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Effect of Electromagnetic Fields on Transmission Line: Case Study of Possible Electrocution from Electromagnetic Fields

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ABSTRACT

This paper investigates the potential for electrocution among field workers due to exposure to electromagnetic fields (EMFs) generated by high-voltage transmission lines. Although few are aware of the dangers posed by these invisible electric and magnetic fields, they can present serious risks. Many field workers have suffered electrocution because of prolonged exposure to such fields. This study explores the various scenarios in which electrocution may occur from the influence of electromagnetic fields, highlighting the need for improved safety measures.

Keywords: *electromagnetic fields, transmission lines, electrocution, high-voltage, field workers, safety, invisible fields, electrical hazards*

1.0 INTRODUCTION

Electromagnetic fields are present all around us. They are present in all our electrical gadgets. In as much as we can use electromagnetic fields to our advantage, prolonged exposure to electromagnetic fields could have side effects on humans over time. However, the side effects linked to electromagnetic fields have not been scientifically fully proven [25], especially for low-frequency electromagnetic fields.

This work is concerned more, with the dangers High-voltage electromagnetic fields, have when field workers come in close contact with them. Electrocution from High voltage is not unusual in our societies, as people do not pay adequate attention to the dangers that may arise while working with high-voltage electromagnetic fields. . field workers working with high-voltage power lines should ensure that they observe a safe distance as provided by regulatory bodies in their countries. Workers should observe safety standards by using personal protection equipment (PPE).

High-voltage power lines have both electric fields and magnetic fields around the conductors. Electric fields are present whenever a charge is present. The electrical fields around conductors are due to the high voltage flowing through the conductors. The electric field increases around the conductor with an increase in voltage. Electric fields are measured in V/m.Magnetic fields on the other hand are current dependent. The magnetic fields induced around the transmission conductors increase with an increase in current. Magnetic fields are measured in A/m.

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World Health Organization(WHO) has stipulated minimum exposure limits for electric and magnetic fields. Minimum close distances to transmission lines have equally been established. A field worker can suffer electrocution from any of the following: arcing, voltage flashover, step voltage, or touch voltage.

Arcing is responsible for a lot of fatal accidents, that have been recorded in the power industries. Arcing can result due to the complete breakdown of air insulation. The air insulation breakdown is given as 30KV/cm. When the air insulation breakdown is exceeded, a lighting spark is seen between the live part and a nearby conductor.

High voltage lines, crossing over other power lines, rail lines, and oil pipelines could be fatal, due to flashover voltage. When high-voltage lines cross over a 33KV line, it is important to observe safety measures to prevent flashover voltage to the distribution voltage. A flashover from 132KV to 33KV could be fatal to the consumers if the protective circuit breakers fail to disconnect the live conductors. At the point at which The High voltage line, crosses over a 33KV line, a “guard wire” could be used to separate the 132KV line from the 33KV line. Also, transposition could be used at the crossing point of power lines over communication lines.Transposition is the interchange or swapping of the position of conductors at regular intervals to reduce crosstalk or interference[29].

Flashover voltage usually, occurs due to the breakdown of the disc insulators. Lightening and several other factors like aging, pollution, etc are responsible for insulation breakdown.

Flashover voltage is given as[28]:

$$V_f = \left(400 + \frac{710}{t^{0.75}}\right) \text{X L} \qquad 1.1$$

V_f =flashvoltage

t= elastic time after lighting strick in μs.

2.0 FIELD EFFECT AROUND HIGH VOLTAGE TRANSMISSION LINES

High-voltage overhead transmission lines generate Electric and Magnetic fields as Voltage and Current flow through the transmission conductors. The source of the Electric field is the Voltage (potential) flowing through the conductor. So also, the source of the magnetic field is the current flowing through the conductor, as loads are connected to the system.

The Electric field around the conductor increases, with the increase in Voltage. This is to say that the 330KV transmission voltage line, has a higher electric field than the 132KV transmission line, as would be seen by the mathematical equation as we progress, so also, the Magnetic field increases with an increase in the current flowing through the conductor.

These fields could be lethal to humans if proper planning and safety measures are not taken while working with them. The magnetic fields induce electric current around human bodies, especially when the fields are strong enough to induce flux density [10]. The current induced by the electric field from the transmission line is greater than the safe body current [5]. Electric charge is distributed on the surface of the human body if the body is inside the field. If the value of the Electric field exceeds the expected safety limit, it could be fatal to humans.

