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LETHALITY OF ELECTROMAGNETIC FIELD IN ELECTRIC POWER DISTRIBUTION NETWORKS: CAPACITIVE EFFECT

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Abstract

Several cases of electrocution incidences experienced on active duty by staff of the Power Industry and Vandals of electrical facilities have resulted from Electromagnetic Field Induction. These usually emanate from ignorance or careless application of basic rules of electricity at new installations, maintenance and system expansions or network integration. Most of these situations result from undue neglect of statutory clearances and approach distance rules, improper network evaluation as well as blatant disregard to the subject of electrical safety. We will be looking at one unfortunate incident of a man electrocuted in Kaduna, and technically evaluating the attendant safety issues involved. Issues involving electromagnetic field effect and its consequences on this case-study is investigated from three premises using electrostatic techniques relating to this phenomenon, based on data of measured values collated from typical sites. The first premise is the consideration of the human anatomy response in the presence of electric and magnetic fields as it affects. The second consideration appraises the interaction of the human body impedances with electromagnetic field on direct contact (with or without Personal Protective Equipment – PPE) as well as impact of electric and magnetic field without direct contacts in the process of electrocution. Conclusions are drawn from charts, tables and excel calculation sheets derived from relevant engineering relationships

Keywords: - *Electric Fields, Magnetic Fields, Statutory Clearances, Approach Distance, Electrostatic Induction, Electromagnetic Induction, Induced Voltage, Capacitive Networks and Dielectric Material.*

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1. WORKING IN ELECTROMAGNETIC FIELD ENVIRONMENT

Nature of electrical accidents reveal the underlying cause to be a combination of three possible factors: work involving unsafe equipment and installations; workplaces made unsafe by the environment; and unsafe work practice.

Therefore, electrical hazards are characterized by:

1. UNSAFE CONDITIONS – equipment/installation and environment
2. UNSAFE WORK PRACTICE – work performance or attitude
3. COMBINATION OF THE TWO

Working on equipment in a de-energized state is required unless de-energizing introduces an increased hazard or is infeasible. This write-up is designed to help ensure that energized electrical work in the Power Industry is performed safely by qualified electrical workers, who are trained and provided with the appropriate safe.

work procedures, protective equipment and other controls. The write-up is intended to give insight to protect employees against electrical shock, burns and other potential electrical safety hazards as well as comply with regulatory requirements.

The Nigerian Electricity Regulatory Commission (NERC) has said that about 162 electrocutions and 132 injuries, all induced by poor safety regulations and compliance were recorded in the Nigerian Electricity Supply Industry (NESI) in 19 months (between January 2012 and July 2013), mostly at various electricity distribution companies. This is on the average nine (9) deaths and seven (7) injuries per month. It is obvious that this trend has continued unabated and on the increase because of non-conformance of electricity distribution companies (DISCOs).

1.1 Work on High-Voltage Systems

Any work on high-voltage equipment and power systems must be performed by qualified and authorized workers in accordance with written safe work procedures acceptable to the NERC. Requirements for working *on* these systems are set out in the Nigerian Electricity Health and Safety Standards (Section 2) and Occupational Health and Safety Regulation, Part 19. For isolation and lockout, workers must follow the safe work procedures set out by the employer and/or the owner of the power system.

Accidents involving high voltages can result in severe injuries and death. When electric current passes through the body, it generates heat and can extensively damage internal tissues. In some cases, the entry and exit wounds are so severe that a foot or hand has to be amputated. The electric current can also stop the heart.

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Electrical workers are frequently in close proximity to energized parts where power arcs can occur. It is not necessary to touch an energized conductor to receive an electrical shock. Qualified electrical workers shall be aware of the final established flash boundary distance as well as the shock protection distances and ensure that unprotected persons near the work area are not allowed to cross the greater distance of the two. This is the shock protection distance from a live part within which (limited space) only a "Qualified Person" may work.

We will now take a look at the various electrocution incidents in recent time and analyze them vis-à-vis the relevant safety standards, evaluate areas of violations and propose solutions to guard against re-occurrence.

1.2 HV/LV Overhead Network Configurations

Most often, workers and vandals tend to overlook some very critical electrical characteristics of this type of network because we are so much in a hurry to accomplish the work without due attention to safety situations peculiar to this type of arrangement. In some cases, it is due to lack of proper training or education.

1.2.1 Recognizing the Hazards

Attending to a dual-voltage network of this form involves:

1. A careful study of interconnecting circuits and interlocks to be painstakingly employed to understand what the risks are in particular network we are workingon and remove danger of electrocution in some cases.
2. Taking all necessary steps and precautions peculiar to electrical distribution equipment or network in accordance with statutory requirements and procedures for removing electrical hazards.

Unless, and until these risks and dangers are recognized and removed or properly addressed, it will always be dangerous to carry out any maintenance or construction work.

2. CASE-STUDY REPORT: MAN ELECTROCUTED TRYING TO REMOVE LV ELECTRIC CABLE

It was reported that an unidentified middle age man was electrocuted at the early hours of Sunday, 27th December 2015 while trying to steal electric cable at a power supply installation in Kaduna. The cable in question was a 150mm^2 4-core up-riser cable at the distribution substation along Accra Crescent, UngwarRimi, Kaduna.

From the cable configuration (4-core) in a distribution substation, it must be a Low Voltage Outgoing cable from a unit of the feeder-pillar. The Google geographical map of the area in question is illustrated in figure 1 below. It is assumed that the 11KV feeder radiated from Dawaki Road Substation, which is about two kilometers (2Km) away. The data obtained from this layout shall be used for our network analysis.

The graphic picture is shown in figure 2 below. Three obvious scenarios can be visualized here:

a) The fellow neatly removed the feeder-pillar fuses to disconnect the incoming end so as to free it from source of power supply, not minding the danger posed by the nearby 11KV Overhead Line.
b) Causes an unscheduled emergency outage on the 11KV incoming supply to the substation, knowing that customers would not in anyway, be surprised or that supply authority will not be in a hurry to restore. He then embarks on step (a) above.

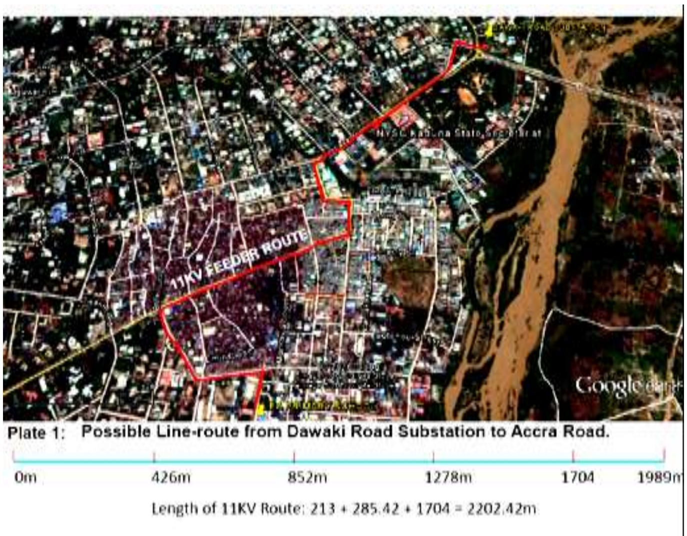

Fig 1: 11KV Line Route from Dawaki Road Substation

c) The vandal confidently goes to the pole end to disconnect the cable from the pole comprising HV/LV configuration with his hand gloves, assuming only the dangers of the LV circuits as shown in figure 3 below.

Fig 2: Victim of electrocution falling off the Pole

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It must be noted here that maintenance of Statutory Approach Clearance Limit cannot be guaranteed in this kind of scenario.

2.1.1 Electromagnetic Field Evaluation and Analysis

A higher-voltage distribution level circuit may feed several lower-voltage distribution circuits through transformers. If the higher voltage circuit is de-energized, and if lower-voltage circuits connected remain energized through other sources, the higher voltage circuit will remain energized.

We will assume here that the transformer LV is completely isolated through the HV drop-out fuses.

Fig 3: HV/LV Line Configurations

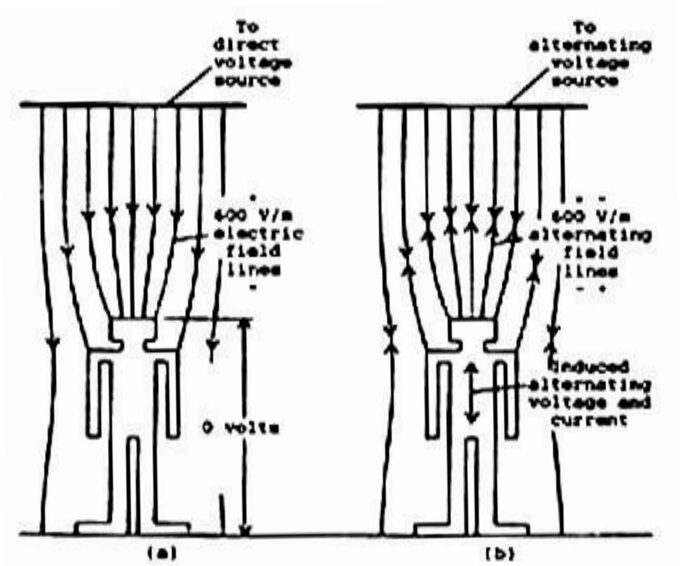
Another problem can arise when de-energized wires become energized through electrostatic or electro-magnetic induction from energized wires in close proximity. It is therefore possible that a person working on a high or low voltage lines close to other energized lines could get electrocuted.

