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Application of Analytical Solutions to Typical Power Distribution Electromagnetic Field Incidents

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Abstract— It has been observed that majority of analytical solutions on the subject of electromagnetic field effect on humans and environment with regards to electric power system has been largely restricted to high-voltage transmission systems. Very few write-ups have been released on medium voltage distribution networks on this subject, yet a great number of fatalities recorded on this subject of electromagnetic field has occurred more on the medium voltage networks. Little or no attention have been paid to electromagnetic field effect when we ecountered problems at this voltage level, and for those who did just know that it is there but did not go further. It is the intetion of this paper to take a step further in establishing the fact that electromagnetic field, rather than direct contact has been largely responsible for most electrocution problems. A typical real-life case-study is addressed and technically analysed so as to establish the analytical and numerical parameters which point to electromagnetic field effect. Resistive and capacitive impedance parameters are used to establish this in the first instance, and classic analytical field solution using simple excel evaluation methods was applied at the second instance. The results in both instances prove the same point.

Index Terms— Capacitive Impedance, Current density, Electric field, Electrocution Current, Induced Voltage. Magnetic Field, Medium Voltage, Resistive impedance, Skin-contact**,** Use about four key words or phrases in alphabetical order, separated by commas.

◆

1 INTRODUCTION

Several interesting proposals and technical evaluations had been published by quite a number of authours on this subject in a bid to validate the age-long electromagnetic field theories but very few have endeavoured to address safety issues encountered in the power distribution industry on daily basis. Cases abound to show that several incidents occur in the power distribution sector to warrant critical review of some procedures and methodology of operation because lives are sacrificed on daily basis at the altar of distribution system operation and maintenance particularly in the underdeveloped countries. This is the object of this analysis.

2 WORKING IN ELECTROMAGNETIC FIELD ENVIRONMENT

Like the transmission lines electromagnetic fields produced by distribution network causes dangerous effects on human beings in close proximity. If the human bodies are projected to high levels of magnetic fields electric currents are produced within the body due to Electric and magnetic fields. Violating statutory clearances constitutes a major area of electromagnetic effects on field workers.

2.1 Work on Medium-voltage systems

Requirements for working *on* Medium Voltage 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.

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.

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).

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2.2 CASE-STUDY REPORT AND ANALYSIS: Two PHCN Employees Die From Electrocution in Lagos

The newspaper report: “Two Power Holding Company of Nigeria (PHCN) employees were electrocuted On Feb 11, 2016, at Kogberegbe Street, Isolo, Lagos. One of them had earlier gone on the pole to work before he got electrocuted…Two other employees were later invited to come and remove his body but sadly, another one got electrocuted too. How unfortunate.” See photographs of the electrocution in figure 18, 19 below.

2.2.1 APPRAISAL OF THE ELECTROCUTION SCENE

A close look at the picture above shows that the incident occurred on **a terminal pole in a distribution substation**. We can immediately gather from the press comments that necessary **critical safety procedures** must have been compromised or ignored. However, based on the configuration of the scene above, other **non-standard and peculiar safety issues** could have also arisen.

Several scenarios can be addressed going by the press reports and reference to the pictures in figures 1 and 2.

Figure 1: Photograph of Electrocuted victim

We will look at it from two perspectives as follows:

- Direct contact with or without PPE
- Contact through electromagnetic field induction

1. **Direct Contact with or without PPE**
   a) The 11KV line was already dead by the time the men climbed the pole
   b) Both men were fully kitted head-to-toe in their PPE
   c) Part of their bodies were between the HV terminals and the channel iron supporting both the lightening arresters and drop-out fuses/LV Lines.
   d) The men had direct contacts with the live lines **when power was restored**.

Figure 2: The Electrocution Pictures at the site in Lagos

Typical universally accepted of human resistance fault-path is shown in figure 3 below [26] and The skin’s resistance change as a function of the moisture present in its external and internal layers, with changes due to ambient temperatures, humidity, fright, anxiety etc with or without PPE is shown on table 1.

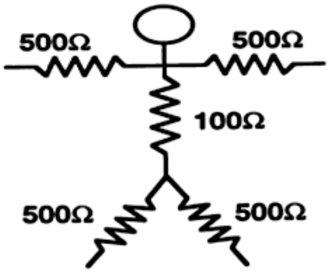


Figure 3: Example of Human Resistance Fault-paths

From provisions of figures 3 and table 1, we will now compute the impedance coupling network for various conditions of direct contact with energized 11KV Line assuming that resistances remain constant at these values for 1000V and above. These are reproduced in the resistance networks of figure 4, 5 and 6. In figure 5, we are assuming full hand contacts without the PPE, while in figure 6 with leather PPE.

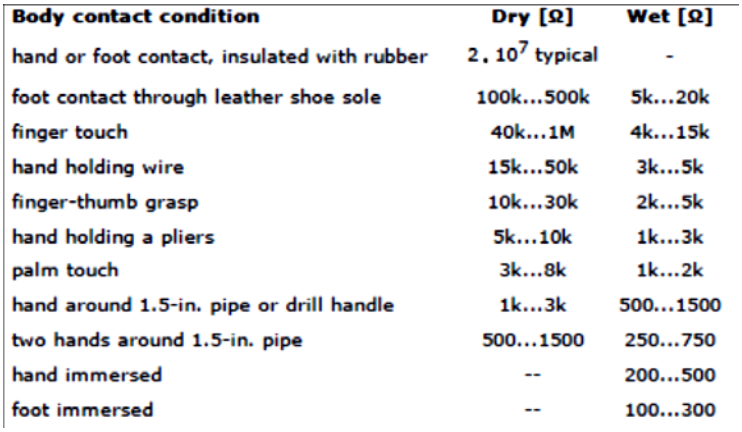
Using these values, we will now proceed to evaluate the resistances of an average human being that is directly linked to ground through the channel iron on the H-pole so as to ascertain the expected current values when the line is energized. We shall look at the implication of this development vis-à-vis what actually happened at site.

Without the PPE insulation;

$$R = (R_A)^2/2R_A + R_B + (R_L)^2/2R_L \qquad (1)$$

Where, R_a = Resistance of one arm, R_B = Internal body Resistance, R_L = Resistance of one leg

Table 1 Human Resistance Values for Various Skin contact Conditions, with or without PPE



Body contact condition	Dry [Ω]	Wet [Ω]
hand or foot contact, insulated with rubber	2, 10^7 typical	-
foot contact through leather shoe sole	100k…500k	5k…20k
finger touch	40k…1M	4k…15k
hand holding wire	15k…50k	3k…5k
finger-thumb grasp	10k…30k	2k…5k
hand holding a pliers	5k…10k	1k…3k
palm touch	3k…8k	1k…2k
hand around 1.5-in. pipe or drill handle	1k…3k	500…1500
two hands around 1.5-in. pipe	500…1500	250…750
hand immersed	--	200…500
foot immersed	--	100…300

With the PPE insulation;

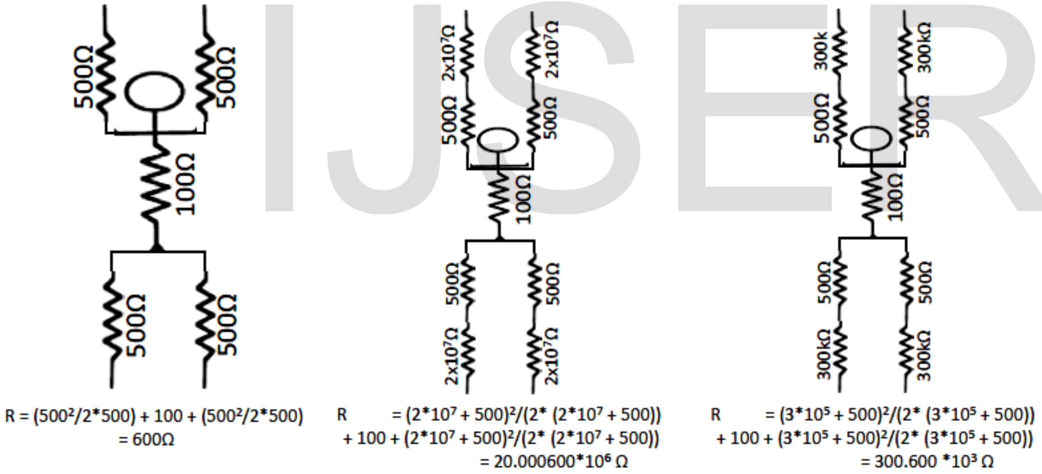
$$R = (R_{PP1} + R_A)^2/2(R_{PP1} + R_A) + R_B + (R_{PP2} + R_L)^2/2(R_{PP2} + R_L) \qquad (2)$$

R_{PP1} = Protective Hand-gloves, R_{PP2} = Safety Shoes

The PPE values were computed as shown in figure 4, based on the provisions of table 1.

We will make the following valid assumptions:

1. When direct-contact short circuit occurs, current is diverted to the path of lowest impedance or resistance, because it is proportional to the inverse of resistance.
2. Power source with lowest impedance is at lower potential with reference to other sources.



$R = (500^2/2{*}500) + 100 + (500^2/2{*}500) = 600\Omega$

$R = (2{*}10^7 + 500)^2/(2{*}(2{*}10^7 + 500)) + 100 + (2{*}10^7 + 500)^2/(2{*}(2{*}10^7 + 500)) = 20.000600{*}10^6\ \Omega$

$R = (3{*}10^5 + 500)^2/(2{*}(3{*}10^5 + 500)) + 100 + (3{*}10^5 + 500)^2/(2{*}(3{*}10^5 + 500)) = 300.600{*}10^3\ \Omega$

NO INSULATION

RUBBER SHOES & RUBBER HAND-GLOVE INSULATION

LEATHER SHOES & LEATHER HAND-GLOVE INSULATION

Figure 4: Evaluation of impedance networks for the various

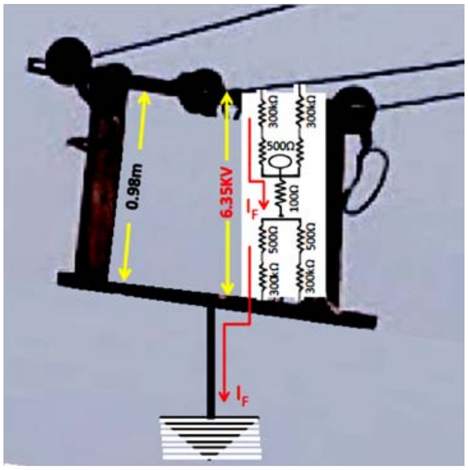


Figure 5: Direct Contact condition on bare hands and feet

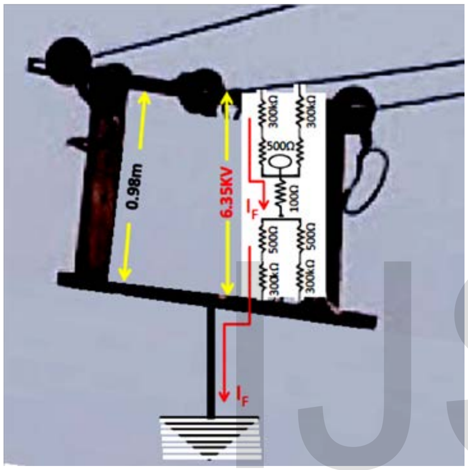


Figure 6: Direct Contact condition on leather PPE

3. If the short-circuit impedance is extremely low compared to other impedances in the faulted circuit, current flow in the short-circuit impedance supersedes, and the other circuit impedances are ignored.
4. The contact point of the victim is between the live-line and earthed channel iron.