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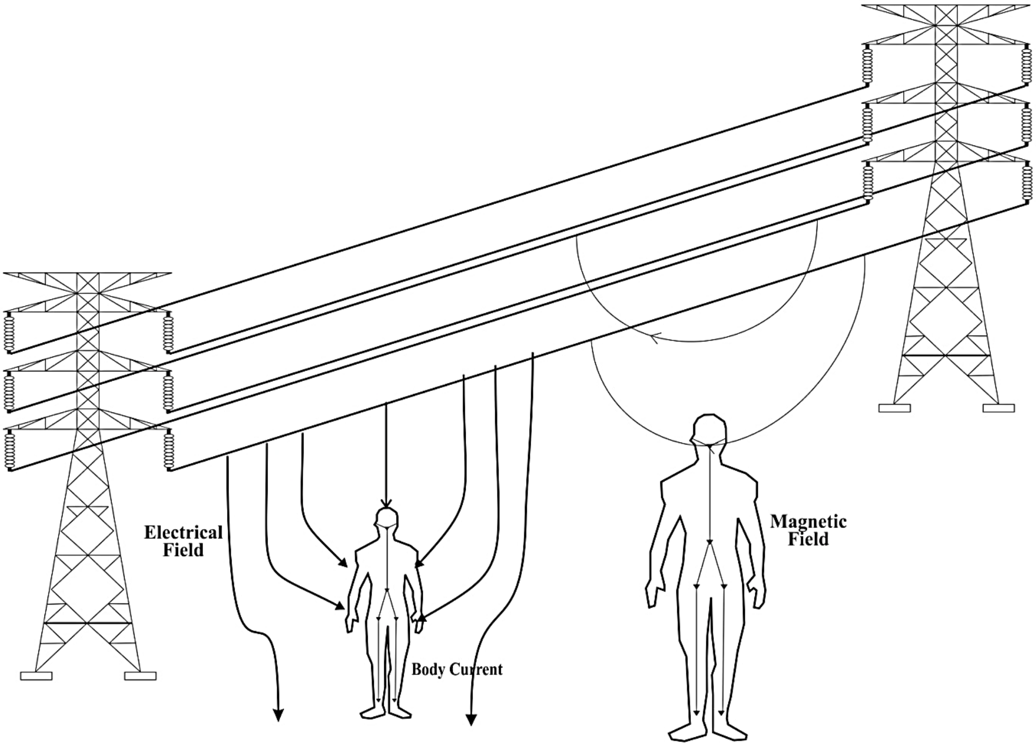

Fig1 Human under High Voltage power line

3.0 EMF EXPOSURE LIMIT VALUE

The International Radiation Protection Association (IRPA), International Commission on Non-ionizing Radiation Protection (ICNIRP), and World Health Organization have laid down standards for the safe time a person stays inside a field and the safety field limit. From the guidelines of ICNIRP, as updated in April 1998, for a frequency of 50Hz, the safety exposure limit for the Electric field is 5KV/m for public exposure and 10KV/m for occupational exposure. The safety exposure for magnetic field is 100µT for public health and 500µT for occupational exposure. (https://www.who.int/news-room/questions-and-answers/item/radiation-electromagnetic-fields).

The exposure time for workers in the field is given by

$$t=\frac{80}{E} \text{ (10<E<30; t in hours)} \qquad 3.1$$

The safety factor for occupational guidelines differs from that for the public. The occupationally exposed population consists of adults, who are trained and experienced in the risk (danger) involved and know how to take precautions to avert danger. The general public comprises individuals of all ages and of varying health status. These set of people are not trained and might not be aware of the danger of their exposure to EMF and are not expected to take safety measures.

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4.0 ELECTRIC FIELD ANALYSIS OF A TRANSMISSION LINE

Transmission line operational voltage in Nigeria is usually 132KV and 330KV. These Voltages are transmitted using Overhead aluminum conductors. These overhead conductors are usually suspended, by high-voltage insulators which are in turn mounted on poles or towers. As the Voltage flows through the conductor, an electric field is generated around the conductor. An electric field is a field around an electric charge.

