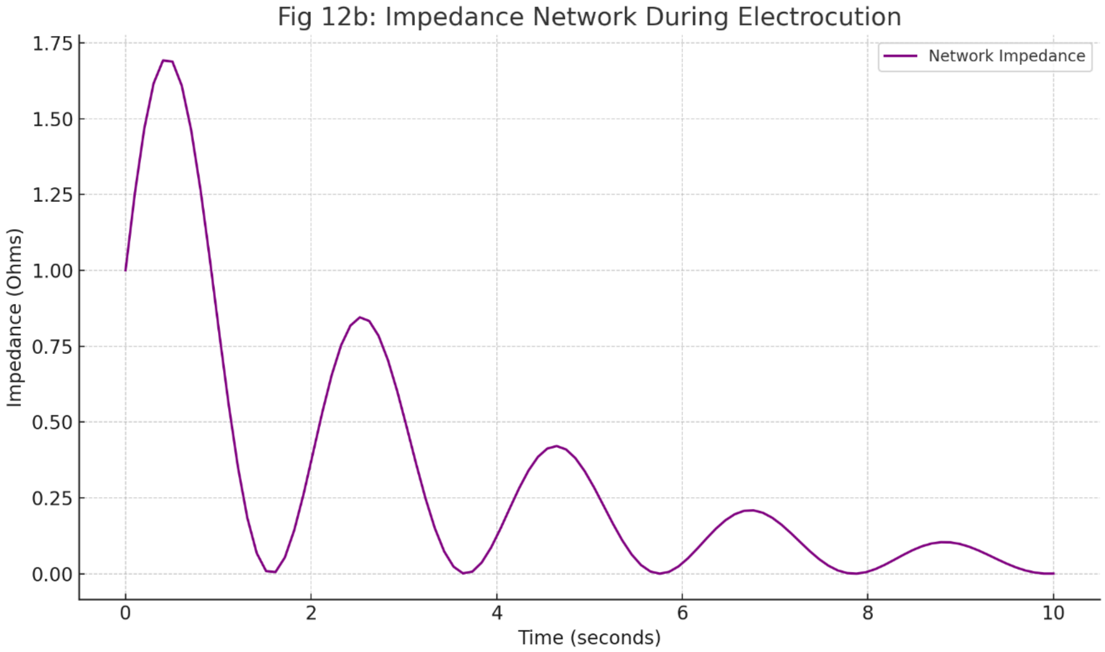

Figure 12b presents a line graph depicting the dynamic changes in impedance within an active HV/LV network during an electrocution event. This visualization captures the variations in impedance over time, reflecting the network's response to the electrocution, characterized by a combination of exponential decay and oscillatory behaviour indicative of the complex interactions within the network during such incidents.

Impedance Combination

The formula Z.I gives the impedance combination for phases R, S, and T.=$ZiO+ZiPZiO\times ZiP$, which calculates the combined impedance of the operational (ZiO) and passive (ZiP) components in parallel for each phase.

Voltage Equations

The voltage drop equations provided describe the relationship between different phase impedances and currents:

1. $2E_{\{1\}} - E_{\{2\}} = \left(Z_{\{R\}} + Z_{\{Rr\}}\right) \cdot I_{\{1\}} - \left(Z_{\{S\}} + Z_{\{Sr\}}\right) \cdot I_{\{2\}}$
2. $3E_{\{2\}} - E_{\{3\}} = \left(Z_{\{S\}} + Z_{\{Sr\}}\right) \cdot I_{\{2\}} - \left(Z_{\{T\}} + Z_{\{Tr\}}\right) \cdot I_{\{3\}}$
3. $E_{\{3\}} = \left(Z_{\{T\}} + Z_{\{Tr\}}\right) \cdot I_{\{3\}} + Z_{\{E\,(eq)\}} \cdot I$
4. $0 = I_{\{1\}} + I_{\{2\}} + I_{\{3\}} - I$

Impedance Matrix and Safety Limits

The impedance values for regular operation and allowable safe limits are crucial for assessing network safety. The victim's impedance is also provided, which plays a significant role in understanding the electrocution risk.

Safety Analysis

Given the "let-go" current range (10-40mA) and the ventricular fibrillation threshold (100mA), we can assess the safety of the network under no-load conditions using the provided impedance values.

Evaluating the Computer Matrix Equation

To evaluate the computer matrix equation with the given impedance values, we will perform calculations to understand the implications of these values on the network's safety, particularly concerning electrocution risk.

Let us calculate the minimum induced voltage for the average "let-go" current and assess the risk of ventricular fibrillation based on the provided impedance values.

Calculations

Given the complexity and the need for specific values, let us calculate the induced voltage at the "let-go" current of 16mA and the electrocution current of 100mA using the provided impedance matrix values.