Based on these assumptions, two basic conditions of the circuit are used for analysis as follows:

1. **Single-phase contact with phase-B with transformer in circuit:**

With this arrangement, all coupling capacitive impedances are ignored, and the equivalent network diagram with victim in circuit is shown in figure 7 below.

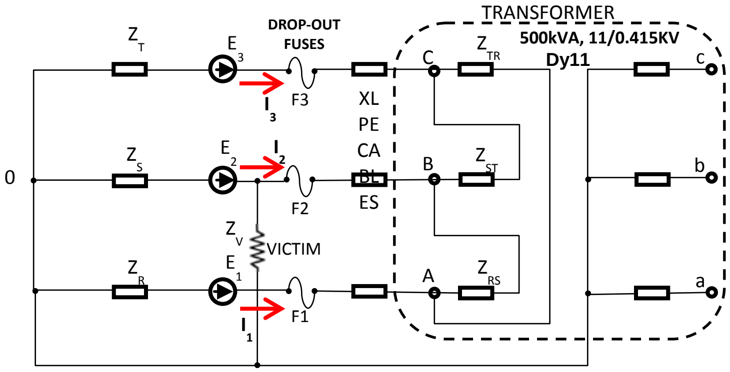


Figure 7: Equivalent Network Diagram of Distribution Substation

2. **Single-phase contact with phase-B and significantly high resistance:**

With this arrangement, it is an open-circuit where only the line and all coupling capacitive impedances are taken into consideration for the circuit analysis as illustrated in figures 8 and 9 below. Point P is the virtual ground of shunt capacitors and O is the Network Source ground.

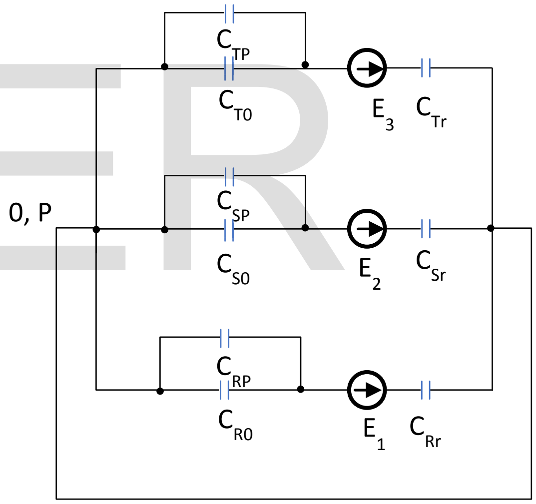


Figure 8: 11KV Open-circuit Capacitive Network

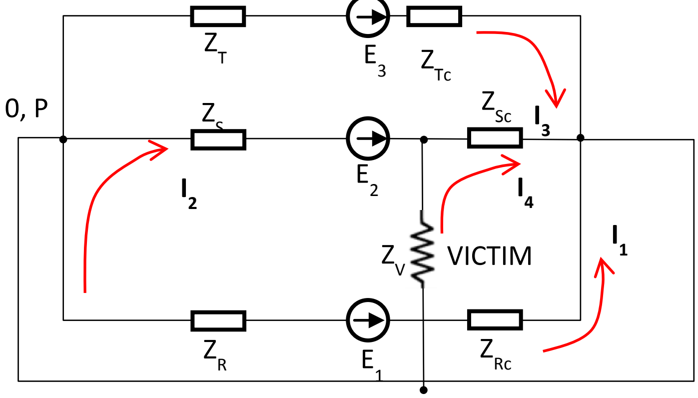
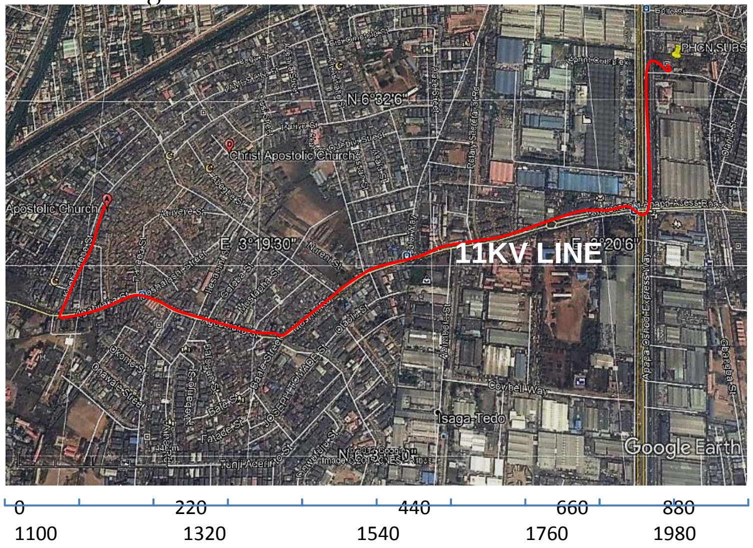


Figure 9: Equivalent 11kV Open-circuit Network

2.2.2 NETWORK ANALYSIS

We will start our analysis with the second condition of open circuit. The Google Map of the area in question is shown in figure 10.



5.1cm=440m, 32.21cm = (440/5.1)*32.21 = 2778.90m
= 2,779m or 2.779km

This impedance matrix for system obtained from mesh/loop analysis are shown in equations (4) below.

The loop for I_4 in figure 9 can be converted to I_2 loop as follows:

$$Z_{SC1} = Z_{SC}*Z_V/(Z_{SC} + Z_V) \qquad (3)$$

Using the Google Map of the area and the length of assumed 11KV line, the coupling capacitors and respective impedances are evaluated using the above data on excel worksheet of table 2 below and transformed into the various elements on the impedance matrix derived

$$\begin{pmatrix} E_1 \\ E_2 - E_1 \\ E_3 - E_2 \end{pmatrix} = \begin{pmatrix} (Z_R + Z_{Rc}) & + \quad 0 & + \quad 0 \\ -\,(Z_R + Z_{Rc}) & + (Z_c + Z_{sc1}) & + \quad 0 \\ 0 & -\,(Z_c + Z_{sc1}) & + (Z_T + Z_{Tc}) \end{pmatrix} \begin{pmatrix} I_1 \\ I_2 \\ I_3 \end{pmatrix} \qquad (4)$$

The HV line and load equivalent circuit for figure 7 is also shown in figure 11 after delta-star transformation of the
transformer HV Delta winding

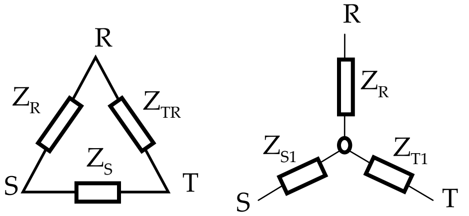


Figure 10: Delta-star Transformation of Transf. HV Wdg.

$$\left.\begin{aligned} Z_{R1} &= Z_{RS}\, Z_{TR}/\, (Z_{RS} + Z_{TR} + Z_{ST}) \\ Z_{S1} &= Z_{RS}\, Z_{ST}/\, (Z_{RS} + Z_{TR} + Z_{ST}) \\ Z_{T1} &= Z_{ST}\, Z_{TR}/\, (Z_{RS} + Z_{TR} + Z_{ST}) \end{aligned}\right\} \qquad (5)$$

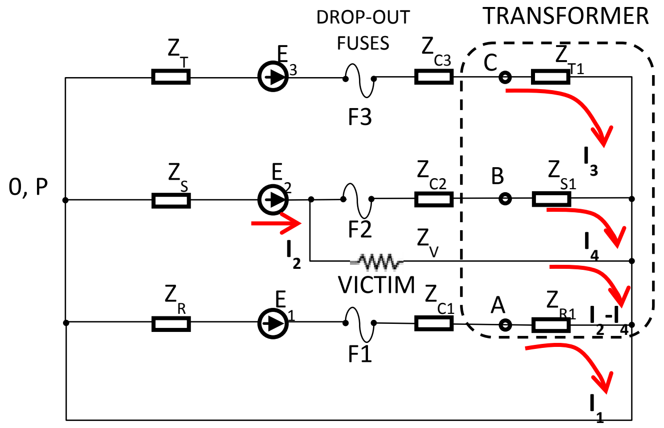


Figure 11: HV line and load equivalent circuit

The load circuit parameters are as follows:

<u>TRANSFORMER IMPEDANCE</u>:

If transformer impedance voltage = 4.5% or 0.045p.u., then;

$Z_{TR} = Z_{RS} = Z_{ST}$

$= Z_{PU}*(KV)^2/(kVA*1000)$

$= 0.045*(0.415)^2/(500*1000)$

$= 1.55 \times 10^{-8}\Omega$

<u>CABLE IMPEDANCE</u>:

For 11kV incoming Cable, it is usual to use $70mm^2$

$Z_C = 0.342 + j0.0967\ \Omega/km$

$Z = \sqrt{(0.342)^2 + (0.0967)^2}$

$= 0.355\ \Omega/km$

Usually, the length is about 15m

$\therefore Z = 0.355*0.015 = 0.005325\Omega$

The equivalent circuit of figure 11 is further simplified to the diagram of figure 12 for analysis based on the following simplifications:

- Load impedance is the combination of cable and transformer impedances.
- The yellow phase total load impedance is the parallel combination of that of victim and cable/transformer.