The overhead transmission line can be considered a line charge ‘q’. Consider two point charges +q and –q separated by a distance ‘d’. Assuming that these charges lie on the vertical axis ‘Z’ as shown in Fig 2. Let ‘P’ be the point on the (x,y,z) with a distance ‘r’.

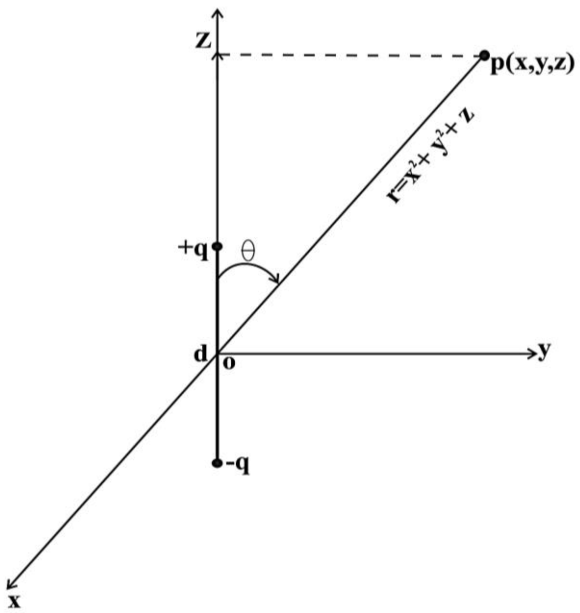

Fig 2. Electric Field Distribution Around Overhead Transmission Line Considering Point Charges

From the fig 2 above, the potential V of charges +q and -q can be estimated as:

$$V(x,y,z) = \frac{1}{4\pi\varepsilon_0}\left[\left[\frac{+q}{\sqrt{x^2+y^2+\left(z-\frac{d}{2}\right)^2}}\right]+\left[\frac{-q}{\sqrt{x^2+y^2+\left(z+\frac{d}{2}\right)^2}}\right]\right] \quad 4.1$$

Expanding $x^2+y^2+\left(z-\frac{d}{2}\right)^2$ in the equation $x^2+y^2+z^2-zd+\frac{d^2}{4}$ 4.2

So also, $x^2+y^2+\left(z+\frac{d}{2}\right)^2$; is equal to $x^2+y^2+z^2+zd+\frac{d^2}{4}$ 4.3

From equation 4.2 and 4.3,r in fig. 2 can be represented as $r^2 = x^2+y^2+z^2$ 4.4

Substituting

$$V(x,y,z) = \frac{1}{4\pi\varepsilon_0}\left[\left[\frac{+q}{\sqrt{r^2-zd+\frac{d^2}{4}}}\right]+\left[\frac{-q}{\sqrt{r^2+zd+\frac{d^2}{4}}}\right]\right] \quad 4.5$$

r >>d; r² >>$d^2/4$; expanding the denominator binomially and neglecting square and higher powers of zd/r^2

$$V(x,y,z) = \frac{q}{4\pi\varepsilon_0 r}\frac{zd}{r^2} = \frac{1}{4\pi\varepsilon_0} \text{ x } \frac{qd}{r^2}\frac{z}{r} \quad 4.6$$

from the fig 2 Cosθ = $\frac{z}{r}$;

Let P equal the moment required to move a charge: p=q X d;

$$V(x,y,z) = \frac{q}{4\pi\varepsilon_0 r}\frac{zd}{r^2} = \frac{1}{4\pi\varepsilon_0} \text{ x } \frac{p\,Cos\theta}{r^2} \quad 4.7$$

The electric field due to the dipole can be calculated using the gradient of the potential component

$$E = -\nabla V \quad 4.8$$

$$E_X = -\frac{\partial V}{\partial X} \;; \qquad E_y = -\frac{\partial V}{\partial y} \;; \qquad E_z = -\frac{\partial V}{\partial z} \quad 4.9$$

From Equation 4.6 $V(x,y,z) = \frac{q}{4\pi\varepsilon_0 r}\frac{zd}{r^2} = \frac{1}{4\pi\varepsilon_0} \text{ x } \frac{qd}{r^2}\frac{z}{r}$