On medium and high voltage level, if the approach clearance limit is violated, electrostatic or electromagnetic induction could result to electrocution.

Two basic phenomena are prevalent in electromagnetic induction with reference to electrocution:

1. The **power frequency electric field** induced currents in the body (eddy current) as well as charges on its surface.
2. **Magnetic induction:** The current induced in the body by magnetic field are greatest near the periphery of the body and smallest at the center of the body.

The field lines through the human body is illustrated in figure 4 below [9].



Direct electric field link Magnetic field induced Voltage

Fig 4: Illustration of Field lines through human body

The main effects of the electromagnetic field are summarized as follows:

- Magnetic field induces a voltage in the tissue of human body, which causes a current to flow through it due to its conductivity.
- The magnetic field has the influence on the tissues of the human body, these maybe beneficial or harmful depending upon the nature.
- The magnitude of the surface charge and internal body currents by any given source of power frequency depends upon many factors. For example, this includes magnitude of the currents and charges in the source, the distance of the body from the source, the presence of other objects that might shield or concentrate the field and the body posture, shape, and orientation. For this reason, the surface charges and the currents, which a given field induces are very different for different for different human beings.
- When a person who is isolated from the ground by some insulating material, comes in close quarters to an overhead transmission line, and electrostatic field is set up in the body of the human being whose ordinary resistance is about 2000Ω. When the same person touches the grounded object, it will discharge through his body causing a large current to flow through the body. Discharge currents from 50Hz electromagnetic field are weaker than natural currents.
- For human beings the limit of the undisturbed field is 15kV/m RMS to experience possible shock.

The human body is a very good conductor. Therefore, when you stand in an electromagnetic field, you become an antenna and are not even aware of it. EMFs, or electromagnetic fields, are created whenever a voltage or a current is present. Electrical current produces a magnetic field, while voltages produce and electric field.

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According to Nigerian Electricity Supply and Installation Standards Regulations (NESIS) 2015 section 3.6.1(c), The minimum clearance between the nearest conductors of different circuits at the point of crossing, including "aerial" earth wire, are well defined on table 3.6.1 PLUS the maximum design sag of the conductor of the lower circuit at the point of crossing.

Columns 6, 7 and Row 5 in Table 3.6.1 of the table falls within the values under consideration for 33/11/0.415KV power distribution systems as applicable to Nigeria.

Figure 5 illustrates the HV/LV pole configuration obtainable in Nigeria, similar to the one under consideration. Electromagnetic Field interferences are avoided as long as the statutory clearance limits are maintained.

It is not unlikely that the victim had earlier disconnected the Low Voltage network whose cable he planned to vandalize. This is a case of double circuit overhead power lines having a passive circuit and an active one. It will be worth noting that it may be necessary to consider determining the induced voltages by the active circuit into the disconnected one.

Electromagnetic fields of low frequency (50 Hz) created by the overhead power transport and distribution lines affect good working and service of all electrical equipment placed nearby,and they could also produce some unwanted effects on the biological organisms located in that area.

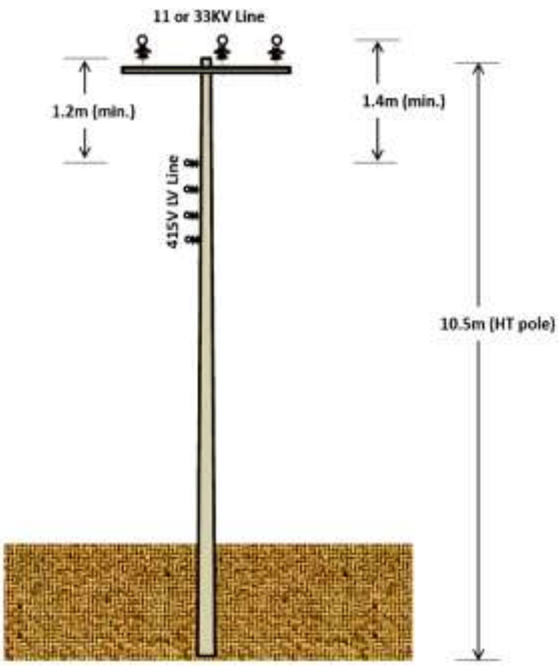

Fig 5: Typical HV/LV Power Line Configuration

As noted earlier, the electro-magnetic disturbance field interferences produce two different types of influences on all the objects located in that area (including the nearby electric lines), namely:

• ***Electric influences*** produced by capacitive connections(or couplings) between the phase conductors of the three phase overhead power lines and the nearby objects or electrical lines;
• ***Magnetic influences*** realized by inductive couplings between the loops of the parallel and adjacent circuits formed by the conductors and the earth.

All these influences are physically reflected on the voltage levels induced by the capacitive or inductive connections in the nearby electrical circuits, on the electric field intensity or potential from the earth, and on the value of the magnetic induction at different points, located near the power mains.

Knowing, as accurate as possible, these electro-magnetic parameters, especially those of the voltages induced in capacitive couplings, as well as magnetic effect, will help us to search for methods and techniques that will enable us to reduce the unwanted effects and to increase the protection of the working staff.

Regardless the type of electromagnetic coupling, the values of induced voltages depend on the geometry of electrical lines, and on the loads transported through them. Our interest in this consideration is the capacitive couplings that produce the induced voltages responsible for electrocution.

In the case of capacitive coupling, the electric line with double circuit represents a complex set of capacitors that are formed due to the differences in potential both between the active circuit phases, and the active circuit conductors and those of the passive circuits insulated from the ground. The point of Electric Field influence for this case and the simplified set of capacitors that are formed are shown in Figure 6, with respect to one passive phase with which the victim was in contact.

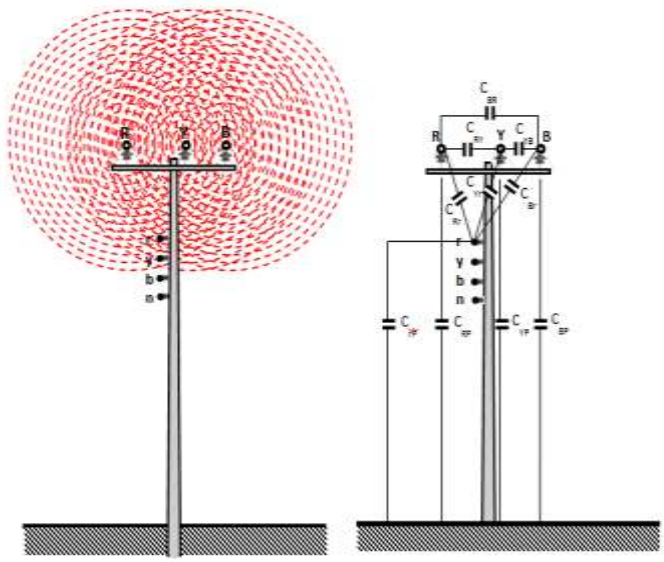

Fig 6: Electric Field Influence/Capacitances between 11 or 33KV HV line and 415V

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Representing the entire phase-phase and active line-to-passive line couplings for the entire configuration will require evolving a complex mathematical model that would be developed for computer simulation. This is beyond the scope of this book. However, it would suffice to know that the electrocution of the victim must have occurred when he was in contact with one of the four low voltage lines (phase or neutral). We will assume the Red Phase in this consideration.

If the human body, being an active electromagnetic material as discussed above bridges the gap, there will be flow of current and it could rise sufficiently to cause electrocution. This is illustrated in figure 7.

To evaluate the inductive effect of this incidence, we shall consider the equivalent circuit[1] of figure 9, which, is the electrical network representing illustrations of figures 7 and 8.