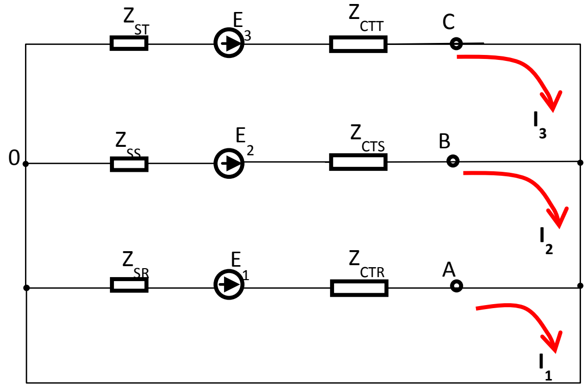


Figure 12: Transformed Impedance Network for Mesh-Current Analysis

$$E_1 = I_1\,(Z_{SR} + Z_{C1} + Z_{R1})$$

$$E_2 - E_1 = I_2(Z_{SS} + Z_{CTS}) - I_1(Z_{SR} + Z_{C1} + Z_{R1})$$

$$E_3 - E_2 = I_3(Z_{ST} + Z_{C3} + Z_{T1}) - I_2(Z_{SS} + Z_{CTS})$$

Let, $Z_{C1} + Z_{R1} = Z_{CTR}$; $(Z_{C2} + Z_{S1})^* Z_V/(Z_{C2} + Z_{S1} + Z_V) = Z_{CTS}$;

$$Z_{C3} + Z_{T1} = Z_{CTT}$$

$$\begin{pmatrix} E_1 \\ E_2 - E_1 \\ E_3 - E_2 \end{pmatrix} \begin{matrix} = \\ = \\ = \end{matrix} \begin{pmatrix} (Z_{SR} + Z_{CTR}) + 0 + 0 + 0 \\ -(Z_{SR} + Z_{CTR}) + (Z_{SS} + Z_{CTS}) \ + 0 \\ 0 \ -(Z_{SS} + Z_{CTS}) + (Z_{ST} + Z_{TT}) \end{pmatrix} \begin{pmatrix} I_1 \\ I_2 \\ I_3 \end{pmatrix} \qquad (6)$$

With the condition of victim integrated into the system, the network is analysed with the diagram of figure 13.

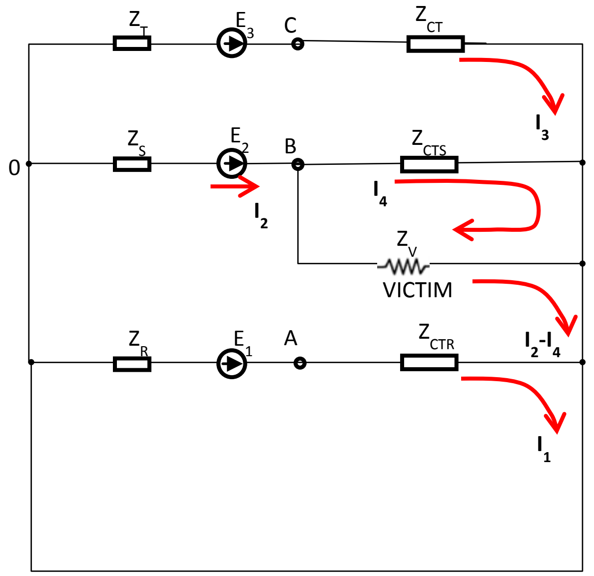


Figure 13: Impedance Network with Victim in Circuit

The corresponding network is given in equation (7) below.

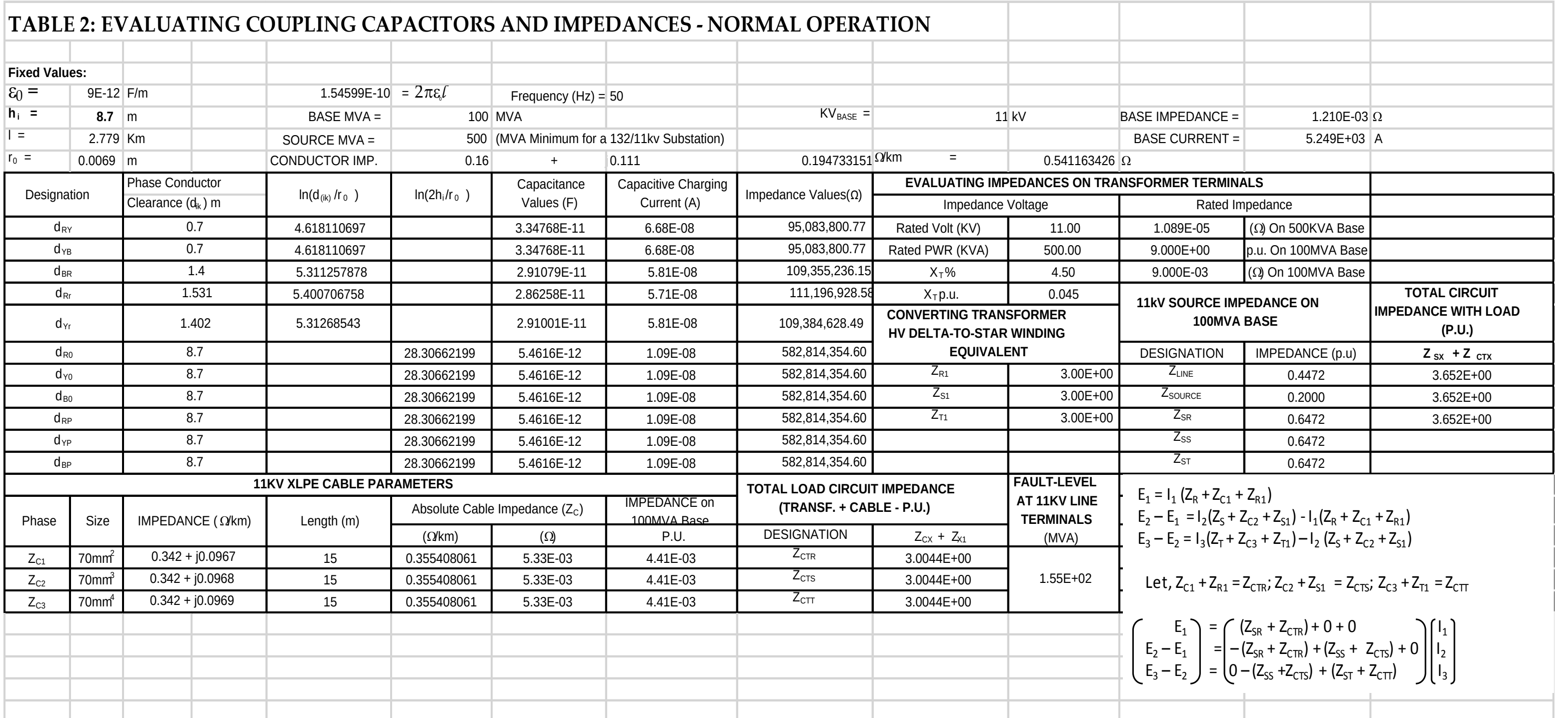


TABLE 2: EVALUATING COUPLING CAPACITORS AND IMPEDANCES - NORMAL OPERATION

Fixed Values:

ε_0 =	9E-12	F/m	1.54599E-10	$= 2\pi\varepsilon_0 l$	Frequency (Hz) =	50			
h_i =	**8.7**	m	BASE MVA =	100	MVA		KV_{BASE} =	11	kV
l =	2.779	Km	SOURCE MVA =	500	(MVA Minimum for a 132/11kv Substation)				
r_0 =	0.0069	m	CONDUCTOR IMP.	0.16	+	0.111	0.194733151 Ω/km	=	0.541163426 Ω

BASE IMPEDANCE = 1.210E-03 Ω

BASE CURRENT = 5.249E+03 A

Designation	Phase Conductor Clearance (d_{ik}) m	ln($d_{(ik)}/r_0$)	ln($2h_i/r_0$)	Capacitance Values (F)	Capacitive Charging Current (A)	Impedance Values(Ω)
d_{RY}	0.7	4.618110697		3.34768E-11	6.68E-08	95,083,800.77
d_{YB}	0.7	4.618110697		3.34768E-11	6.68E-08	95,083,800.77
d_{BR}	1.4	5.311257878		2.91079E-11	5.81E-08	109,355,236.15
d_{Rr}	1.531	5.400706758		2.86258E-11	5.71E-08	111,196,928.58
d_{Yr}	1.402	5.31268543		2.91001E-11	5.81E-08	109,384,628.49
d_{R0}	8.7		28.30662199	5.4616E-12	1.09E-08	582,814,354.60
d_{Y0}	8.7		28.30662199	5.4616E-12	1.09E-08	582,814,354.60
d_{B0}	8.7		28.30662199	5.4616E-12	1.09E-08	582,814,354.60
d_{RP}	8.7		28.30662199	5.4616E-12	1.09E-08	582,814,354.60
d_{YP}	8.7		28.30662199	5.4616E-12	1.09E-08	582,814,354.60
d_{BP}	8.7		28.30662199	5.4616E-12	1.09E-08	582,814,354.60

EVALUATING IMPEDANCES ON TRANSFORMER TERMINALS

Impedance Voltage		Rated Impedance	
Rated Volt (KV)	11.00	1.089E-05	(Ω) On 500KVA Base
Rated PWR (KVA)	500.00	9.000E+00	p.u. On 100MVA Base
X_T%	4.50	9.000E-03	(Ω) On 100MVA Base
X_T p.u.	0.045		

CONVERTING TRANSFORMER HV DELTA-TO-STAR WINDING EQUIVALENT

Z_{R1}	3.00E+00
Z_{S1}	3.00E+00
Z_{T1}	3.00E+00

11kV SOURCE IMPEDANCE ON 100MVA BASE		**TOTAL CIRCUIT IMPEDANCE WITH LOAD (P.U.)**
DESIGNATION	IMPEDANCE (p.u)	**$Z_{SX} + Z_{CTX}$**
Z_{LINE}	0.4472	3.652E+00
Z_{SOURCE}	0.2000	3.652E+00
Z_{SR}	0.6472	3.652E+00
Z_{SS}	0.6472	
Z_{ST}	0.6472	

11KV XLPE CABLE PARAMETERS

Phase	Size	IMPEDANCE (Ω/km)	Length (m)	Absolute Cable Impedance (Z_C)		IMPEDANCE on 100MVA Base
				(Ω/km)	(Ω)	P.U.
Z_{C1}	$70mm^2$	0.342 + j0.0967	15	0.355408061	5.33E-03	4.41E-03
Z_{C2}	$70mm^3$	0.342 + j0.0968	15	0.355408061	5.33E-03	4.41E-03
Z_{C3}	$70mm^4$	0.342 + j0.0969	15	0.355408061	5.33E-03	4.41E-03

TOTAL LOAD CIRCUIT IMPEDANCE (TRANSF. + CABLE - P.U.)		**FAULT-LEVEL AT 11KV LINE TERMINALS** (MVA)
DESIGNATION	$Z_{CX} + Z_{X1}$	
Z_{CTR}	3.0044E+00	1.55E+02
Z_{CTS}	3.0044E+00	
Z_{CTT}	3.0044E+00	

$$E_1 = I_1 (Z_R + Z_{C1} + Z_{R1})$$
$$E_2 - E_1 = I_2(Z_S + Z_{C2} + Z_{S1}) - I_1(Z_R + Z_{C1} + Z_{R1})$$
$$E_3 - E_2 = I_3(Z_T + Z_{C3} + Z_{T1}) - I_2 (Z_S + Z_{C2} + Z_{S1})$$