Resolving equation 4.6 for x-component:

$$E_X = -\frac{\partial V}{\partial X} = -\frac{\partial}{\partial x}\left(\frac{1}{4\pi\varepsilon_0 r}\;\frac{qd}{r^2}\,\frac{z}{r}\right) \quad 4.10$$

$$= \frac{qd}{4\pi\varepsilon_0}\left(\frac{-3z}{r^4}\right)\left(\frac{\partial r}{\partial x}\right) = \frac{qd}{4\pi\varepsilon_0}\left(\frac{-3z}{r^4}\right)\left(\frac{x}{r}\right) \quad 4.11$$

So also, $E_y = \frac{\partial V}{\partial y} = -\frac{qd}{4\pi\varepsilon_0}\left(\frac{3yz}{r^5}\right)$ 4.12

$$E_z = \frac{\partial V}{\partial z} = \frac{qd}{4\pi\varepsilon_0}\frac{\partial}{\partial z}\left(\frac{z}{r^3}\right) = \frac{qd}{4\pi\varepsilon_0}\left[\frac{1}{r^3} - \frac{3z^2}{r^5}\right] \quad 4.13$$

(cosθ = $^z/_r$;sinθ = $\sqrt{x^2+y^2}$ /r see fig. 2

Type equation here.The transverse component,

$$E_+ = \sqrt{x^2+y^2} = \frac{qd}{4\pi\varepsilon_0}\frac{3z}{r5}\sqrt{x^2+y^2} \quad 4.14$$

The magnitude of the total field is given by:

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$$E = \sqrt{E_+{}^2 + E_z{}^2} = \frac{qd}{4\pi\varepsilon_0}\frac{(3cos^2\theta+1)^{1/2}}{r^3} \qquad 4.15$$

From equation 4.15, it can be seen that the Electric field varies inversely to the cube of the distance from the dipole. If the angle θ is at 0º at a specific dipole distance:

It follows that $\cos^2 0^o = 1$;

Therefore $3\cos^2 0^o + 1 = 3 + 1 = 4$;

$(3cos^2\theta + 1)^{1/2}$ =2.

Similarly, if θ = 90º:

$\cos^2 90^o = 0$;

Therefore, $3\cos^2 90^o + 1 = 1$, $(3cos^2\theta + 1)^{1/2}$ =1

It, therefore, means that the Electric field at 0º is twice as strong as the Electric field at 90º. From equation 4.15 it follows that the Electric field is stronger closer to the transmission line and decreases with an increase in distance. At the ground level, the Electric field is the greatest at the support(at the support θ is closest to 0º) and where the transmission line is closest to the ground.fig 3 describes the representation of the Electric- field profile, in KV per meter, from the center line of the tower(pole). The graph below indicates the maximum field and the location of the maximum field. The maximum from the graph can be traced at 12m, from the tower. This is due to the sag of the live aluminum conductors[21].

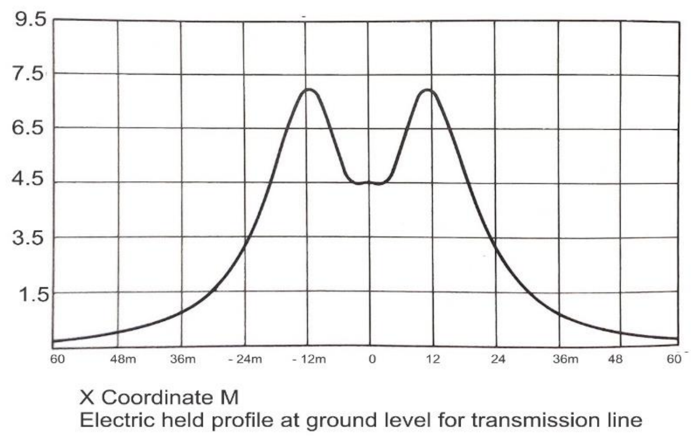

Fig. 3 Electric Field Profile in kV/m from the Center Line of the Transmission Tower