Here we shall assume points **O** and **O′** as imaginary points of contact with floating earth through the concrete pole and Channel Iron Cross-arm as well as LV shackle bolts for HV

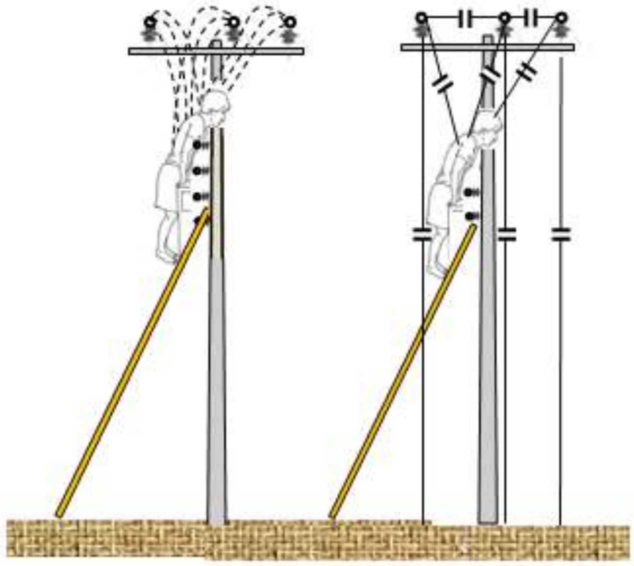

Fig 7: Effect of Induced Electric Field on Human

and LV terminals respectively. Point **P** is the actual hypothetical earth return terminal for both HV and LV live terminals

From the picture of figure 2, it is obvious that the victim with average of height of 1.5-1.6m.must have gone half-way or more into the gap between the Medium Voltage line and the LV Network, with the clearance gap reduced by 0.8metres.

The current source from active HV line shall be used as the drivingcurrent establishing the impedance produced by the capacitive network from the source.The optimized equivalent circuit is shown in figure 11 below, with the impedance network in figure 12.

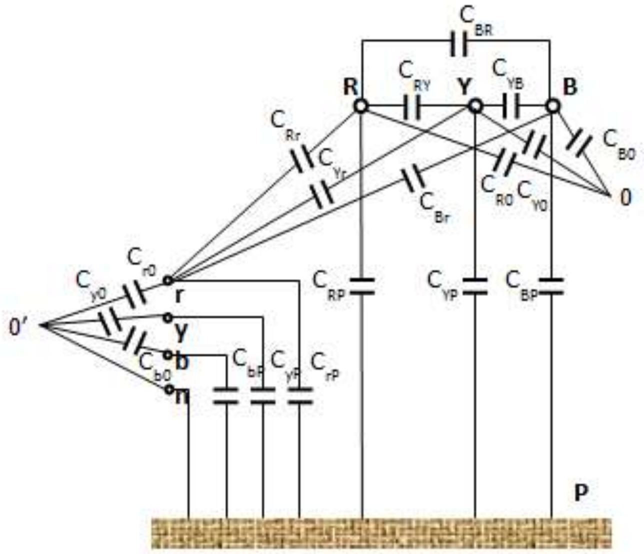

Fig 8: Capacitive Network between HV and LV

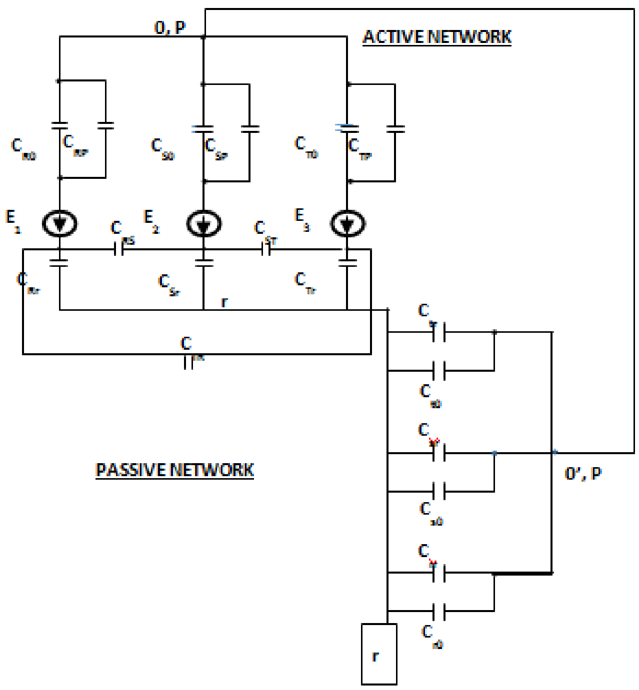

Fig 9: Equivalent Circuit of the Capacitive Network

Delta-star transformation was performed onthe HV/LV capacitive couplings of figure 9 and the resulting impedance network of figure 10 was established.

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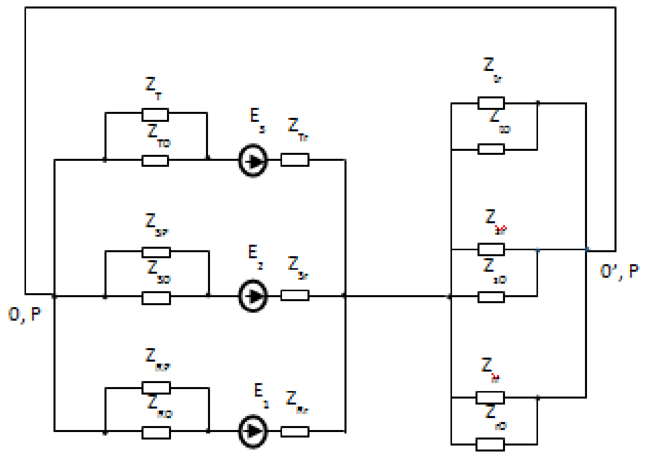

Fig 10: Equivalent Impedance Network

2.1.2 Electric Circuit Analysis

The values of the partial capacitances between phases and between phases and ground are calculated by the followig relations:

- for the partial capacitances between phases:

$$C_{ik} = \frac{2\pi\varepsilon_0 l}{\ln\frac{d_{ik}}{r_0}} \quad \textbf{(1)}$$

- for the partial capacitances between phases and ground:

$$C_{pi} = \frac{2\pi\varepsilon_0 l}{\ln\left(\frac{2h_i}{r_0}\right)} \quad (2)$$

where: l - the length of the line taken into account,
d_{ik}- the distance between phase conductors, according to geometric dimensions of the lines
r - the radius of the phase conductor (assume a = 150mm^2 for both HV and LV).

Table 1 shows minimum clearances of electric lines obtainable in Nigeria at various voltage levels.

Table 1: Minimum Clearances of Electric lines at various Voltage Levels

Voltage	Normal Equivalent Span	Phase to Phase Clearance	Phase to Structures/Earth Clearance
400 volts	45 metres	200mm	25mm
3,300 volts	45 metres	400 mm	130 mm
6,600 volts	45 metres	600mm	130 mm
11,000 volts	90 metres	700 mm	180 mm
33,000 volts	90 metres	1,200 mm	300mm
66,000 volts	190 metres	1,800 mm	600mm
132,000 volts	210 metres	2,400 mm	1,200 mm
330,000 volts	450 metres	600mm	2,400 mm
750,000 volts			

From table 1 above and figure 6(b) also reproduced in a close-up dimension of figure 11 below, assuming 11KV supply;

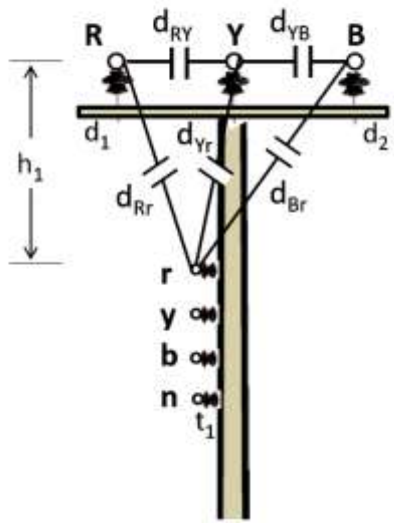

Fig 11: Close-up view of Capacitive Network Dimensions.

d_{RY} = d_{YB} = 0.7m
d_{ry} = d_{yb} = d_{bn}
= 0.2m
h_1 = 1.4m

where, h_1 – vertical clearance between HV 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)

r_0 = S150/π = 6.91mm
∴ d_1 = d_2= (1.8-1.4)/2 = 0.2m
t_1 = 0.08m (LV Insulator clearance)
d_{Rr} = S[h_1^2 + $(d_{RY} – t_1)^2$] = S[1.4^2 + $(0.7-0.08)^2$]
= 1.531m

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d_{Yr} = S$[h_1^2 + t_1^2]$= S$[1.4^2 + 0.08^2]$ = 1.402m

d_{Br}= S$[h_1^2 + (d_{YB} + t_1)^2]$=S$[1.4^2 + (0.7+ 0.08)^2]$ = 1.603m

h_i = (10.5 – 2) + (1.4 – 1.2) =8.7m

At Safe Minimum Distance

Taking the safe limit allowable by law,

h_1 = h_{11} = (1.4 – 0.8)m = 0.6m

$\therefore d_{Rr}$ = S$[h_{11}^2 + (d_{RY} – t_1)^2]$=S$[0.6^2 + (0.7\text{-}0.08)^2]$ = 0.863m

d_{Yr} = S$[h_{11}^2 + t_1^2]$ = S$[0.6^2 + 0.08^2]$ = 0.605m

d_{Br} = S$[h_{11}^2 + (d_{YB} + t_1)^2]$=S$[0.6^2 + (0.7+ 0.08)^2]$ = 0.984m

The evaluated Impedances are shown on tables 2&3 below.