Let, $Z_{C1} + Z_{R1} = Z_{CTR}$; $Z_{C2} + Z_{S1} = Z_{CTS}$; $Z_{C3} + Z_{T1} = Z_{CTT}$

$$\begin{pmatrix} E_1 \\ E_2 - E_1 \\ E_3 - E_2 \end{pmatrix} \begin{matrix} = \\ = \\ = \end{matrix} \begin{pmatrix} (Z_{SR} + Z_{CTR}) + 0 + 0 \\ -(Z_{SR} + Z_{CTR}) + (Z_{SS} + Z_{CTS}) + 0 \\ 0 - (Z_{SS} + Z_{CTS}) + (Z_{ST} + Z_{CTT}) \end{pmatrix} \begin{pmatrix} I_1 \\ I_2 \\ I_3 \end{pmatrix}$$

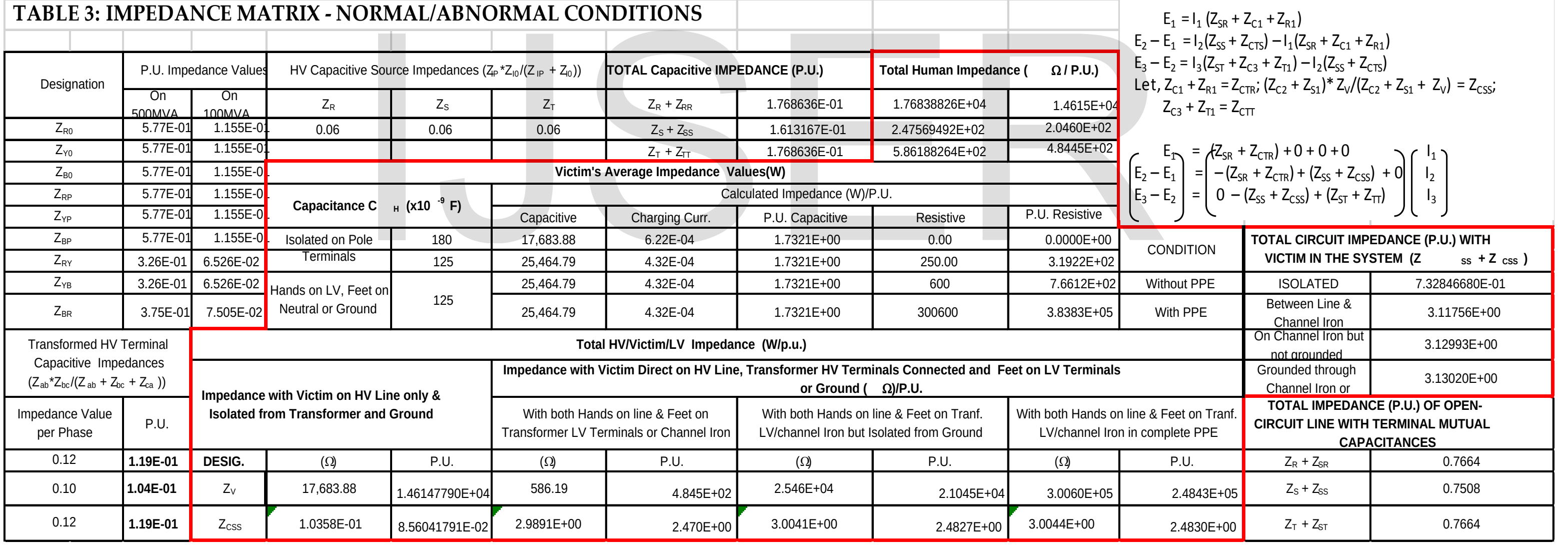


TABLE 3: IMPEDANCE MATRIX - NORMAL/ABNORMAL CONDITIONS

Designation	P.U. Impedance Values	
	On 500MVA	On 100MVA
Z_{R0}	5.77E-01	1.155E-01
Z_{Y0}	5.77E-01	1.155E-01
Z_{B0}	5.77E-01	1.155E-01
Z_{RP}	5.77E-01	1.155E-01
Z_{YP}	5.77E-01	1.155E-01
Z_{BP}	5.77E-01	1.155E-01
Z_{RY}	3.26E-01	6.526E-02
Z_{YB}	3.26E-01	6.526E-02
Z_{BR}	3.75E-01	7.505E-02

HV Capacitive Source Impedances ($Z_{IP}*Z_{I0}/(Z_{IP} + Z_{I0})$)		
Z_R	Z_S	Z_T
0.06	0.06	0.06

TOTAL Capacitive IMPEDANCE (P.U.)		**Total Human Impedance (Ω / P.U.)**	
$Z_R + Z_{RR}$	1.768636E-01	1.76838826E+04	1.4615E+04
$Z_S + Z_{SS}$	1.613167E-01	2.47569492E+02	2.0460E+02
$Z_T + Z_{TT}$	1.768636E-01	5.86188264E+02	4.8445E+02

$$E_1 = I_1 (Z_{SR} + Z_{C1} + Z_{R1})$$
$$E_2 - E_1 = I_2(Z_{SS} + Z_{CTS}) - I_1(Z_{SR} + Z_{C1} + Z_{R1})$$
$$E_3 - E_2 = I_3(Z_{ST} + Z_{C3} + Z_{T1}) - I_2(Z_{SS} + Z_{CTS})$$

Let, $Z_{C1} + Z_{R1} = Z_{CTR}$; $(Z_{C2} + Z_{S1}) * Z_V/(Z_{C2} + Z_{S1} + Z_V) = Z_{CSS}$;
$Z_{C3} + Z_{T1} = Z_{CTT}$

$$\begin{pmatrix} E_1 \\ E_2 - E_1 \\ E_3 - E_2 \end{pmatrix} \begin{matrix} = \\ = \\ = \end{matrix} \begin{pmatrix} (Z_{SR} + Z_{CTR}) + 0 + 0 + 0 \\ -(Z_{SR} + Z_{CTR}) + (Z_{SS} + Z_{CSS}) + 0 \\ 0 - (Z_{SS} + Z_{CSS}) + (Z_{ST} + Z_{TT}) \end{pmatrix} \begin{pmatrix} I_1 \\ I_2 \\ I_3 \end{pmatrix}$$

Victim's Average Impedance Values(W)

Capacitance C_H ($x10^{-9}$ F)		Calculated Impedance (W)/P.U.					
		Capacitive	Charging Curr.	P.U. Capacitive	Resistive	P.U. Resistive	CONDITION
Isolated on Pole Terminals	180	17,683.88	6.22E-04	1.7321E+00	0.00	0.0000E+00	
	125	25,464.79	4.32E-04	1.7321E+00	250.00	3.1922E+02	
Hands on LV, Feet on Neutral or Ground	125	25,464.79	4.32E-04	1.7321E+00	600	7.6612E+02	Without PPE
		25,464.79	4.32E-04	1.7321E+00	300600	3.8383E+05	With PPE

TOTAL CIRCUIT IMPEDANCE (P.U.) WITH VICTIM IN THE SYSTEM ($Z_{SS} + Z_{CSS}$)	
ISOLATED	7.32846680E-01
Between Line & Channel Iron	3.11756E+00
On Channel Iron but not grounded	3.12993E+00
Grounded through Channel Iron or	3.13020E+00

Transformed HV Terminal Capacitive Impedances ($Z_{ab}*Z_{bc}/(Z_{ab} + Z_{bc} + Z_{ca})$)	
Impedance Value per Phase	P.U.
0.12	**1.19E-01**
0.10	**1.04E-01**
0.12	**1.19E-01**

Total HV/Victim/LV Impedance (W/p.u.)

Impedance with Victim on HV Line only & Isolated from Transformer and Ground			**Impedance with Victim Direct on HV Line, Transformer HV Terminals Connected and Feet on LV Terminals or Ground (Ω)/P.U.**					
			With both Hands on line & Feet on Transformer LV Terminals or Channel Iron		With both Hands on line & Feet on Tranf. LV/channel Iron but Isolated from Ground		With both Hands on line & Feet on Tranf. LV/channel Iron in complete PPE	
DESIG.	(Ω)	P.U.	(Ω)	P.U.	(Ω)	P.U.	(Ω)	P.U.
Z_V	17,683.88	1.46147790E+04	586.19	4.845E+02	2.546E+04	2.1045E+04	3.0060E+05	2.4843E+05
Z_{CSS}	1.0358E-01	8.56041791E-02	2.9891E+00	2.470E+00	3.0041E+00	2.4827E+00	3.0044E+00	2.4830E+00

TOTAL IMPEDANCE (P.U.) OF OPEN-CIRCUIT LINE WITH TERMINAL MUTUAL CAPACITANCES	
$Z_R + Z_{SR}$	0.7664
$Z_S + Z_{SS}$	0.7508
$Z_T + Z_{ST}$	0.7664

$$E_1 = I_1 (Z_R + Z_{CTR})$$
$$E_2 - E_1 = I_2(Z_S + Z_V) - I_4 Z_V - I_1 (Z_R + Z_{CTR})$$
$$E_3 - E_2 = I_3(Z_T + Z_{CTT} + Z_{CTS}) - I_4 (Z_{CTS})$$
$$0 = I_4 (Z_V + Z_{CTS}) - I_2(Z_V) - I_3(Z_{CTS})$$

$$\begin{pmatrix} E_1 \\ E_2 - E_1 \\ E_3 - E_2 \\ 0 \end{pmatrix} \begin{matrix} = \\ = \\ = \\ = \end{matrix} \begin{pmatrix} (Z_R + Z_{CTR}) + 0 + 0 + 0 \\ -(Z_R + Z_{CTR}) + (Z_S + Z_V) + 0 - Z_V \\ 0 + 0 + (Z_T + Z_{TT} + Z_{CTS}) - Z_{CTS} \\ 0 + - Z_V - Z_{CTS} + (Z_V + Z_{CTS}) \end{pmatrix} \begin{pmatrix} I_1 \\ I_2 \\ I_3 \\ I_4 \end{pmatrix} \qquad (7)$$

2.2.3 RESULT EVALUATION

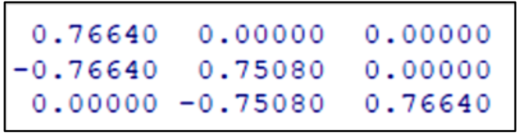
We will start our analysis by evaluating the set of results from normal operation. We will establish short-circuit currents for the various conditions evaluated, using the base current from table 2 above.

From table 2; **I_{BASE} = 5.25x10³A**

Table 4 shows calculated open circuit line parameters with terminal mutual capacitance, ignoring shunt capacitances.

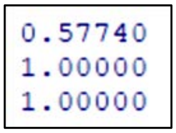
Table 4: Results of Open-circuit Analysis

Input Matrix A:



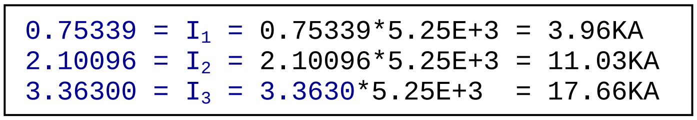
```
 0.76640  0.00000  0.00000
-0.76640  0.75080  0.00000
 0.00000 -0.75080  0.76640
```

Input Matrix B



```
0.57740
1.00000
1.00000
```

Solution A*X=B

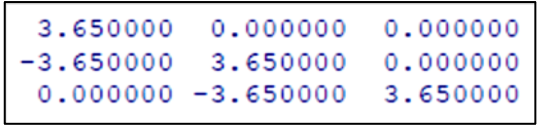


```
0.75339 = I1 = 0.75339*5.25E+3 = 3.96KA
2.10096 = I2 = 2.10096*5.25E+3 = 11.03KA
3.36300 = I3 = 3.3630*5.25E+3  = 17.66KA
```

Table 5 shows the parameters with transformer connected.