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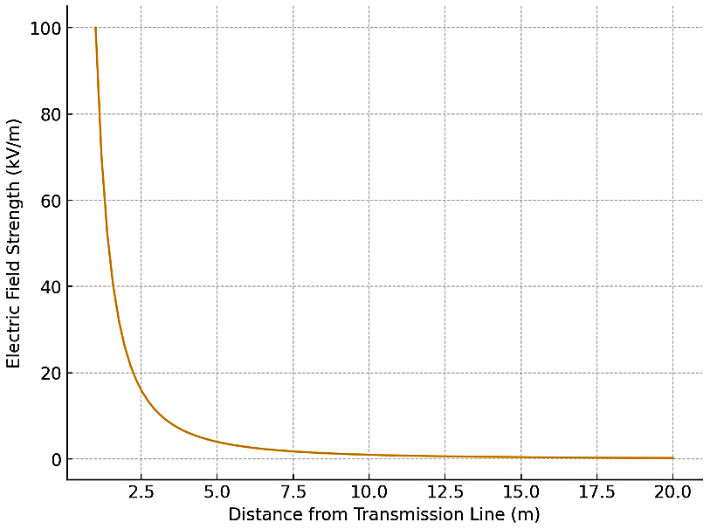

Fig. 4 Electric Field Strength vs. Distance from High-Voltage Transmission Line

X-axis: Distance from Transmission Line (meters)

Y-axis: Electric Field Strength (kV/m)

Figure 4 typically shows the relationship between the electric field strength and the distance from the high-voltage transmission line. The field strength decreases as the distance from the transmission line increases, with a steep drop-off close to the line.

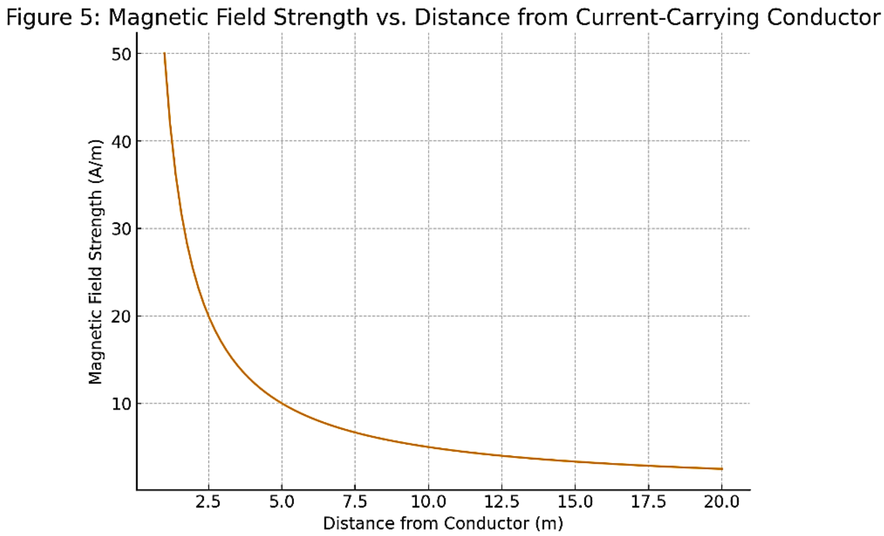

Fig. 5 Magnetic Field Strength vs. Distance from Current-Carrying Conductor

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X-axis: Distance from Conductor (meters)

Y-axis: Magnetic Field Strength (A/m)

Figure 5 demonstrates the relationship between the magnetic field strength and the distance from a current-carrying conductor. Similar to the electric field, the magnetic field strength decreases as the distance from the conductor increases, following an inverse relationship.

5. MAGNETIC FIELD ANALYSIS OF A TRANSMISSION LINE

Magnetic forces are forces between current or moving changes [20]. Considering the forces on a moving charge produced by an external agent. This force is given by Lorentz force law[20]:

$$F= q\left(\vec{E} + \vec{v}\, X\ \vec{B}\right) \qquad 5.0$$

The vector $\vec{B}$ is independent of q and v.It depends only on moving charges in the surroundings. This vector is called the magnetic induction or magnetic flux density. The unit for $\vec{F}$ is measured in Newtons, 'q' in coulombs, and $\vec{v}$ in meters per second.$\vec{B}$ has the units of Newton per Ampere-meter(Weber per meter square)

$$d\overrightarrow{F_1}=\frac{\mu_0}{4\pi}\, i_1 i_2\, \frac{d\vec{l}\ X\,(d\vec{l}\,X\,\vec{r}\,)}{r^3} \qquad 5.1$$