Re-arranging re-evaluating the impedance diagram of figure 10 we have the configuration of figure 12. Figure 12(a) illustrates situation before and figure 12(b) during the electrocution incidence. It is worth noting from figure 7 above that when the human being engages in the activity of disconnecting the LV cable, he is still immersed in the zone of the live HV electromagnetic field even if the LV supply has been de-energized.

However, we are only considering a situation where only HV is energizedand LV is disconnected. This could happen when the victim climbs the pole during the usual power failure from the HV(automatically knocking off the LV side of the substation) and there is a sudden power restoration, which always happens in 90% of this type of scenario.

Our impedance network analysis will first consider the situation of a normal operation and then the case of the man in question climbing the pole for his activities. We shall compare the results of the two conditions and its effect on the victim.

TABLE 2: EVALUATING COUPLING CAPACITORS AND IMPEDANCES - NORMAL OPERATION

Fixed Values:				
ε_0 =	8.85E-12	F/m	1.23E-10	= $2\pi\varepsilon_0 l$
h_i =	**8.7**	m		
l =	2.202	Km		
r_0 =	0.00691	m		

Designation	Phase Conductor Clearance (d_{ik}) m	$\ln(d_{(ik)}/r_0)$	$\ln(2h_i/r_0)$	Capacitance Values (F)	Impedance Values (Ω)	EVALUATING MUTUAL HV/LV IMPEDANCES (Ω)			
d_{RY}	0.7	4.618		2.653E-11	1.200E+08	DELTA-STAR TRANSFORM OF IMPEDANCES		HV/LV Impedance	
d_{YB}	0.7	4.618		2.653E-11	1.200E+08				
d_{BR}	1.4	5.311		2.306E-11	1.380E+08	Z_{Ro1}	4.23E+07	Z_{Rr}	46,073,871.23
d_{Rr}	1.531	5.401		2.268E-11	1.403E+08	Z_{So1}	4.16E+07		
d_{Yr}	1.402	5.313		2.306E-11	1.380E+08	Z_{ro1}	4.86E+07		
d_{Br}	1.603	5.447		2.249E-11	1.415E+08	Z_{So2}	4.15E+07	Z_{Sr}	46,297,634.88
d_{rv}	0.2	3.365		3.640E-11	8.745E+07	Z_{To2}	4.25E+07		
d_{rb}	0.4	4.058		3.018E-11	1.055E+08	Z_{ro2}	4.89E+07		
d_{R0}	8.7		7.831	1.564E-11	2.035E+08	Z_{Ro3}	4.61E+07	Z_{Tr}	45,141,187.20
d_{Y0}	8.7		7.831	1.564E-11	2.035E+08	Z_{To3}	4.65E+07		
d_{B0}	8.7		7.831	1.564E-11	2.035E+08	Z_{ro3}	4.73E+07		
d_{RP}	8.7		7.831	1.564E-11	2.035E+08	**EVALUATING IMPEDANCES ON TRANSFORMER LV TERMINALS**			
d_{YP}	8.7		7.831	1.564E-11	2.035E+08	Impedance Voltage		Rated Impedance (Ω)	
d_{BP}	8.7		7.831	1.564E-11	2.035E+08	Rated Volt (KV)	11.00	1.089E-05	
d_{r0}	0.6		5.157	2.375E-11	1.340E+08	Rated PWR (KVA)	500.00		
d_{v0}	0.4		4.752	2.578E-11	1.235E+08	X_T%	4.50		
d_{b0}	0.2		4.058	3.018E-11	1.055E+08	X_Tp.u.	0.045		

TABLE 3: IMPEDANCE MATRIX - NORMAL CLEARANCE

Designation	Impedance Values (Ω)	HV Self Impedances ($Z_{IP}*Z_{I0}/(Z_{IP} + Z_{I0})$)			LV Self/mutual Impedances ($Z_{i0}*Z_{ir}/(Z_{i0} + Z_{ir})$)			Equivalent LV Impedances in Parallel	
		Z_R	Z_S	Z_T	Z_r	Z_s	Z_t	$_{rs} = Z_r*Z_s/(Z_r + Z_s$	$Z_{E(eq)} = Z_{rs}*Z_t/(Z_{rs} + Z_t)$
Z_{Rr}	46,073,871.23	1.017E+08	1.017E+08	101,745,414.08	8.080E+07	51,190,820.55	52,728,866.63	31,336,752.68	19,655,496.10
Z_{Yr}	46,297,634.88								
Z_{Br}	45,141,187.20	HV Total Impedances (Ω)			**Victim's Average Impedance Values(Ω)**				
Z_{rv}	87,446,689.23	$Z_R + Z_{Rr}$	$Z_S + Z_{Sr}$	$Z_T + Z_{Tr}$	Capacitance C_H ($\times 10^{-9}$F)		Calculated Impedance (Ω)		
Z_{rb}	105,457,733.26	1.478E+08	1.480E+08	146,886,601.29			Capacitive	Resistive	Average
Z_{R0}	203,490,828.17				Isolated on Pole	180	17,683.88	NIL	17,683.88
Z_{Y0}	203,490,828.17				Hands on LV	125	25,464.79	250	247.57
Z_{B0}	203,490,828.17				Hands on LV, Feet on Neutral	125	25,464.79	600	586.19
Z_{RP}	203,490,828.17								
Z_{YP}	203,490,828.17				**Total HV/Victim/LV Impedance (Ω)**				
Z_{BP}	203,490,828.17				Impedance with Victim Direct on LV Line Terminals only (Ω)		Impedance with Victim Direct on Transformer LV Terminals (Ω)		
Z_{r0}	134,004,562.63								
Z_{v0}	123,468,777.28				Without Transf.	Feet on Transf. w dg	With both Hands	Across Tranf. Wdg.	
Z_{b0}	105,457,733.26				19,673,179.98	17,683.88	247.57	1.089E-05	

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From figure 12(a)

$$\left.\begin{aligned} \mathbf{Z_T} &= \mathbf{Z_{TP}* Z_{T0}/(Z_{TP} + Z_{T0})} \\ \mathbf{Z_S} &= \mathbf{Z_{SP}* Z_{S0}/(Z_{SP} + Z_{S0})} \\ \mathbf{Z_R} &= \mathbf{Z_{RP}* Z_{R0}/(Z_{RP} + Z_{R0})} \end{aligned}\right\} \quad \textbf{(3)}$$

$\mathbf{Z_r = Z_{r0}}$

$\mathbf{Z_{rS} = Z_r* Z_s/(Z_r+ Z_s)}$

$\mathbf{Z_s = Z_{s0}*Z_{sr}/(Z_{s0} + Z_{sr})}$

$\mathbf{Z_{E(eq)}= Z_{rs}*Z_t/(Z_{rs} + Z_t)}$

$\mathbf{Z_t = Z_{t0}*Z_{tr}/(Z_{t0} + Z_{tr})}$

Since our consideration is purely electric field effect,**HumanBody capacitance,**the physical property of the human body that has it act as a capacitor like any other electrically-conductive object. The human body capacitance **to a far ground** is 100-200 pF. We shall assume 180pF in this case. This is now inserted between the HV and LV terminals in figure 12b.

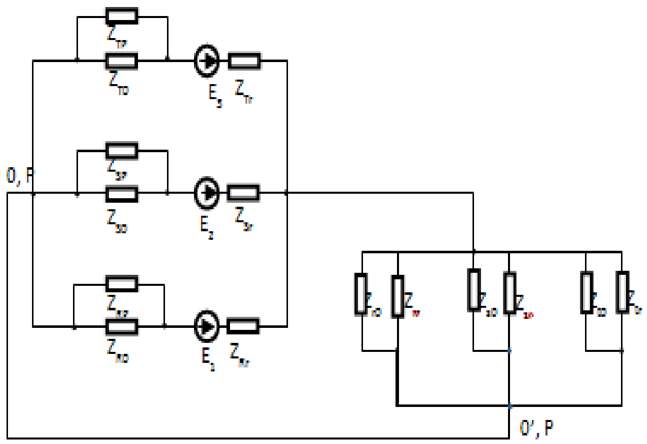

Fig 12a: Impedances of active HV/LV Network

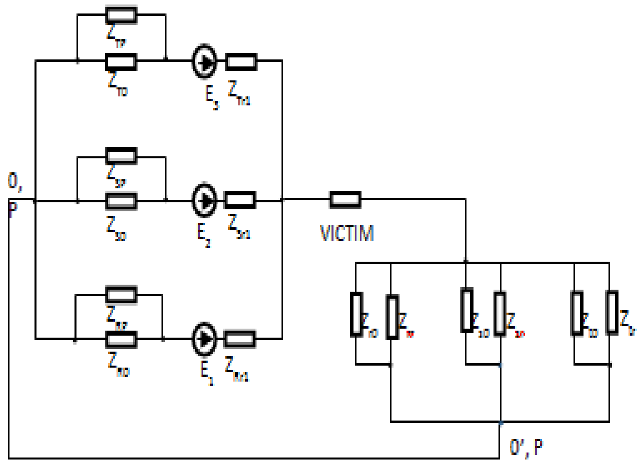

Fig 12b: Impedance Network during the Electrocution.