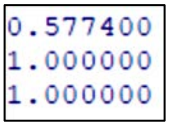
Table 5: Results with transformer load

Input Matrix A:



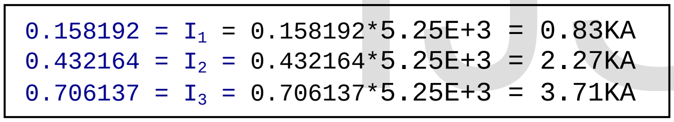
```
 3.650000  0.000000  0.000000
-3.650000  3.650000  0.000000
 0.000000 -3.650000  3.650000
```

Input Matrix B



```
0.577400
1.000000
1.000000
```

Solution A*X=B



```
0.158192 = I1 = 0.158192*5.25E+3 = 0.83KA
0.432164 = I2 = 0.432164*5.25E+3 = 2.27KA
0.706137 = I3 = 0.706137*5.25E+3 = 3.71KA
```

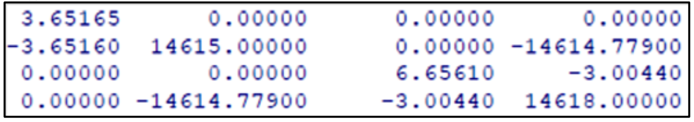
We now want to establish here the implications of various direct contact possibilities of electrocuted victim. We will investigate two boundary conditions as follows:

1. Case of victim completely isolated from ground, and
2. Victim grounded through the channel iron

Going by direct contact analysis only, the following results were obtained using online computer matrix simulations:

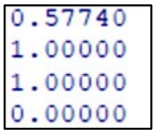
Table 6: Results with Victim in contact with line but isolated from ground

Input Matrix A:



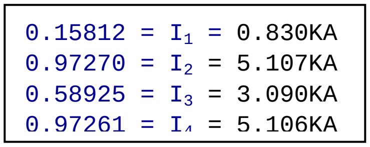
```
 3.65165       0.00000      0.00000       0.00000
-3.65160   14615.00000      0.00000  -14614.77900
 0.00000       0.00000      6.65610      -3.00440
 0.00000  -14614.77900     -3.00440   14618.00000
```

Input Matrix B



```
0.57740
1.00000
1.00000
0.00000
```

Solution A*X=B



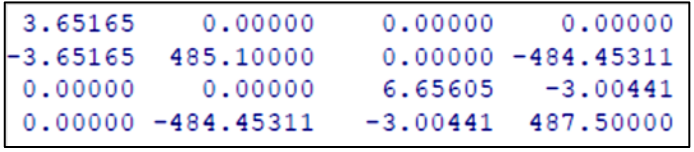
```
0.15812 = I1 = 0.830KA
0.97270 = I2 = 5.107KA
0.58925 = I3 = 3.090KA
0.97261 = I4 = 5.106KA
```

From table 6 and figure 13, it can be seen here that the current through the victim is given by:

$$I_V = I_2 - I_4 = (0.97270 - 0.97261) = 0.00009*I_{BASE}\ (A)$$
$$= 0.00009*5.25E+3 = 0.4725A$$

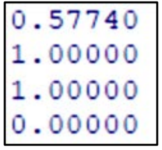
Table 7: Results with Victim in contact with line and Grounded through channel iron

Input Matrix A:



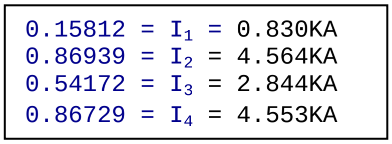
```
 3.65165     0.00000     0.00000     0.00000
-3.65165   485.10000     0.00000  -484.45311
 0.00000     0.00000     6.65605    -3.00441
 0.00000  -484.45311    -3.00441   487.50000
```

Input Matrix B



```
0.57740
1.00000
1.00000
0.00000
```

Solution A*X=B



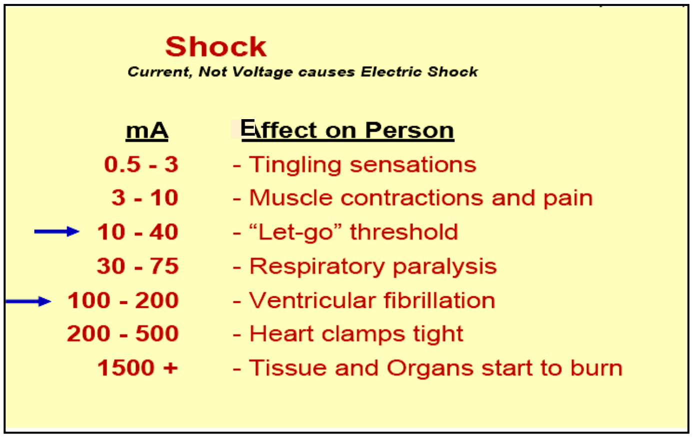
```
0.15812 = I1 = 0.830KA
0.86939 = I2 = 4.564KA
0.54172 = I3 = 2.844KA
0.86729 = I4 = 4.553KA
```

From table 7 and figure 13, it can be seen here that the current through the victim is given by:

$$I_V = I_2 - I_4 = (0.86939 - 0.86729) = 0.0021*I_{BASE}\ (A)$$
$$= 0.0021*5.25E+3 = 11.025A$$

From the above analysis, it is obvious that direct contact with the line could not have been the cause of electrocution but capacitive effect. This is because the magnitude of current on direct contact as indicated in table 8 [26] is far above what can result to an Arc-flash or Arc-blast, but the picture of scene of accident in figures 1 & 2 does not suggest this. At this point, there is total insulation breakdown that could result to Arc-flash, Arc-blast or flash-burns. **There is no evidence of this from the picture**.

Table 8: Electrocution Current Effect on Humans



Shock

Current, Not Voltage causes Electric Shock

mA	Effect on Person
0.5 - 3	- Tingling sensations
3 - 10	- Muscle contractions and pain
→ 10 - 40	- "Let-go" threshold
30 - 75	- Respiratory paralysis
→ 100 - 200	- Ventricular fibrillation
200 - 500	- Heart clamps tight
1500 +	- Tissue and Organs start to burn

Calculations for the various possible interactions are given in table 9 below.

Conditions 1 to 3 above assumes that the Victim has no PPE on such that conditions 1 and 2 would be largely due to shunt capacitors, and condition 3 implies that the victim could have been 'roasted' on line.

Table 9: Short-circuit Currents and Fault Levels

I_{BASE}(Amps) = 5.25E+03		V_{BASE} (kV) = 11	
NETWORK CONDITION	**CALCULATED S-C CURRENT (P.U.)**	**ACTUAL CURRENT VALUE (AMPS)**	**FAULT-LEVEL (MVA)**
Open-circuit Line with terminal Capacitance	0.75339	3.955E+03	6.218E+02
	2.10096	1.103E+04	
	3.363	1.765E+04	
Network with Transformer Load	0.158192	8.303E+02	1.297E+02
	0.432164	2.268E+03	
	0.706137	3.707E+03	
Victim completely Isolated from Ground	0.15812	8.300E+02	1.720E+02
	0.9727	5.106E+03	
	0.58925	3.093E+03	
	0.97261	5.105E+03	
Victim on Channel Iron but Isolated from Ground	0.15812	8.300E+02	6.728E+01
	0.25108	1.318E+03	
	0.26356	1.383E+03	
	0.25106	1.318E+03	
Victim between Line & Grounded Channel Iron	0.15812	8.300E+02	1.569E+02
	0.86939	4.563E+03	
	0.54172	2.843E+03	
	0.86729	4.552E+03	
Victim in complete PPE	0.15812	8.300E+02	2.600E+01
	-0.03333	-1.749E+02	
	0.13519	7.096E+02	
	-0.03334	-1.750E+02	

It can be concluded from table 9 that the highest Fault Level at a particular location occurs in an open-circuited line and it is due largely to Terminal Mutual Capacitance of the line. With transformer load, the fault-level drops to about 20% of the open-circuit value.

The electrocution currents for the various possible conditions of the victim in table 9 are tabulated in table 10 below.

Table 10: Evaluating Electrocution Currents

I_{BASE}(Amps) = 5.25E+03		V_{BASE} (kV) = 11	
NETWORK CONDITION	**CALCULATED S-C CURRENT (P.U.)**	**ELECTROCUTION CURRENT (P.U.)**	**ELECTROCUTION CURRENT (AMPS)**
Victim completely Isolated from Ground	0.15812	9.000E-05	4.724E-01
	0.9727		
	0.58925		
	0.97261		
Victim on Channel Iron but Isolated from Ground	0.15812	2.000E-05	1.050E-01
	0.25108		
	0.26356		
	0.25106		
Victim between Line & Grounded Channel Iron	0.15812	2.100E-03	1.102E+01
	0.86939		
	0.54172		
	0.86729		
Victim in complete PPE	0.15812	1.000E-05	5.249E-02
	-0.03333		
	0.13519		
	-0.03334		

Condition 4 is the realistic case of this victim on direct contact. From table 8 above shows that 52mA could only result in respiratory paralysis which may not lead to lethality if not sustained.

2.1.1 ELECTROMAGNETIC FIELD EFFECT

From the above analysis, it is obvious we turn our attention to the electromagnetic field effect. When a conducting or semi-conducting body mass comes between the air-gap of capacitive vacuum between the High Voltage line and ground, to the extent of violating the approach limit, a new link of impedance network is established to re-define the current path or voltage drop between the line and ground. **This could be electrostatic or/and magnetic in nature**, giving rise to a conductive path other than resistive into the human body.

More than 99% of the body's resistance to electric current flow is at the skin. **The skin acts like an electrical device such as a capacitor** in that it allows more current to flow if a voltage is changing rapidly. A calloused, dry hand may have more than 100,000 Ω because of a thick outer layer of dead cells in the ***stratum corneum***. However, like the capacitor, the skin resistance can be effectively bypassed if there is skin **breakdown from high voltage**, a cut, a deep abrasion, or immersion in water. At 500 V or more, high resistance in the outer layer of the skin breaks down. This lowers the body's resistance to current flow greatly. The result is an increase in the amount of current that flows with any given voltage.