$\mu_0 = 4\pi \text{ x } 10^{-7} = 1.257 \text{ x } 10^{-6}$ H/m

$$\text{Since } \vec{\nabla}\left(\frac{1}{r}\right) = -\frac{\vec{r}}{r^3} = \frac{\hat{r}}{r^2} \qquad 5.2$$

Equation 5.1 can be written as:

$$d\overrightarrow{F_1}=\frac{\mu_0}{4\pi}\, i_1 i_2\, d\overrightarrow{l_2}\ \text{X}\ \left(d\vec{l}_2\, X\, \vec{\nabla}\left(\frac{1}{r}\right)\right) \qquad 5.3$$

introducing a vector $\vec{B}$ known as magnetic induction. The element of the induction is:

$$d\overrightarrow{F_1} = i_1\, d\vec{l}_1 \text{ X } d\vec{B}_2 \qquad 5.4$$

substituting into equation 5.1

$$d\vec{B}_2 = \frac{\mu_0}{4\pi}\, i_2\, \frac{d\vec{l}_2\ \ X\ \vec{r}}{r^3} \qquad 5.5$$

A magnetic field can be defined by auxiliary vector $\vec{H}$.

$$\vec{H} = \frac{1}{4\pi}\oint \frac{d\vec{l}}{r^2} \text{ x } \hat{r} \qquad 5.6$$

The unit of $\vec{H}$ is Ampere per meter.

Consider an infinite straight transmission conductor, carrying current I, still in the z-axis as shown in Fig. 6 below.

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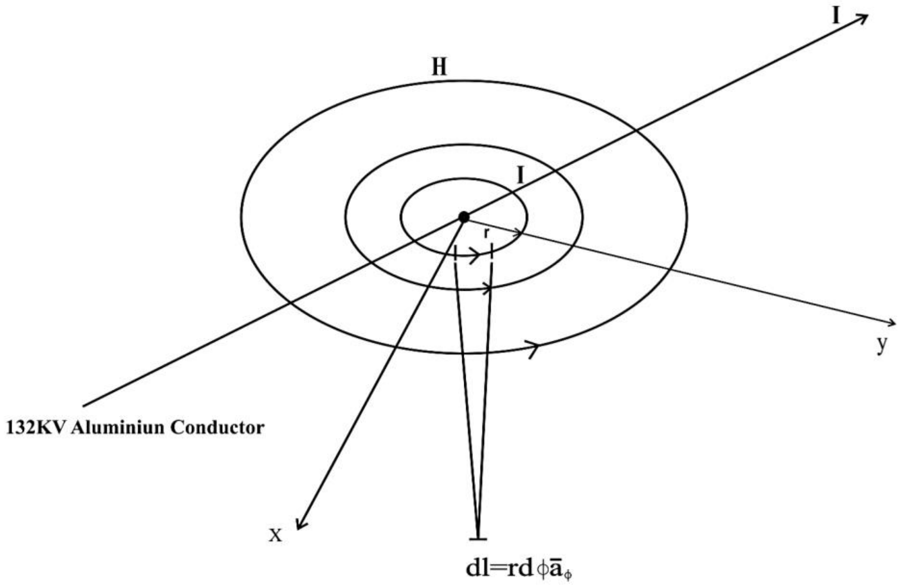

Fig 6. Magnetic field around a current carrying conductor

Ampere's circuital law states that the line integral of $\vec{H}$ about any closed path is exactly equal to the direct current enclosed by that path[22].

$$\oint \vec{H}.d\vec{l} = I_{enclosed} \text{ (A)} \quad 5.7$$

$$\int_{\phi=0}^{2\pi} H_\phi \, \vec{a}_\phi . r \, d\phi \, \vec{a}_\phi = \text{I} \quad 5.8$$

$$\int_{\phi=0}^{2\pi} H_\phi \text{ r d}\phi = \text{I} \quad 5.9$$

$$H_\phi \quad \text{r } (\phi)_0^{2\pi} = \text{I} \quad 5.10$$

$$H_\phi \quad \text{r } 2\pi = \text{I} \quad 5.11$$

$$H_\phi = \frac{I}{2\pi r} \quad 5.12$$

$$\vec{H} = \frac{I}{2\pi r} \overrightarrow{a_\phi} \quad 5.13$$

Equation 5.13 shows that the Magnetic field around the transmission conductor is dependent on the current flowing through the conductor at a particular time. As the current flowing through the transmission line increases, the Magnetic field around the conductor equally increases. However, the magnetic field around the conductor decreases with an increase in distance. This implies that the Magnetic field around the surface of the conductor is greater than the magnetic field 10m from the surface of the conductor. This further decreases with every increase in distance.