In the first instance we are assuming live conductors in both cases (HV and LV).The impedances of the active/passive Low Voltage Network now form the return path through ground in series with the victim's body resistance as shown in figure 12b above.

From figure 12(a), after combination of $Z_{iO}$and Z_{iP} in parallel, i.e $Z_I= (Z_{iO}*Z_{iP})/(Z_{iO} + Z_{iP})$ for I = R, S, T

$$\left.\begin{aligned} \mathbf{E_1- E_2} &= \mathbf{(Z_R+ Z_{Rr})\cdot I_1- (Z_S+ Z_{Sr})\cdot I_2} \\ \mathbf{E_2 - E_3} &= \mathbf{(Z_S+ Z_{Sr})\cdot I_2- (Z_T+ Z_{Tr})\cdot I_3} \\ \mathbf{E_3} &= \mathbf{(Z_T+ Z_{Tr})\cdot I_3 + Z_{E(eq)}I} \\ \mathbf{0} &= \mathbf{I_1 + I_2 + I_3 - I} \end{aligned}\right\} \quad \textbf{(4)}$$

$$\begin{pmatrix} \mathbf{E_1- E_2} \\ \mathbf{E_2 - E_3} \\ \mathbf{E_3} \\ \mathbf{0} \end{pmatrix} = \begin{pmatrix} \mathbf{(Z_R+ Z_{Rr}) - (Z_S+ Z_{Sr}) + 0 + 0I_1} \\ \mathbf{0 + (Z_S+ Z_{Sr}) - (Z_T+ Z_{Tr})+ 0I_2} \\ \mathbf{0 + 0 + (Z_T+ Z_{Tr}) + Z_{E(eq)}I_3} \\ \mathbf{1 + 1 + 1 - 1 \; I} \end{pmatrix} \quad (5)$$

From figure 12b

$$\begin{pmatrix} \mathbf{E_1- E_2} \\ \mathbf{E_2 - E_3} \\ \mathbf{E_3} \\ \mathbf{0} \end{pmatrix} = \begin{pmatrix} \mathbf{(Z_R+ Z_{Rr1}) - (Z_S+ Z_{Sr1})+ 0 + 0 \; I_1} \\ \mathbf{0 + (Z_S+ Z_{Sr1}) - (Z_T+ Z_{Tr1})+ 0I_2} \\ \mathbf{0 + 0 + (Z_T+ Z_{Tr1}) +(Z_E+ Z_{E1(eq)})I_3} \\ \mathbf{1 + 1 + 1 - 1 \; I} \end{pmatrix} \quad \textbf{(6)}$$

The evaluated results of the transformed Impedance Network are follows:

IMPEDANCE MATRIX - NORMAL OPERATION

$Z_R + Z_{Rr}$	147,819,285.31
$Z_S + Z_{Sr}$	148,043,048.96
$Z_T + Z_{Tr}$	146,886,601.29

IMPEDANCE MATRIX - ALLOWABLE SAFE LIMIT

$Z_R + Z_{Rr}$	143,542,809.23
$Z_S + Z_{Sr}$	144,205,490.72
$Z_T + Z_{Tr}$	141,266,047.19
Z_{VICTIM}	17,683.88

The Matrix equation is of the form:

$$A*X=B$$

It must be borne in mind that that the **'let-go'** current for an average man as confirmed by NIOSH studies is 16mA [19]. Consensus universal studies peg it at 10-40mA. Therefore, we will simulate condition of **average let-go current** to determine **minimum value of induced voltage** in this situation.

From the same reference, **ventricular fibrillation threshold** is 100mA; and so we assume the**minimum electrocution current**100mA. We shall use this values to evaluate practical results and establish the implications of the above impedance values.

Assuming a condition of no-load, we will evaluate Computer Matrix Equation for table3 using:

1. The impedance values on the table above

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2. Various positions of the victim at allowable safe clearance limit
3. Minimum threshold of Electrocution Current.

The results of the evaluationsare given as follows with the circulating current distributable as shown:

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

Input Matrix A:

143542809.230	-144205490.720	0.000	0.000
0.000	144205490.720	0.000	0.000
0.000	0.000	141266047.190	19655496.100
1.000	1.000	1.000	-1.000

Input Matrix B:	Solution A*X = B
11000.0000	0.000153 = I_1
11000.0000	0.000076 = I_2
6350.0000	0.000011 = I_3
0.0000	0.000241 = I

It is obvious from the above results the there is virtually no enough current flow under normal operating condition to result to significant induced voltage on the LV terminals. We therefore decided to investigate effect with the victim between HV terminals and LV Lines as shown on table 5 below.

Table 5: Solution to Matrix A*X=B for Victim between HV and LV line terminals only

Input Matrix A:

143542809.230	-144205490.720	0.000	0.000
0.000	144205490.720	-141266047.190	0.000
0.000	0.000	141266047.190	19673179.880
1.000000	1.000000	1.000000	-1.000000

Input Matrix A:	Solution A*X = B
11000.0000	0.000162 = I_1
11000.0000	0.000085 = I_2
6350.0000	0.000009 = I_3
0.0000	0.000257 = I

For the Victim in Direct contact with the transformer LV terminals, the results are as follows:

Table 6: Solution to Matrix A*X=B for Victim between HV and transformer LV terminals

Input Matrix A:

143542809.230	-144205490.720	0.000	0.000
0.000	144205490.720	-141266047.190	0.000
0.000	0.000	141266047.190	17683.880
1.000000	1.000000	1.000000	-1.000000

Input Matrix A:	Solution A*X = B
11000.0000	0.000197 = I_1
11000.0000	0.000120 = I_2
6350.0000	0.000045 = I_3
0.0000	0.000363 = I

Four obvious positions of the victim used for this analysis as in table 3 are as follows:

a) In contact with LV lines isolated from transformer.
b) Standing in Electric Field feet on transf. LV terminals
c) With both hands direct on transformer LV terminals
d) Both hands on LV windings, feet on neutral/Ground.

It was obvious from our analysis as in the table6above that whatever the position, the current cannot be more than 0.363mA which is below the **'let-go' current**. This current is contributedfrom the phases as follows:

Red	=	54% of Circulating Current;
Yellow	=	33% of Circulating Current
Blue	=	13% of Circulating Current

This forms our basis for allocating simulation current for further evaluation.

The above evaluation has assumed the phase-neutral Capacitive impedances for the Lines on each phase as follows:

$$Z_A = 101{,}745{,}414.08\Omega$$
$$Z_B = 101{,}745{,}414.08\Omega$$
$$Z_C = 101{,}745{,}414.08\Omega$$
$$Z_{LV(eq)} = 19{,}655{,}496.10\Omega$$

The impedances network with LV passive (i.e. de-energised)is illustrated in the equivalent diagram of figure 13 below.

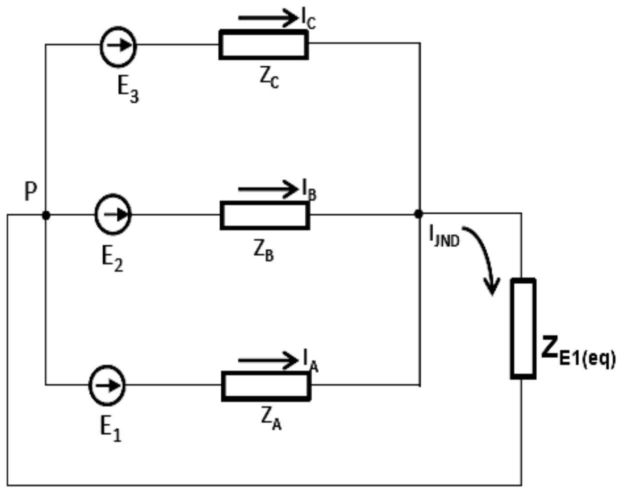

Fig 13: Network Equivalent Impedances

The scenario where the standard clearance (impedances) are maintained between the HV and LV phases and the man climbs up the pole was evaluated. It shows that even if the victim's impedance was connected across transformer LV windings (about 109mΩ from table 3), the total circuit current cannot be more than 0.363mA as indicated earlier.