It should be noted that Magnetic field induces a voltage in the tissue of human body, which causes a current to flow through it due to its conductivity. The physical interaction of time-varying magnetic fields with the human body results in induced electric fields and circulating electric currents**.**

From the picture of the electrocution, it is obvious that the portion of the first victim that is exposed to the surrounding electric field is the head region, but even the PPE poses no barrier to the magnetic field. The electromagnetic interactions are as illustrated in figure 14, 15 below.

Current density estimation at the head region will be considered by using magnetic field model assuming that the body has a homogenous and isotropic conductivity and current path is circular. The electromagnetic field evaluation proceeds as earlier applied.

Geometry of the power line and observation point above the ground is presented in the Figure 16 below.

The line consists of Three equal and parallel conductors to the ground stretched conductor images. Wires of the line have linear charge densities $-\lambda_i$ (i = A, B, C). We assume that wires are straight and perform the analysis for line arranged in the height h equal to distance to the ground to the point of the real wires maximal sag.

Figure 14: Production of Electric Field and resulting Current

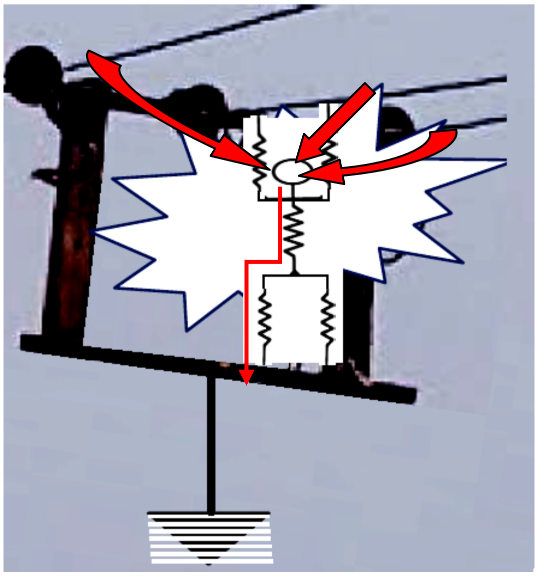


Figure 15: Victim engulfed by surrounding electromagnetic Field.

If the distance of the three-phase conductors from the earth's surface is the same and equal to h, then the distance from the images will approximately be $h'=h$. Height of the observation point V is y m. We assume that the ground is plane and smooth. The linear charge density images of any line have the same values and opposite signs: $\tau'_A = -\tau_A$, $\tau'_B = -\tau_B$, $\tau'_C = -\tau_C$ ($\tau_i = I*\lambda_i$).

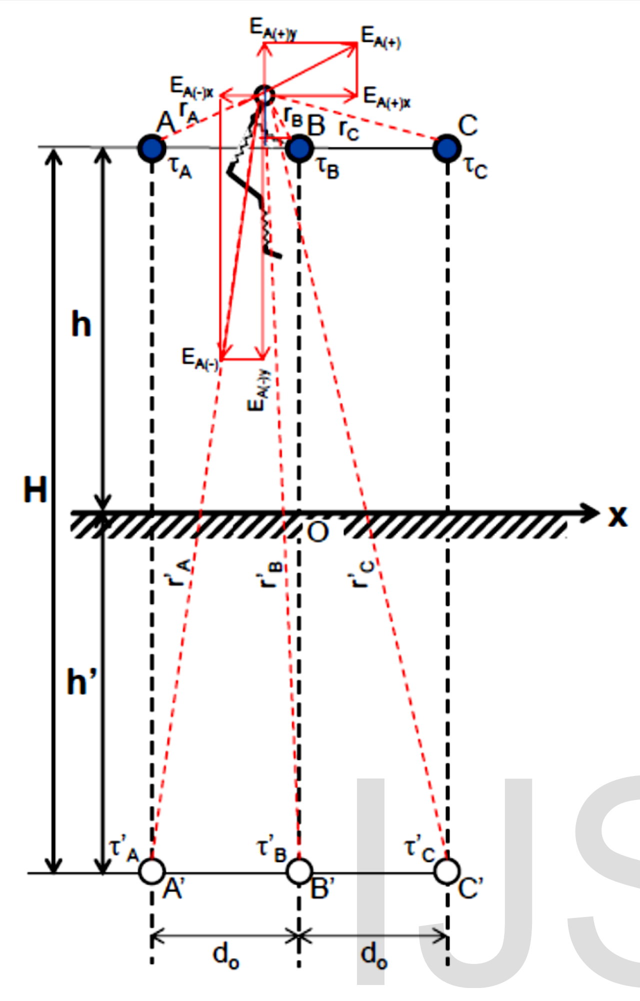
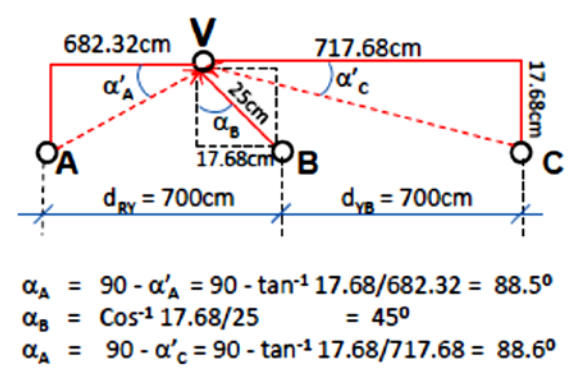


Figure 16a: Components of the electric field strength generated on the Victim



$\alpha_A = 90 - \alpha'_A = 90 - \tan^{-1} 17.68/682.32 = 88.5^0$
$\alpha_B = \cos^{-1} 17.68/25 = 45^0$
$\alpha_A = 90 - \alpha'_C = 90 - \tan^{-1} 17.68/717.68 = 88.6^0$

Figure 16b: Geometric Resolution of the electric field strength

Resolving the geometric components

$$\left.\begin{array}{l} r_A = (X_A^2 + Y^2)^{1/2},\ r_B = (X_B^2 + Y^2)^{1/2}, \\ r_C = (X_C^2 + Y^2)^{1/2} \\ r'_A = (X_A^2 + (H+Y)^2)^{1/2},\ r'_B = (X_B^2 + (H+Y)^2)^{1/2}, \\ r_C = (X_C^2 + (H+Y)^2)^{1/2} \\ \textbf{(where, } \mathbf{Y_A = Y_B = Y_C = Y}\textbf{)} \end{array}\right\} \quad (8)$$

$$\left.\begin{array}{l} r_A = ((d_o - d_v)^2 + Y^2)^{1/2},\ r_B = (d_v^2 + Y^2)^{1/2}, \\ r_C = ((d_o + d_v)^2 + Y^2)^{1/2} \\ r'_A = ((d_o - d_v)^2 + (H+Y)^2)^{1/2}, \\ r'_B = (d_v^2 + (H+Y)^2)^{1/2}, \\ r'_C = ((d_o + d_v)^2 + (H+Y)^2)^{1/2} \end{array}\right\} \quad (9)$$

According to WikiAnswers (http://www.answers.com/Q/) **the minimum distance from the eye at which an object appears to be distinct** or least distance of distinct vision (LDDV) or the reference seeing distance (RSD) or near point is about **25cm** from the eye. If this occurs at angle 45^0 and for the victim to be in a comfortable working position, two-thirds of his body trunk must be below the line of vision. It means the vertical height from the eye to the point of action is about one-third (0.33) of the victim's height.

From our figure 1& 2 we can estimate that the victim is about 1.5m tall, and if the gap between the D-fitting Channel Iron and the Terminal Pole Cross-arm is about 0.98m (as generally obtainable in Nigeria), then the vertical height from the eye to the point of action is given by;

h_V = 1.5 – 0.98 = 0.52m
= 0.52/1.5 = 0.35

This agrees with our assumption of **0.33 above.

This also establishes the dimensions for our geometric components as derived above and it is used for field evaluations in the excel format of table 11 below.

The following field equations are now adopted from equation (1) and (2) to calculate the magnetic and electric fields

$$B_x = \sum_{j=1}^{n} \frac{\mu_0 * I_j * y_j}{2\pi\,(x_j^2 + y_j^2)} \quad (10)$$

$$B_y = \sum_{j=1}^{n} \frac{\mu_0 * I_j * x_j}{2\pi\,(x_j^2 + y_j^2)} \quad (11)$$

$$Magnetic\ Field\ |B| = \sqrt{|B_x|^2 + |B_y|^2} \quad (12)$$

The horizontal and vertical electric field is given by;

$$\begin{cases} E_{hi} = \dfrac{Q_i}{2\pi\varepsilon_0}(x-x_i)\left[\dfrac{1}{(D_i)^2} - \dfrac{1}{(D_i^{'})^2}\right] \\ E_{vi} = \dfrac{Q_i}{2\pi\varepsilon_0}\left[\dfrac{(y-y_i)}{(D_i)^2} - \dfrac{(y+y_i)}{(D_i^{'})^2}\right] \end{cases}$$

from eqn. (1)

Our magnetic field evaluation is composed as follows:

$$\left.\begin{array}{l} B_{XA} = (kI_0/r_A)\sin\alpha_A\ ,\ B_{YA} = (kI_0/r_A)\cos\alpha_A \\ B_{XB} = (kI_0/r_B)\sin\alpha_B\ ,\ B_{YB} = (kI_0/r_B)\cos\alpha_B \\ B_{XC} = (kI_0/r_C)\sin\alpha_C\ ,\ B_{YC} = (kI_0/r_C)\cos\alpha_C \end{array}\right\} \quad (13)$$

Where, $k = \mu_0/2\pi$

The Electric Field components are given as follows:

Equation (14)

$E_{XA} = 2k\lambda(((d_o - d_v)/((d_o - d_v)^2 + y^2)) - ((d_o - d_v)/((d_o - d_v)^2 + (y+H)^2)))$

$E_{XB} = 2k\lambda((d_v/(d_v^2 + y^2)) - (d_v/(d_v^2 + (y+H)^2)))$

$E_{XC} = 2k\lambda((d_o + d_v)/((d_o + d_v)^2 + y^2)) - ((d_o + d_v)/((d_o + d_v)^2 + (y+H)^2)))$

Equation (15)

$E_{YA} = 2k\lambda((y/((d_o - d_v)^2 + y^2)) - ((y+H)/((d_o - d_v)^2 + (y+H)^2)))$

$E_{YB} = 2k\lambda((y/(d_v^2 + y^2)) - ((y+H)/(d_v^2 + (y+H)^2)))$

$E_{YC} = 2k\lambda(y/((d_o + d_v)^2 + y^2)) - ((y+H)/((d_o + d_v)^2 + (y+H)^2)))$

Where, $k = 1/4\pi\varepsilon_0$

Therefore, we now need to resolve each current into vertical and horizontal in-phase and an out-of-phase components and use them for our field evaluations as indicated in the excel format of table 11.