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6.0 POTENTIAL DISTRIBUTION OVER STRINGS OF SUSPENDED INSULATORS.

Transmission line conductors are suspended with the aid of an insulator, which is supported by towers. The insulators are made in the form of discs(suspension type). The number of insulator discs used is dependent on the Voltage under consideration. For 132KV lines 9-10 discs are typically used,330KV Lines with 16-18 discs are used, and 400KV with 19 discs of overall length 3.84m[21,23]. Insulators are usually made of glass or porcelain. The span between two towers depends on the recommended distance and allowable sag between towers.

These insulators have internal capacitance and resistance existing between them. This resistance is affected by pollution such as dust and other air pollutants. Fig 6 below shows a typical transmission tower carrying a conductor suspended with the aid of insulators. The circuit below shows The equivalent circuit of a string of suspended insulators. The internal capacitance of the insulator is given as C_1=internal capacitance of disc; C=capacitance of disc to earth, and C_2= capacitance of disc to line. R = leakage resistance [23].

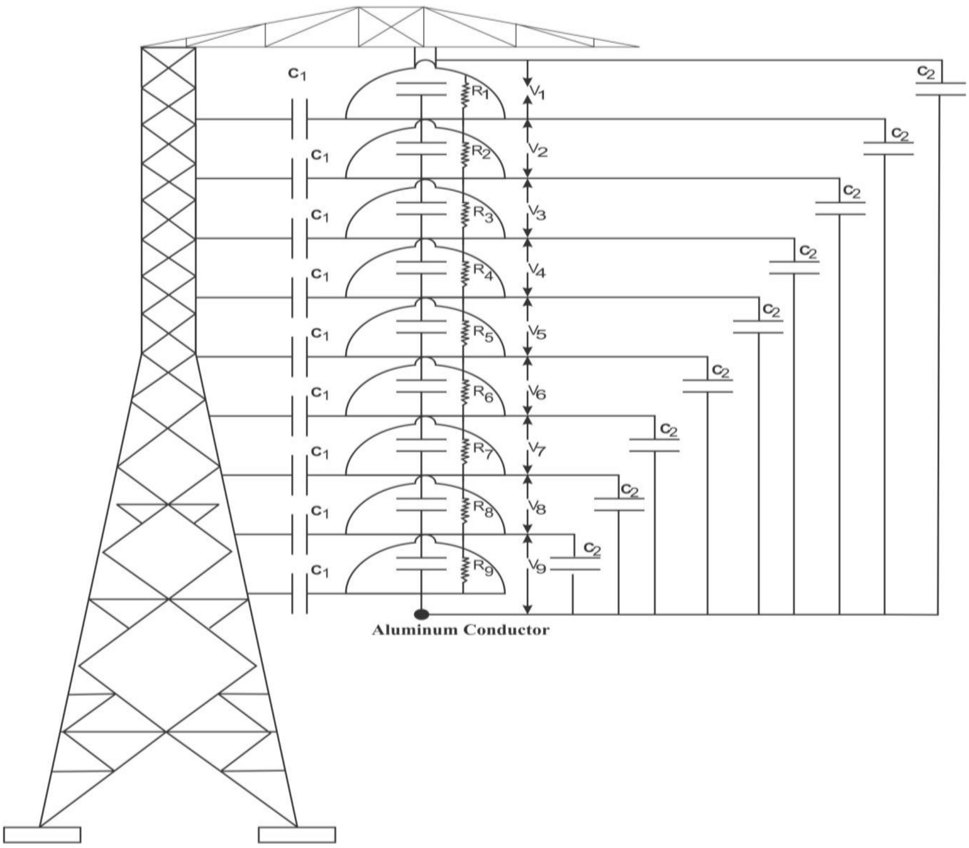

Fig 7 a: Equivalent Circuit of a Suspension Insulator String on a Transmission Tower