We will now assume a minimum electrocution current of 100mA and establish the impedances that can cause this current to circulate as shown in the matrix table 7 below. This current is distributable on the phases as earlier evaluated:

Red = 54% of Circulating Current = 54mA
Yellow = 33% of Circulating Current = 33mA
Blue = 13% of Circulating Current = 13mA

Table 7: Results with Electrocution Current of 100mA

Input Matrix A

```
0.054 -0.033 0.000 0.000
0.000 0.033 -0.013 0.000
0.000 0.000 0.013 0.100
1.000 1.000 1.000 -0.100
```

Input Matrix B

```
11000.000
11000.000
6350.000
0.000
```

Solution A*X = B

```
300106.380  = ZA
157749.834  = ZB
-445711.959 = ZC
121442.555  = ZE
```

$Z_R + Z_{Rr}$ = Z_A = 300,106.38Ω
$Z_S + Z_{Sr}$ = Z_B = 157,749.83Ω
$Z_T + Z_{Tr}$ = Z_C = -445,711.96Ω
$Z_{E1(eq)}$ = Z_4 = 121,442.56Ω

Therefore, Induced voltage during electrocution is given by:

V_{IND} = $I_E Z_E$ =0.100*121,442.56
= 12,144.256Volts
V_{IND} = 12.144KV

Our equivalent clearance evaluation shows that the victim could have been within the following clearance ranges for the given conditions:

Table 8: Evaluated Clearances for various Conditions

Phase Impedances	Impedance Values (MΩ)	Coordinate Imp.(MΩ)		Capacitances (µF)		Clearance (m)
		Z_Y	Z_X	C_Y	C_X	$d_X = d_{(ik)}$
VALUES FOR NORMAL OPERATION						
Z_A	242.08	101.75	140.33	0.313	0.227	1.531
Z_B	239.79	101.75	138.05	0.313	0.231	1.402
Z_C	243.27	101.75	141.53	0.313	0.225	1.603
VALUES FOR ALLOWABLE SAFE LIMIT						
Z_A	227.18	101.75	125.38	0.313	0.254	0.863
Z_B	217.95	101.75	116.21	0.313	0.274	0.605
Z_C	230.59	101.75	128.85	0.313	0.247	0.984
VALUES FOR ELECTROCUTION CURRENT (100mA)						
Z_A	0.300	0.134	0.165	0.0024	0.0019	0.0070
Z_B	0.157	0.074	0.084	0.043	0.0038	0.0069
Z_C	0.445	0.196	0.249	0.0016	0.0013	0.0070

2.1.3 Influence of Human Dielectric Constant

Calculation of the electric field strength is made according to image and superposition theorems. The permittivity of vacuum, $\varepsilon_0 = 8.85 \cdot 10^{-12}$ F/m, is assumed everywhere and the earth is considered as a perfect conductor. Lateral distribution of the electric field strength depends on the phase arrangement in power lines. Underneath the power line, the same phase arrangement produces the highest electric field strength.

Electric field is force per charge and potential is potential energy per charge. So electric field and potential are linked in the same way that the concepts of force and potential energy are linked.

If electric field is defined as the electric force per unit charge andthe direction of the field is taken to be the direction of the force it would exert on a positive test charge, then;

$$\vec{E} = F/q = kQ/r^2 \quad (7)$$

$$F = qE \quad (8)$$

A charged particle's potential energy U at the point is given by the simple relation:

$$U = qV \quad (9)$$

It is established that change in potential energy is defined as the negative of the work done by a conservative force,

$$\Delta U = -\Delta W \quad (10)$$

Since the field is uniform the force doesn't change and the work done by the electrostatic force is just the product of the

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displacement and force's component in the direction of the displacement;

$$W = -qEl \quad (11)$$

Since the change in PE is equal to minus the work done by the electrostatic force

$$U_B - U_A = qEl \quad (12)$$

Potential difference between points A and B is the **change in Potential Energy** per charge, i.e.

$$V_B - V_A = El \quad (13)$$

Therefore, **Minimum Electric Field** value in this electrocution can be evaluated using this relation together with the result of induced voltage calculation above.

Now, from the relationship;

$$X_C = 1/(2\pi fC) \quad (14)$$

It is obvious that reduction in impedance means increase in capacitance, therefore, an increase in relative permittivity.

An Electric Field perpendicular to two poles of the enclosed air dielectric between the HV/LV terminals can be visualized as indicated in figure 14 below causes charges of magnitude **P**per unit area on the terminals. The field strength **E** inside the dielectric is then given by;

$$E = E_O - P/\varepsilon_O \quad (15)$$

Where, $\varepsilon_O = 8.854 \times 10^{-12}\ Fm^{-1}$(the permittivity of vacuum).

It will have a Capacitance **C** between the two terminals each of surface area **A**, separated by a distance **d** in vacuo and connected to a voltage source of strength **V** (figure 15a). Current flows from the voltage source until there is a charge of magnitude **Q** on each terminal, so that;

$$Q = CV \quad (16)$$

The **Capacitance** of the **Capacitor** is given by;

$$C = \varepsilon_O A/d \quad (17)$$

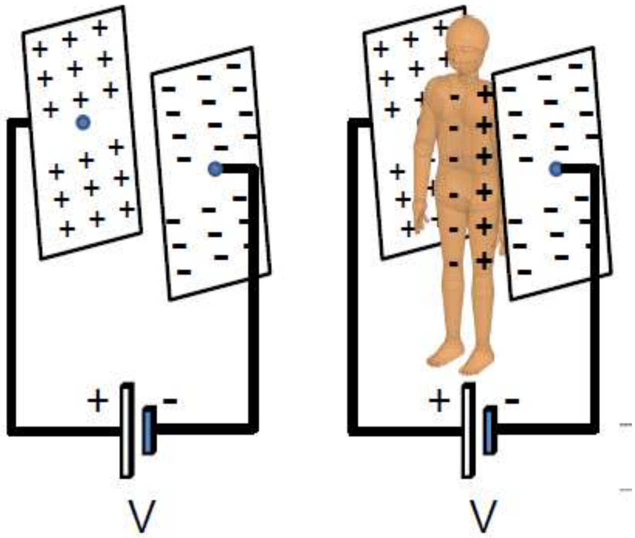

Fig 14: Capacitor (a) without and (b) with human dielectric

When a new dielectric material is placed in the gap, it becomes polarized due to the field and charges appear on the surface of the material (the victim in this case) as shown in figure 14b.

The voltage difference of the terminals will remain constant because they are connected to the source so that current flows from source to build up an extra charge on each terminal. This extra charge is equal to the final induced charge on the dielectric surface and of opposite sign. The total charge is then given by;

$$Q' = C' V \quad (18)$$

$$C' = \varepsilon A/d \quad (19)$$

Where, ε is the permittivity of the human body. Typical values of the **Dielectric Constants** of various parts of human body are shown on table 9 below.

When the '***humandielectric***' is placed between the plates of a capacitor it increases the capacitance. The capacitance increases by the factor κ when the dielectric completely fills the region between the plates($\kappa$is the **dielectric constant** of the material).

It can be shown from equations (9) and (12) that;

$$Q' = Q + Q_0 = Q + PA \quad (20)$$

And from (7) and (10) above;

$$\varepsilon AV/d = \varepsilon_O AV/d + PA \quad (21)$$

$$\therefore P = (\varepsilon - \varepsilon_0)V/d \quad (22)$$

$$= (\varepsilon - \varepsilon_0)E \quad (23)$$

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Table 9: Complex Dielectric Constants for Various Human Structures

Anatomical Structure	Epsilon (ε)	Sigma (σ)
Bone	12.4	0.2
Fat	4.72	0.05
Muscle	60	1.32
Skin	39.9	0.72
Lung	20.5	0.42
Heart	57.48	1.22
Trachea	55.9	1.12
Cerebra Spinal Fluid	68.1	2.45
Esophagus	71.1	1.35

Where **E (= V/d)** is the **electric field**.

The ratio of the two capacitances, **C** and **C′** is given by;

$$\varepsilon_r = C'/C = \varepsilon/\varepsilon_0 \quad (24)$$

Where ε_r is the relative permittivity or **dielectric constant** given on table 9 above.

In electromagnetism, permittivity or absolute permittivity is the measure of resistance that is encountered when forming an electric field in a medium. In other words, permittivity is a measure of how an electric field affects, and is affected by, a dielectric medium. The permittivity of a medium describes how much electric field (more correctly, flux) is 'generated' per unit charge in that medium. More electric flux exists in a medium with a low permittivity (per unit charge) because of polarization effects.

The case under consideration can be adequately evaluated as illustrated in figure 15.