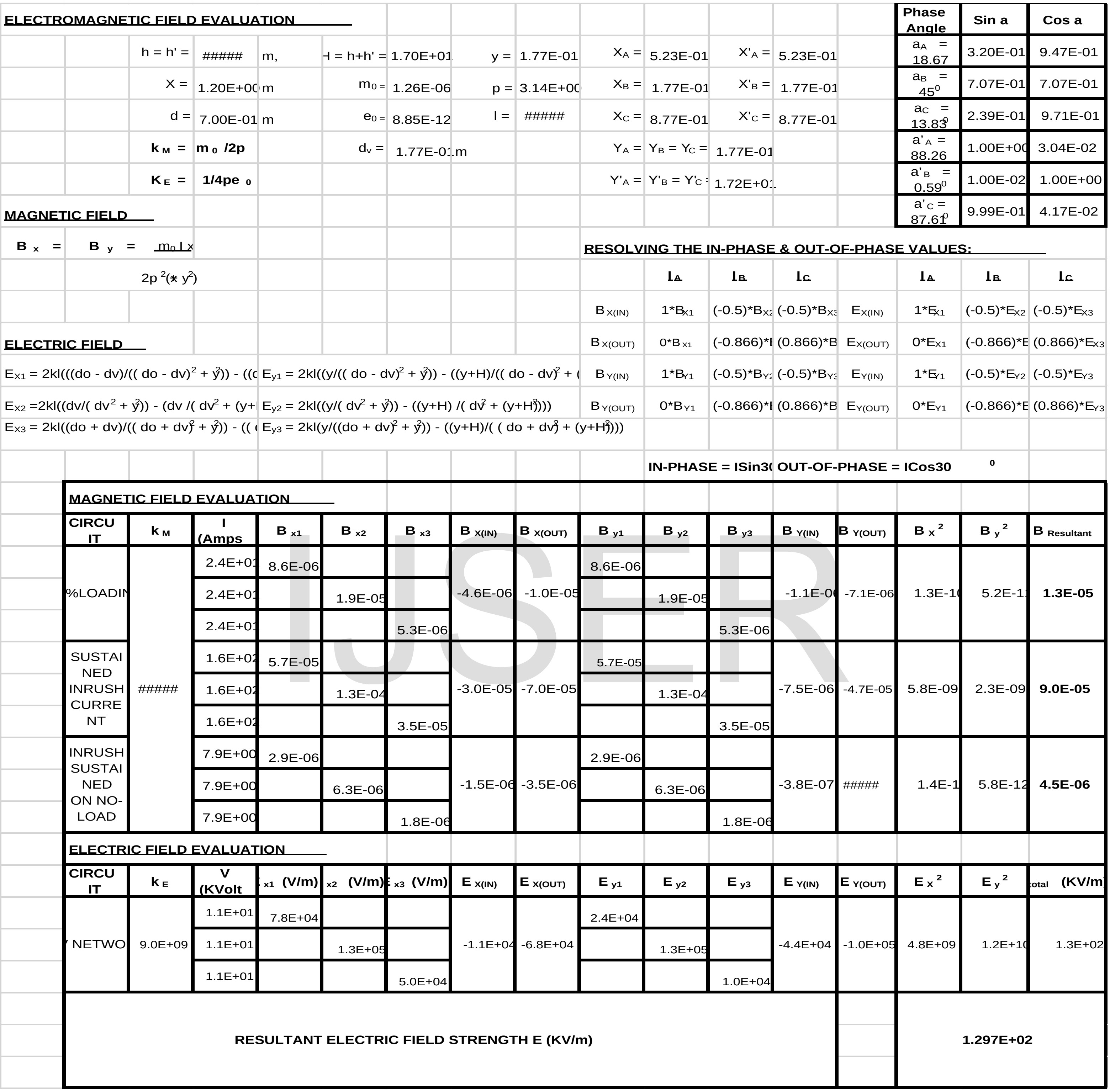
2.1.2 INTERPRETATION OF RESULTS

From table 11 we can visualize what actually happened during the time of the electrocution incidence under consideration.

From the table above, the following points are notable:

a. The maximum magnetic field evaluated for this incidence is 89.97μT (see table 11), and by the provisions of Tables 12/13, it has not exceeded the tolerable limit.

Table 11: EXCEL FORMAT OF ELECTROMAGNETIC FIELD VALUES FROM THE ELECTROCUTION INCIDENCE



ELECTROMAGNETIC FIELD EVALUATION

h = h' = ###### m, H = h+h' = 1.70E+01 y = 1.77E-01 X_A = 5.23E-01 X'_A = 5.23E-01
X = 1.20E+00 m m_0 = 1.26E-06 p = 3.14E+00 X_B = 1.77E-01 X'_B = 1.77E-01
d = 7.00E-01 m e_0 = 8.85E-12 I = ###### X_C = 8.77E-01 X'_C = 8.77E-01
k_M = m_0 /2p d_v = 1.77E-01 m Y_A = Y_B = Y_C = 1.77E-01
K_E = 1/4pe $_0$ Y'_A = Y'_B = Y'_C = 1.72E+01

Phase Angle	Sin a	Cos a
a_A = 18.67	3.20E-01	9.47E-01
a_B = 45^0	7.07E-01	7.07E-01
a_C = 13.83^0	2.39E-01	9.71E-01
a'_A = 88.26	1.00E+00	3.04E-02
a'_B = 0.59^0	1.00E-02	1.00E+00
a'_C = 87.61^0	9.99E-01	4.17E-02

MAGNETIC FIELD

$$B_x = B_y = \frac{m_0 I x}{2p^2(x^2 + y^2)}$$

ELECTRIC FIELD

$E_{X1} = 2kl(((do - dv)/((do - dv)^2 + y^2)) - (($
$E_{y1} = 2kl((y/((do - dv)^2 + y^2)) - ((y+H)/((do - dv)^2 + ($
$E_{X2} = 2kl((dv/(dv^2 + y^2)) - (dv /(dv^2 + (y+$
$E_{y2} = 2kl((y/(dv^2 + y^2)) - ((y+H) /(dv^2 + (y+H)^2)))$
$E_{X3} = 2kl((do + dv)/((do + dv)^2 + y^2)) - (($
$E_{y3} = 2kl(y/((do + dv)^2 + y^2)) - ((y+H)/((do + dv)^2 + (y+H)^2)))$

RESOLVING THE IN-PHASE & OUT-OF-PHASE VALUES:

	I_A	I_B	I_C		I_A	I_B	I_C
$B_{X(IN)}$	$1*B_{X1}$	$(-0.5)*B_{X2}$	$(-0.5)*B_{X3}$	$E_{X(IN)}$	$1*E_{X1}$	$(-0.5)*E_{X2}$	$(-0.5)*E_{X3}$
$B_{X(OUT)}$	$0*B_{X1}$	(-0.866)*	(0.866)*B	$E_{X(OUT)}$	$0*E_{X1}$	(-0.866)*E	$(0.866)*E_{X3}$
$B_{Y(IN)}$	$1*B_{Y1}$	$(-0.5)*B_{Y2}$	$(-0.5)*B_{Y3}$	$E_{Y(IN)}$	$1*E_{Y1}$	$(-0.5)*E_{Y2}$	$(-0.5)*E_{Y3}$
$B_{Y(OUT)}$	$0*B_{Y1}$	(-0.866)*	(0.866)*B	$E_{Y(OUT)}$	$0*E_{Y1}$	(-0.866)*E	$(0.866)*E_{Y3}$

IN-PHASE = ISin3 OUT-OF-PHASE = ICos30^0

MAGNETIC FIELD EVALUATION

CIRCUIT	k_M	I (Amps	B_{x1}	B_{x2}	B_{x3}	$B_{X(IN)}$	$B_{X(OUT)}$	B_{y1}	B_{y2}	B_{y3}	$B_{Y(IN)}$	$B_{Y(OUT)}$	B_X^2	B_y^2	$B_{Resultant}$
%LOADIN	#####	2.4E+01	8.6E-06			-4.6E-06	-1.0E-05	8.6E-06			-1.1E-0	-7.1E-06	1.3E-1	5.2E-1	**1.3E-05**
		2.4E+01		1.9E-05					1.9E-05						
		2.4E+01			5.3E-06					5.3E-06					
SUSTAINED INRUSH CURRENT		1.6E+02	5.7E-05			-3.0E-05	-7.0E-05	5.7E-05			-7.5E-06	-4.7E-05	5.8E-09	2.3E-09	**9.0E-05**
		1.6E+02		1.3E-04					1.3E-04						
		1.6E+02			3.5E-05					3.5E-05					
INRUSH SUSTAINED ON NO-LOAD		7.9E+00	2.9E-06			-1.5E-06	-3.5E-06	2.9E-06			-3.8E-07	#####	1.4E-1	5.8E-12	**4.5E-06**
		7.9E+00		6.3E-06					6.3E-06						
		7.9E+00			1.8E-06					1.8E-06					

ELECTRIC FIELD EVALUATION

CIRCUIT	k_E	V (KVolt	x1 (V/m)	x2 (V/m)	x3 (V/m)	$E_{X(IN)}$	$E_{X(OUT)}$	E_{y1}	E_{y2}	E_{y3}	$E_{Y(IN)}$	$E_{Y(OUT)}$	E_X^2	E_y^2	otal (KV/m
NETWO	9.0E+09	1.1E+01	7.8E+04			-1.1E+04	-6.8E+04	2.4E+04			-4.4E+04	-1.0E+05	4.8E+09	1.2E+10	1.3E+02
		1.1E+01		1.3E+05					1.3E+05						
		1.1E+01			5.0E+04					1.0E+04					

RESULTANT ELECTRIC FIELD STRENGTH E (KV/m)	**1.297E+02**

b. It can be seen from table 17 that there is evidence of intense electric field (129.71KV/m) during the electrocution incidence. This value is about 6.5times the tolerable limit given for occupational exposure (high action) level in the ICNIRP/EU provisions of table 12 above.

Evaluating the Induction Current Density (J):

$$J = \pi R_F \sigma B$$

AND, $J/\sigma = E$

$$\sigma(T) = \sigma_0(1 + \alpha(T - T_0)) \quad (14)$$

Evaluating the Induction Current Density (J):

From equation (25) to (26) above, The electric field intensity between the HV terminals and the dielectric material, E_0, and inside the dielectric material, E_1, are, respectively;

$$\left.\begin{aligned} E_0 &= \sigma_C/\varepsilon_0 \\ E_1 &= \sigma_C/\varepsilon_1 \end{aligned}\right\} \qquad (15)$$

Where, σ_C is the surface charge density on the HV terminals. The influence of the electric field will now be considered from the Line of Distinct Vision we earlier used for calculation as shown in figure 17 below. This is because the head portion is assumed the main area of direct contact.

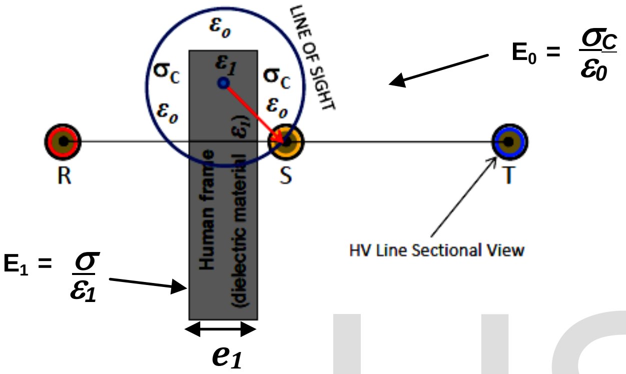


Figure 17: Effect of Electric Field on Human Structure

According to C. Pailler Mattei 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 [4].