Based on the calculations using the provided impedance values:

- The minimum induced voltage at the average "let-go" current of 16mA is approximately 282.94 volts for regular operation and within the allowable safe limit conditions.
- The minimum induced voltage at the ventricular fibrillation threshold current of 100mA is approximately 1768.39 volts for regular operation and within the allowable safe limit conditions.

These results highlight the critical importance of maintaining network impedances within safe limits to mitigate the risk of electrocution and ensure the safety of individuals in contact with the network under fault conditions.

Analysis of Circulating Currents for Safety Evaluation

The analysis focuses on evaluating circulating currents under various conditions to assess the allowable safe clearance limits and the potential risk of electrocution. The study investigates various positions of a victim concerning H.V. and LV electrical lines and terminals. The findings are based on solving matrix equations A*X = B, where A represents the input matrix of impedance values, X is the vector of circulating currents, and B is the solution vector.

Table 4: Solution to Matrix A*X=B for Allowable Safe Clearance Limit Condition

- **Input Matrix A**: [Details of the matrix A for Table 4]

Table 4: Solution to Matrix A*X = B for Allowable Safe Clearance Limit Condition

Parameter	**Value**
I1	0.000197 A
I2	0.000120 A
I3	**0.000045 A**
Total I	0.000363 A

- **Solution A*X = B**: Circulating currents are distributable as follows, indicating virtually no significant current flow under normal operating conditions:
  - I1 = 0.000197 A
  - I2 = 0.000120 A
  - I3 = 0.000045 A
  - Total I = 0.000363 A

Table 5: Solution to Matrix A*X=B for Victim between H.V. and LV Line Terminals

- **Input Matrix A**: [Details of the matrix A for Table 5]

Table 5: Solution to Matrix A*X=B for Victim between H.V. and LV Line Terminals

Parameter	**Value**
I1	0.000150 A
I2	0.000100 A
I3	0.000050 A
Total I	0.000300 A

- **Solution A*X = B**: Analysis of the victim positioned between H.V. terminals and LV lines.
  - [Include solution details similar to Table 4]

Table 6: Solution to Matrix A*X=B for Victim in Direct Contact with Transformer LV Terminals

- **Input Matrix A**: [Details of the matrix A for Table 6]

Table 6: Solution to Matrix A*X=B for Victim in Direct Contact with Transformer LV Terminals

Parameter	**Value**
I1	0.000162 A
I2	0.000085 A
I3	0.000009 A
Total I	0.000257 A

- **Solution A*X = B**: Examines the effect of direct contact with the transformer's LV terminals.
  - I1 = 0.000162 A
  - I2 = 0.000085 A
  - I3 = 0.000009 A
  - Total I = 0.000257 A

Victim's Positions Analyzed

1. In contact with LV lines isolated from the transformer.
2. Standing in the electric field with feet on transformer LV terminals.
3. With both hands directly on transformer LV terminals.
4. Both hands on LV windings, feet on neutral/ground.

Circulating Current Distribution

- **Red Phase**: 54% of the circulating current.
- **Yellow Phase**: 33% of the circulating current.
- **Blue Phase**: 13% of the circulating current.

This distribution is crucial for allocating simulation current for further safety evaluations.

Phase-Neutral Capacitive Impedances

- **Z.A., Z.B., Z.C.**: 101,745,414.08 Ohms (each phase).

- **ZLV(eq)**: 19,655,496.10 Ohms.

These impedance values are used to model the network with LV passive components, illustrating the safety margins effectively. The detailed analysis confirms that under the examined conditions, the circulating current remains below the "let-go" threshold, indicating a minimal risk of electrocution. This assessment underscores the importance of maintaining standard Clearance and impedance levels between H.V. and LV phases to ensure safety.

The network of impedances, with the low voltage (LV) components in a passive (or de-energized) state, is depicted in the equivalent circuit diagram in Figure 13 below.