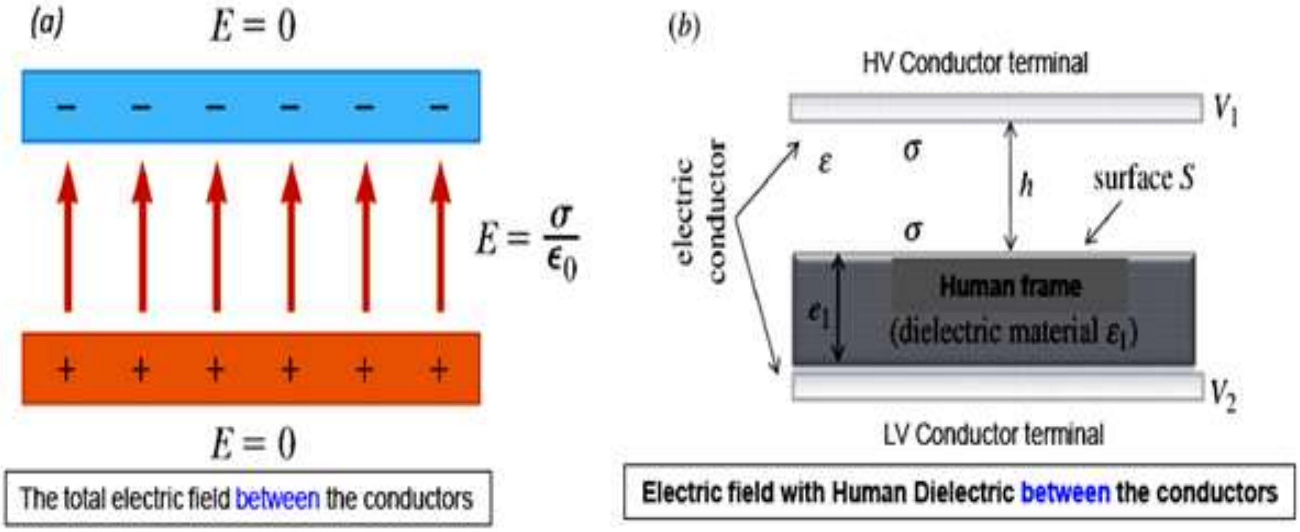

Fig 15: Illustrating capacitive effect with human dielectric

It should be noted that the man's physical contact is with the LV conductor terminal. According to C. PaillerMattei et al, if we neglect the boundary effect, the electric charge, *Q*, on the skin surface can be estimated using the example of capacitor with dielectric material inside the model [3].

The electric field intensity between the HV terminal and the dielectric material, E_0, and inside the dielectric material, E_1, are, respectively

$$E_0 = \frac{\sigma}{\varepsilon_0} \quad (25)$$

And,

$$E_1 = \frac{\sigma}{\varepsilon_1}, \quad (26)$$

Where, σ is the surface charge density on the HV terminal. If the HV terminal is above the victim at a distance *h*, and the thickness, e_1, of the dielectric material inside the imaginary capacitor, symbolizes the human body-mass, the electrical potential difference, *V*, between the LV metallic support for the forearm and the HV terminal is given as [3];

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$$V = V_1 - V_2 = E_0 h + E_1 e_1, \tag{27}$$

Therefore (from (18) and (19));

$$V = \sigma\left(\frac{h}{\varepsilon_0} + \frac{e_1}{\varepsilon_1}\right). \tag{28}$$

If S is the surface area of the victim in contact with the electric field, the surface charge density, σ, is defined as $\sigma = Q/S$; therefore, the potential difference can be written as a function of electric charge, Q, as

$$V = \frac{Q}{S}\left(\frac{h}{\varepsilon_0} + \frac{e_1}{\varepsilon_1}\right). \tag{29}$$

As a consequence the electric charge, Q, on the human skin surface is

$$Q = \frac{\varepsilon_0 VS}{(h + (e_1/\varepsilon_{r(\text{skin})}))}, \tag{30}$$

Where, $\varepsilon_{r(skin)}$is the skin relative permittivity given by
$\varepsilon_1 = \varepsilon_0\, \varepsilon_{r(skin)}$.

The electrical properties of many biological materials are known to exhibit frequency dispersions. In the human skin, the impedance measured at various frequencies closely describes a circular locus of the Cole-Cole type in the complex impedance plane.

With the results obtained in the analysis and table 9, actual values of parameters can be evaluated.

2.1.4 Interpretation & Conclusion

Going by the various technical evaluations above, it can be safely concluded that:

i. The victim actually acted as a ***human dielectric material inserted between the HV and LV terminals*** and not as a mere parallel impedance with LV terminalas assumed. The body capacitanceof a human being would be low when standing on top of a pole isolated from ground. The capacitive reactance becomes more significant than the body resistance. Therefore, the true picture of the illustration of figures 7(a), (b) is correctly reproduced in figure 16 below.

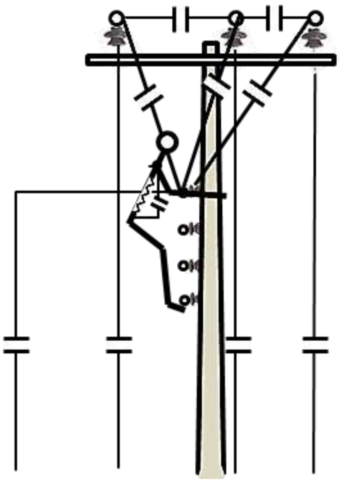

Fig 16: The Human Resistive Network between HV/LV

Now from (29),

$$Q = \frac{\varepsilon_0 VS}{(h + (e_1/\varepsilon_{r(\text{skin})}))},$$

And

Z_C	=	**1/(2πfC)**	from (8)
Q	=	**CV**	from (10)

The results of the impedance and equivalent clearancecalculationsat power frequency of 50Hz, have already been obtained. It is obvious that, all things being equal, for this electrocution to rely on capacitive reactance alone, the victim has to be pretty close to the HV terminals.

However, we will take a look at other related areas.
Average Body Surface area of a man is given as;
BSA = 1.9m²

Average Body Thickness,
ABT = 23.75cm
ABT = e_1 **= 0.24m**

Vertical clearance between HV and LV conductors as given in figure 6 is,
h_1 **= 1.4m**

ii. From **Magnetic Field** point of view, it has been stated earlier in this write-up that Magnetic field induces a voltage in the tissue of human body, which causes a current to flow through it due to its conductivity. There are three established basic coupling mechanisms through which time-varying electric and magnetic fields interact directly with living matter.
   - **Coupling to low-frequency electric fields:-** which leads to electric current, formation of electric dipoles and reorientation of electric dipoles already present in the tissue.

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- **Coupling to low-frequency magnetic fields:-** which lead to induced electric fields and circulating electric current.
- **Absorption of energy from electromagnetic fields:-** resulting into highly non-uniform deposition and distribution of energy within the body.

The first two cases are our point of concentration.

The physical **interaction of time-varying magnetic fields with the human body** results in **induced electric fields** and **circulating electric currents**. At low frequencies, the magnetic and electric fields are decoupled. The exact path and magnitude of the resulting current induced in any part of the body will depend on the electrical conductivity of the tissue.

Exposure to time-varying electric and magnetic fields result in **induction of internal body current**, and the known adverse effects are **associated with nerve excitation**. The primary dosimetric measure is the local induced electric field. This measure is selected because thresholds of the excitable tissue stimulation are defined by the electric field and its spatial variation. However, current density is used in some exposure guidelines. Among the measurements often reported are the average, root mean square (rms) and maximum induced electric field and current density values

Current density estimation at the head region will be considered by using magnetic field model by assuming that the body has a homogenous and **isotropic conductivity and current path is circular** [15].An assessment of human exposure toextremely-low-frequency (ELF) electric field generated by a power line is usually made using the **rotationally-cylindrical body model** [16].The model for the estimation of current density at the head region uses the following equation derived based on the formulation of faraday's law of induction. Basic equation related with a magnetic fields induction current analysis are as follows**.**

$$\nabla \times B = j\omega \quad (31)$$

$$\nabla \cdot J = j\omega \quad (32)$$

$$J = \sigma E \quad (33)$$

$$J = \pi R f \sigma B \quad \mathbf{(34)}$$

Also, by ***Lorentz force law,***

$$\mathbf{F = q(E + v \times B)} \quad (35)$$

Where **E** = induced electric field, **B** = magnetic flux density,**ω**= angular frequency, **σ**= conductivity, **R** = radius of loop (m),f = power-line frequency J = induction current density, a force **F, v** is the particle's velocity,and time differential is transformed into **jω**.