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

$$E_0 = \frac{\sigma}{\varepsilon_0} \qquad (16)$$

And,

$$E_1 = \frac{\sigma}{\varepsilon_1}, \qquad (17)$$

If the HV terminals are within the range indicated with respect to the victim at a distance d = LDDV, 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 HV terminals is given as;

$V = V_1 - V_2 = E_0 d + E_1 e_1$ from eqn. (17)

FROM (27) AND (28),

$$V = \sigma_C\left(\frac{d}{\varepsilon_0} + \frac{e_1}{\varepsilon_1}\right) \qquad (18)$$

As before, if S is the surface area of the victim in contact with the electric field and Q is the electric charge, the surface charge density, σ_C, is defined as $\sigma_C = Q/S$;

Therefore, from equation (18) above, the potential difference can be written as a function of electric charge, Q, as

$$\mathbf{V} = \frac{Q}{S}\left(\frac{d}{\varepsilon_0} + \frac{e_1}{\varepsilon_1}\right) = Jt^*\left(\frac{d}{\varepsilon_0} + \frac{e_1}{\varepsilon_1}\right) \text{ from eqn. (19)}$$

For I = **Q**/**t** Coul./sec**, J = I/S = Q/tS** (where **t** is period or time)

As a consequence the electric charge, Q, on the human skin surface it produces current **I** given by;

$$I = \frac{\varepsilon_0 \mathbf{VS}}{t\,(d \qquad +} \qquad (20)$$

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

These will subsequently be used for the evaluation of the induced voltage and current.

To properly analyse the influence of Electric Field, we illustrate the concentric circle of Field Influence as shown in figure 18 below.

The electric field of an infinite cylindrical conductor with a uniform linear charge density is obtained by a using Gauss' law. Considering a Gaussian surface in the form of a cylinder at radius **r > R**, the electric field has the same magnitude at every point of the cylinder and is directed outward.

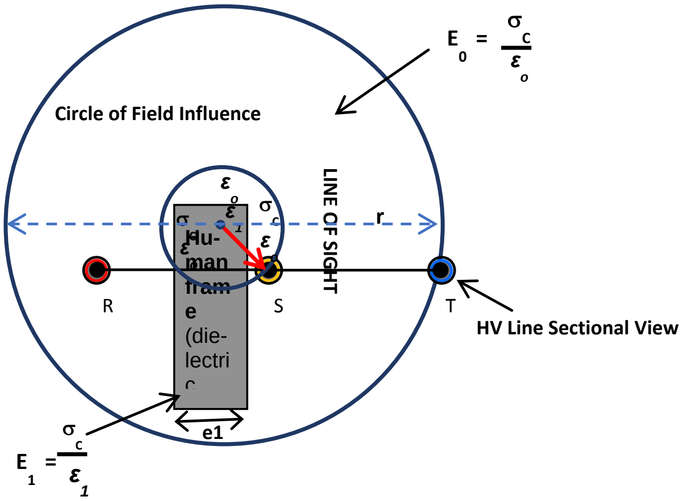


Figure 18: Illustration of Circle of Electric Field Influence Structure

The electric flux is then just the electric field times the area of the cylinder.

$$\Phi = E2\pi rL = \frac{\lambda L}{\varepsilon_0}$$

For r ≥ R

$$E = \frac{\lambda}{2\pi r\varepsilon_0} \qquad (21)$$

Where, R = cylindrical conductor radius
r = Surface radius of field point of influence.
λ = charge per unit length

The conductor Surface Charge Density **is given by;**

$\sigma_C = \lambda/2\pi R$ **(22)**

Theoretically, the Magnetic Field Density Produced from Power Lines 11kV Horizontal Configuration consisting of three conductors lying on the horizontal plane and using the centre conductor as the reference point o with d_0 as the distance of the two other conductors from centre line and I is the conductors current. According to **Ahmed Hossam-Eldin** et al, [1] the magnetic field density B in Tesla can be found as in equation (47) below.

$$B = \frac{\mu_0 d_0 I}{2\pi r}\left(\frac{3r^2 + (d_0^2)}{(r^4 - 2r^2 d_0^2 \cos 2\varphi_r + d_0^4)}\right)^{1/2} \qquad (23)$$

Where r is the distance from any point of interest and the centre point of power line o, φ_r is the angle between the vector r and the horizontal central line as shown in figure 4.36 below.

The current density in A/m2 induced due to electric field which is produced from the magnetic field can be determined using equation (10).

i.e. $J = \pi Rf\sigma B$

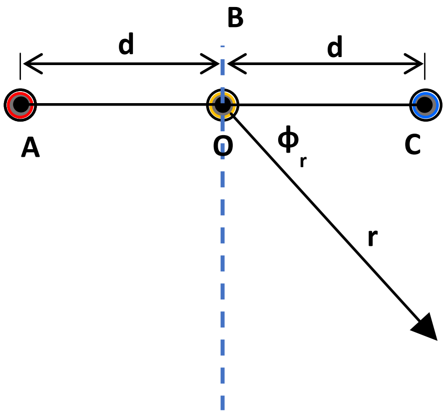


Figure 19: Conductors arrangement on Horizontal Single Circuit Configuration

3. CONCLUSIONS

From the analysis conducted on the case-study and the results of our electromagnetic evaluations, it is here concluded that the fatality of electrocutions resulting from electromagnetic fields in medium voltage electric power distribution systems are largely due to electromagnetic field rather than direct contacts. 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.

The following points are pertinent in this case-study:

- **Protective Grounding**: My observation on the picture of figures 1 and 2 is that there is no evidence protective grounding to secure the worksite. The need to observe the crucial safety measure of providing **Personnel protective grounds (PPG)** as well as **lines and equipment grounding** must have been compromised. It is obvious from the photographs the all-important process of personnel protective grounding was not observed. It is supposed to be nearest to the workplace as possible, but there is no evidence in the picture to show this!

Personnel protective grounds are applied to de-energized circuits to provide a low-impedance path to ground should the circuits become re-energized while personnel are working on or near conductive parts. In addition, the personnel protective grounds provide a means of draining off static and induced voltage from other sources while work is being performed on a circuit (see Fig. 30).

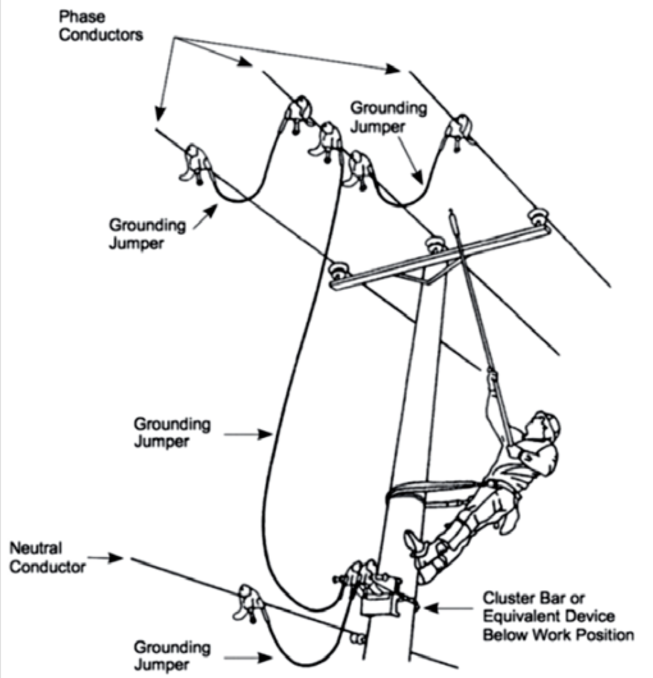


Figure 20: Protective Grounding of Lines and Equipment [Courtesy: Seattle City Light]

The purpose of **Equipment Protective Grounding**

(EPG) is to provide protection for the worker that is on an equipment or high-voltage line against potential drop across the body of the worker. It is known as **Personal Protective Grounding**.

The primary function of personal protective grounds is to provide maximum safety for personnel while they are working on de-energized lines or equipment. Double isolation protective grounding is provided as shown in figure 21 for this purpose.

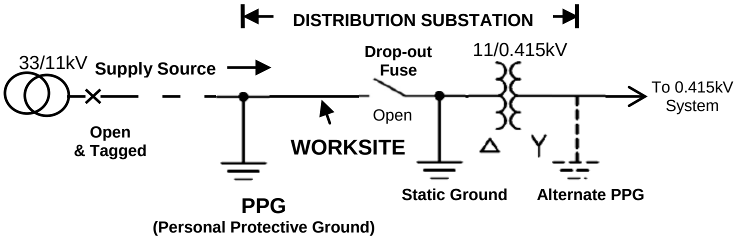


Figure 21: Basic double-isolation protective grounding scheme.

The personal protective grounds should **provide a low-impedance path to ground to ensure prompt operation of the circuit protective devices**. For more information, see Section 4.15.2 and IEEE 80.

- **Operator Error:** One of the commentaries said the operator may have left the control room unattended. This is of no consequence because when a **station guarantee** is issued, the operator has no power over the switchgear until the person in custody of the permit surrenders it. An eyewitness account confirmed that the procedure for station guarantee which includes **Lockout/tag-out** was duely complied with.

- **Power from Alternative Source**: there is a likelihood of **transfer potential** from other sources even when we have made sure that we have our secure station guarantee. This is a **VERY POSSIBLE** scenario in Nigeria, where anything goes! Before the second person climbed the pole for rescue operation, he must have been sure that the 11KV line had been de-energised. The fact that not one person confidently climbed the pole after the first electrocution is a confirmation. **In fact, an eyewitness from Nigerian Electricity Management Agency (NEMSA) investigating the accident said the permit holder was waiting for a 'go-ahead' confirmation from the field when the incident occurred. So the line couldn't have been energised.**

  Let us take a close look at the upriser configuration again. There are a minimum of three to four (3-4) uprisers radiating from this station and, given the Nigerian situation, any of the upriser is a potential hazard in terms transfer potential. It could be from an adjacent or nearby substation, given the ease and indiscriminate way with which unauthourised persons connect load to the LV lines. **It could even be from a nearby diesel generator since the 11KV feeder that serves the area has been switched off!!**

  This scenario could lead to a **step-up voltage** situation from the transformer in the substation and **the worker will encounter full 11KV supply headlong even when the source of the main supply is off**. No amount of Personal Protective Equipment.

- **High Voltage Testers**: It will be necessary to re-introduce High Voltage Test Rods or Phasing Sticks to ensure establishment of potential before work commencement.

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