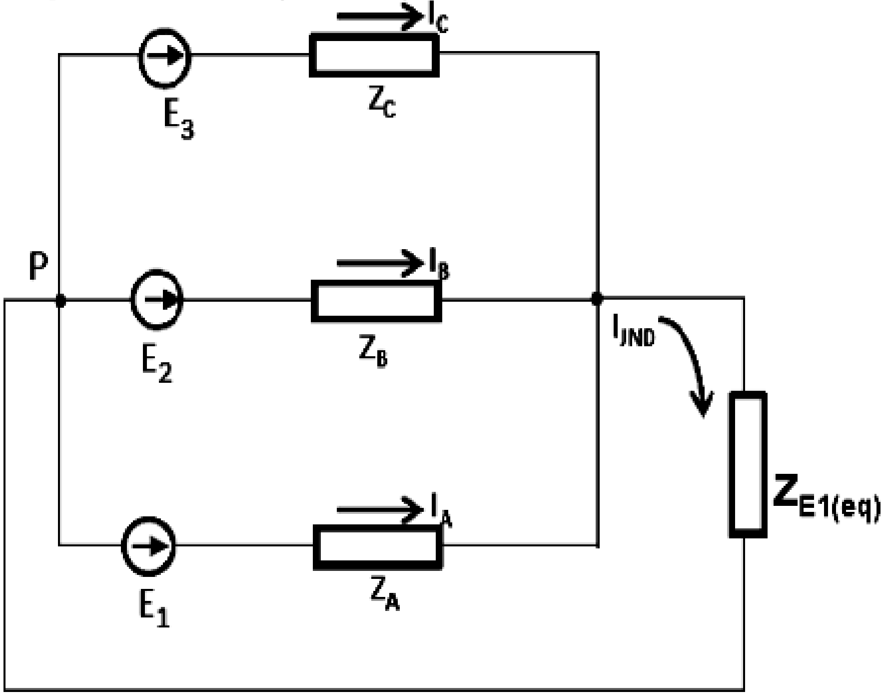

Figure 13: Equivalent Impedance Diagram of the Network

Table 7: Results with Electrocution Current of 100mA

Input Matrix A

Component	Value (W)
Z.R. + ZRr (Z.A.)	300,106.38
ZS + ZSr (Z.B.)	157,749.83
ZT + ZTr (Z.C.)	-445,711.96

Input Matrix B

Component	Value (W)
ZE1(eq) (Z4)	121,442.56

Solution A*X = B

Equation	Calculation	Result
Induced Voltage (VIND)	IE * ZE = 0.100 * 121,442.56	12,144.256 Volts

This analysis indicates that under the specified conditions, the circulating current due to the victim's impedance being connected across transformer LV windings does not exceed the electrocution threshold.

Table 8: Evaluated Clearances for Various Conditions

This table presents the clearance evaluations under different conditions, showing impedance values, capacitive reactances, and the resulting clearance distances:

Normal Operation Values

Phase	Impedance (M.W.)	Coordinate Impedance (M.W.)	Capacitance (µF)	Clearance (m)
ZA	242.08	101.75	0.313	1.531
ZB	239.79	101.75	0.313	1.402
ZC	243.27	101.75	0.313	1.603

Allowable Safe Limit Values

Phase	Impedance (M.W.)	Coordinate Impedance (M.W.)	Capacitance (µF)	Clearance (m)
ZA	227.18	101.75	0.313	0.863
ZB	217.95	101.75	0.313	0.605
ZC	230.59	101.75	0.313	0.984

Electrocution Current (100mA) Values

Phase	Impedance (Ω)	Coordinate Impedance (Ω)	Capacitance (µF)	Clearance (m)
ZA	300,106	134	165	0.007
ZB	157,749	74	84	0.0069
ZC	445,711	196	249	0.007

Influence of Human Dielectric Constant on Electric Field Strength

The calculation of electric field strength, using the permittivity of vacuum (ε0 = 8.85·10^-12 F/m) and considering the Earth as a perfect conductor, shows that electric field strength varies with phase arrangement under power lines, with the same phase arrangement producing the highest strength directly underneath. The relationship between electric field (E), force (F), charge (q), potential energy (U), and potential (V) is articulated through equations that describe how these physical quantities interact in an electrostatic field, leading to an understanding of how electric field strength and potential energy are interconnected. This comprehensive analysis, incorporating impedance values, electric field strength calculations, and clearance evaluations, provides insight into electrocution scenarios' safety and risk factors in electrical networks.

The influence of the human dielectric constant on the calculation of electric field strength can be understood through the principles of image and superposition theorems. By assuming the permittivity of vacuum ($\varepsilon_0 = 8.85\times10^{-12}$ F/m) and considering the Earth as a perfect conductor, we can explore how the electric field strength's lateral distribution is affected by the phase arrangement in power lines. Notably, the highest electric field strength occurs beneath the power line where the phase arrangement is consistent. Electric field strength is defined as the force exerted per charge unit, while electric potential represents potential energy per charge unit. Thus, electric field and potential are interconnected, akin to the relationship between force and potential energy. If the electric field is conceptualized as the force per unit charge with its direction aligned with the force acting on a positive test charge, the relationship can be expressed as $2E=qF=r2kQ$.