For a point **P** on the axis of a closed circular current loop with radius **R**, the total induced field **B** can be obtained as:

$$B = \frac{\mu_0}{2\pi} i \frac{\pi R^2}{r^3} = \frac{\mu_0}{2\pi} \frac{|\mathbf{m}|}{r^3}. \quad (36)$$

Where, dipole moment **m** is associated with the current loop with a magnitude of $|\mathbf{m}| = \pi R^2 i$ i.e. the current times the area enclosed by the loop**.** This shows the spatial attenuation of the field as 1 over distance cubed**.**

In the estimation of induced current density in the head region, at extremely low frequency, tissues conductivities σ are of the order of $0.2\ S/m$ while a radius **R**of $0.075\ meters$ of the induction loop are assumed for the head and a maximum Magnetic Field Strength **B** of 100mG (10μT) was measured in a substation location in Nigeria (Ocheni Abdullahi Usman and Adam Usman) [7]. For a human being in such environment, the current density is evaluated from equation (4) above:

⇒ J = π*0.075*50*0.2*0.00001
= $\mathbf{23.562 \times 10^{-6}\ A/m^2}$

If the average height of a normal human being is $\mathbf{h_B = 1.75m}$ and the height of the HV line as earlier discussed is $\mathbf{h_P = 8.5m}$ above ground level, then the clearance of the HV line to the head of our model on ground in this calculation is given by;

$$\mathbf{r = h_P - h_B = 6.75m}$$
$$\mathbf{\mu_0 = 4\pi \times 10^{-7}}$$

Therefore, from equation (6);

$$\mathbf{B = (4\pi \times 10^{-7} \times m)/(2\pi \times 6.75^3)}$$
$$\mathbf{10\mu T = 6.50 \times 10^{-10} \times m}$$
$$\mathbf{m = 0.000010/6.50 \times 10^{-10}}$$
(current dipole moment)
$$\mathbf{= 15.38KA\text{-}m^2}$$

Now, as was seen in earlier discussions, the distance between the HV and LV point of incidence is **r = 1.4m**, given that the HV and LV terminals form two parallel plate Dipole terminals. Assuming that the man is operating within least distance of distinct vision (LDDV) or the reference seeing distance (RSD) which is about 25cm from the eye, at angle 45^0 (33% of his height is above line of distinct vision), two-thirds of his body trunk must be below the LV line of vision.

$$\mathbf{r = 1.4 - (0.33 \times 1.75)}$$
$$\mathbf{= 0.8225m}$$
$$\mathbf{\Rightarrow B = (4\pi \times 10^{-7} \times 15380)/(2\pi \times 0.823^3)}$$
$$\mathbf{= 0.00553T}$$
$$\mathbf{B = 5.53mT}$$

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Assuming average body trunk radius of R = 0.165m

J = **π*0.165*50*0.2*0.00553**
= **0.0287A/m^2**
J = **28.7mA/m^2**

We will now compare these values with the effect of **magnetic field exposure** limits given on table 10 below:

Table 10: Magnetic Field Exposure Effect

Electric current density (mA/m^2) (at 50/60Hz)	Effect
1 to 10 (500 to 5,000 µT)	Minor biological effects have been reported.
10 to 100 (5,000 to 50,000 µT)	There are well established effects, including visual and nervous system effects. Facilitation of bone fracture reunion has been reported.
100 to 1,000 (50,000 to 500,000 µT)	Stimulation of excitable tissue is observed and there are possible health hazards.
>1,000 (>500,000 µT)	Extra systoles and ventricular fibrillation, i.e., acute health hazards, have been established.

We can conclude here that there is magnetic field strength of 5,530µT, and Current densityof 28.7mA/m^{2}circulating within his body. Going by the provisions of table 13, this falls within cases of a well establishedmagnetic field effect of visual and nervous system breakdown.

iii. Exposure to these fields in turn induces fields and currents inside the body. If only the induced electric field and resultant current density in tissues and cells are considered, as the internal magnetic field in tissues and cells is the same as the external field. At extremely low frequencies, exposure is characterized by the electric field strength (E) or the electric flux density (also called the displacement) vector (D), and the magnetic field strength (H) or the magnetic flux density (also called the magnetic induction) (B**)**

The **induced AC current density** (J_{AC}) at victim's body-mass is a function of the induced voltage on victim (V_{IND}), body resistivity (ρ_B), and body thickness (e_1). Based on our earlier assumption of cylindrical anatomical structure of the body mass, it can be computed as follows:Using the limiting values on table 12 below, the reason for the electrocution is very obvious. The limit for professionally trained workers (Competent Persons) is 20KV/m.

Table 11: ICNIRP, the EU Recommendation, and the Control of Electro-magnetic Fields at Work Regulations

Public exposure	magnetic	360 µT
	electric	9 kV/m
Occupational exposure (High Action Level)	magnetic	6000 µT
	electric	20 kV/m

$$J_{AC} = \frac{8.V_{IND}}{\rho_B . \pi . e_1} \quad (37)$$

Knowing that, ρ_B = RS/L

Using the parameters for an average man, the conducting part between head and feet can be approximated as a cylinder 1.75m long and surface area of 1.9m^2.

S = **1.9**m² (body surface area)
L = **1.75**m
R = **1100Ω** (assuming conducting part between head and feet)
⇒ρ_B = **1100*1.9/1.75**
= **1,194.29Ω-m**

Consider half of the above calculated induced voltage

V_{IND} = 6.072kV
∴ J_{AC} = **8*6,072/1194.29*π*0.24**
= **53.94A/m^2**

Again, if tissues conductivities σ are of the order of $0.2\ S/m$ and a radius **R**of $0.075\ meters$ of the induction loop are assumed for the head, with induced current of at least 100mA;

⇒ I_{AC} = S_h*J_{AC}
J_{AC} = **100x10^{-3}/(π*0.0750^2)**
= **5.66A/m^2**
E = **5.66/0.2 = 28.3kV/m**

Two of fewdetermining factors of electric field intensity at the surface of the body and induced currents passing through various segments of the body are:

a) The location of the body relative to ground and other conductors; and
b) Any conduction currents from the body to ground or other conductors.

A body is coupled to an electric field in proportion to its capacitance such that the greater the capacitance the greater the current flow in the body. Human beings have capacitances of about 125 pF, when in close proximity with ground [18]. We now turn our attention to the capacitance component of the victim.

We shall assume here that the victim is so close to or even in direct contact with the transformer LV terminals that it can be taken as direct return path to earth. Therefore, only the body capacitance and the transformer LV inductive network apply as shown in figure 17 below.

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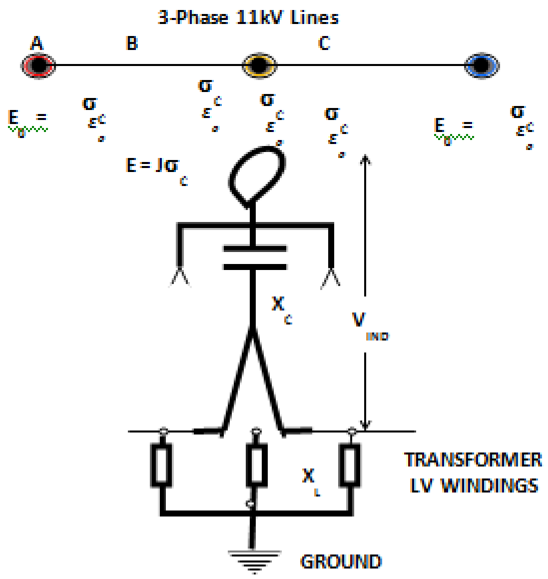

Fig 17: Capacitive Link to Ground through Victim.

From the diagram;

$$X_C = 1/j\omega C = 1/(2\pi fC)$$
$$= 1/(2\pi*50*125x10^{-9})$$
$$= 25{,}464.791\Omega$$

X_L is calculated from the transformer Impedance Voltage. Typical Impedance Voltage rating for a 0-630KVA Distribution Transformer is given by;

$$X_T\% = 4.0 – 4.5\%$$

We will assume $X_T\%=4.5\%=0.045pu$,for a 500KVA transformer

$$\Rightarrow X_T = (0.045 \text{ x (base kV)}^2)/(\text{base kVA x } 1000)$$
$$= (0.045*11^2)/(500*1000)$$
$$= 10.89 \text{ x } 10^{-6}\Omega$$

It is obvious from this evaluation that only the capacitive reactance is significant and the entire current flow to ground will be based on.

Therefore, if we assume of 6.072kV as before, Actual current passing through the body is given by;

This

$$I_{AC} = V_{IND} /X_C$$
$$= 6{,}072/25{,}464.791$$
$$= 0.2384A$$
$$= 238mA$$

From standard tables of electrocution effects, this results in Ventricular Fibrillation maximum Threshold and will tend towards Cardiac Standstill.

3. CONCLUSION

From the analysis conducted on this case-study and the results of our electromagnetic evaluations, it is here concluded that the lethality of electrocutions resulting from electromagnetic fields in electric power distribution systems are largely due to violation of approach limits within the electric field. It was established that the human structure in the vicinity of electromagnetic field transforms into a dielectric material (human dielectric), resulting into **significant electric field influence** that caused electrocutions.

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