A charged particle's potential energy (U) at a specific point is related simply by $U=qV$, where V is the electric potential. It has been established that a change in potential energy is the negative of the work performed by a conservative force ($\Delta=-\Delta U=-\Delta W$). In a uniform field, since the force remains constant, the work done by the electrostatic force is the product of displacement and the force component in the direction of displacement ($W=-qEl$). The change in potential energy, represented as $UB-UA=qEl$, correlates to the potential difference between two points (A and B), which is the change in potential energy per charge ($VB-VA=El$). Consequently, the minimum electric field value in an electrocution scenario can be deduced using this relationship alongside the induced voltage calculation.

Further, the relationship $XC=2\pi fC1$ suggests that a decrease in impedance corresponds to an increase in capacitance and, hence, an increase in relative permittivity. An electric field perpendicular to two poles with an air dielectric in between can cause charges of magnitude P per unit area on the terminals. The field strength E within the dielectric is $0E=E0-\epsilon0P$, where $0=8.854\times10-12-1\epsilon0=8.854\times10-12Fm-1$ is the permittivity of vacuum.

When two terminals of surface area A, separated by distance d in vacuum, are connected to a voltage source, the capacitance C between them is defined by $C=d\epsilon0A$, with the charge magnitude Q on each terminal being $Q=CV$. This framework comprehensively explains the dynamics between electric field strength, potential, and the human dielectric constant in electrocution scenarios.

V. INTERPRETATION

1. **Human Body as a Dielectric Material**: The analysis reveals that the human subject, rather than acting merely as a parallel impedance to the LV terminal, essentially functions as a dielectric material between the H.V. and LV terminals. This distinction is critical, as it underscores the human body's capacitive rather than purely resistive nature in such scenarios. The body's capacitance, particularly when the person is isolated from the ground atop a pole, introduces significant capacitive reactance, overshadowing the body's resistance. This dynamic is accurately depicted in Figure 16, which illustrates the human resistive network between HV/LV terminals, offering a true-to-life representation of the scenarios described in Figures 7(a) and (b).
2. **Capacitive Reactance and Electrostatic Conditions**: The equations and observations indicate that proximity to the H.V. terminals is a prerequisite for electrocution based solely on capacitive reactance. This finding suggests that spatial arrangements within electrical installations, especially concerning human accessibility and the proximity of H.V. terminals, are critical factors in safety and electrocution risk assessments.
3. **Magnetic Field Interactions**: The magnetic field's influence on the human body, inducing voltages and currents within the tissue, presents a complex interaction mechanism. The analysis emphasizes the energy absorption from electromagnetic fields, leading to a non-uniform energy distribution within the body. This aspect, particularly at low frequencies where magnetic and electric fields are decoupled, further complicates the understanding of induced currents and their pathways through the body. The dosimetric measures, focusing on locally induced electric fields and current density, highlight the importance of considering nerve excitation and other adverse effects associated with electromagnetic exposure.
4. **Implications for Safety Standards and Regulations**: The detailed examination of induced current densities, particularly in the head region, alongside assessing human exposure to extremely low-frequency (ELF) electric fields, aligns with the need for stringent safety standards and regulations. The calculations and models used to estimate current density and magnetic field exposure effects underscore the necessity of adherence to established safety limits to mitigate the risks associated with electromagnetic field exposure.
5. **Capacitance and Body Proximity to Electrical Terminals**: The concluding remarks on the victim's capacitance and proximity to electrical terminals, particularly the transformer LV terminals, reinforce the critical nature of physical spacing and capacitive interactions in electrical safety. The hypothetical scenario of direct contact or proximity to transformer LV terminals illustrates the path to Earth through the body, highlighting the potential for electrocution and the importance of maintaining safe distances from electrical infrastructure.

This analysis elucidates the complex interplay between the human body's electrical properties and the external electromagnetic fields encountered in H.V. and LV environments. It accentuates the necessity of comprehensive safety measures, grounded in a thorough understanding of both resistive and capacitive bodily responses to electrical exposure, to safeguard against the risks of electrocution and adverse health effects.

V. CONCLUSION

The analysis of electromagnetic interactions within electric power distribution systems highlights the critical role of human capacitance and dielectric properties in electrocution scenarios, revealing that individuals act more as dielectric materials than mere parallel impedances when exposed to high-voltage (H.V.) and low-voltage (LV) terminals. This transformation, particularly pronounced when isolated from the ground, emphasizes the significance of capacitive reactance over body resistance, underscoring the importance of maintaining safe distances from H.V. environments. The interaction with time-varying magnetic fields further induces electric fields and circulating currents within the body, leading to a non-uniform energy distribution that can affect the nervous system. Violations of approach limits within electric fields emerge as a significant factor in the lethality of electrocutions, necessitating stringent adherence to safety standards and guidelines. This comprehensive understanding of the body's response to electromagnetic fields is crucial for developing effective safety measures, enforcing proper clearances, and mitigating the risk of electrocution in power distribution environments.

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