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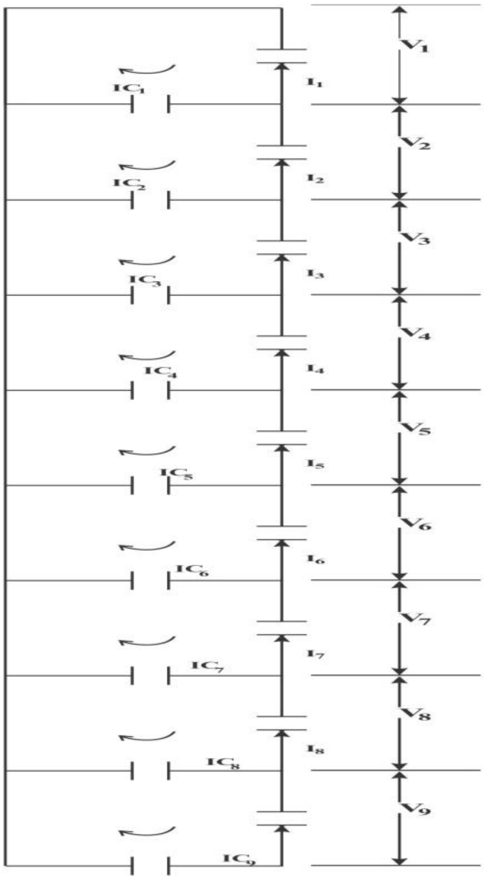

Fig 7 b Equivalent Circuit Representation of Capacitance and Voltage Distribution Across Insulators in a Suspension String

Let C=C_1

n = $\frac{capacitance\ \ per\ insulator}{capacitance\ to\ ground} = \frac{nC}{C}$ 6.1

V=Voltage, from line to ground and V_1, V_2,V_3 , V_4 6.2

From Fig. 6 b

$I_2 = I_1 + I_{c1}$ 6.3

Q=CV 6.4

nωCV_2 = nωCV_1 +ω CV_1 6.5

$V_2 = V_1\left(\frac{1}{n} + 1\right)$ 6.6

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From loop 2 in Fig 6

$$I_3 = I_2 + I_{C2} \qquad 6.7$$

$$n\omega C V_3 = n\omega C V_2 + \omega C\,(V_1 + V_2) \qquad 6.8$$

From equation 6.6, the value of V_2 is substituted into equation 6.8

$$V_3 = V_1\left(\frac{1}{n^2} + \frac{3}{n} + 1\right) \qquad 6.9$$

$$V_4 = V_1\left(\frac{1}{n^3} + \frac{5}{n^2} + \frac{6}{n} + 1\right) \qquad 6.10$$

$$V_5 = V_1\left(\frac{1}{n^4} + \frac{7}{n^3} + \frac{15}{n^2} + \frac{10}{n} + 1\right) \qquad 6.11$$

$$V_6 = V_1\left(\frac{1}{n^5} + \frac{9}{n^4} + \frac{30}{n^3} + \frac{35}{n^2} + \frac{15}{n} + 1\right) \qquad 6.12$$

$$V_7 = V_1\left(\frac{1}{n^6} + \frac{11}{n^5} + \frac{47}{n^4} + \frac{96}{n^3} + \frac{70}{n^2} + \frac{21}{n} + 1\right) \qquad 6.13$$

$$V_8 = V_1\left(\frac{1}{n^7} + \frac{13}{n^6} + \frac{56}{n^5} + \frac{181}{n^4} + \frac{222}{n^3} + \frac{126}{n^2} + \frac{28}{n} + 1\right) \qquad 6.14$$

$$V_9 = V_1\left(\frac{1}{n^8} + \frac{15}{n^7} + \frac{81}{n^6} + \frac{294}{n^5} + \frac{537}{n^4} + \frac{474}{n^3} + \frac{210}{n^2} + \frac{36}{n} + 1\right) \qquad 6.15$$

If n > 1. Let n = 10 (132 KV has 9-10 insulators),

V_2= 1.1V_1; V_3= 1.31V1, V_4 =1.65V_1 , V_5 =2.107V_1 , V_6 =2.88V_1 , V_7 =3.9V_1, V_8 =5.3V_1, V_9 =7.26V_1.

V_9 =Voltage across the string=132KV.

V_1= 18,181.82 Voltage.

This clearly shows the distribution of Voltage along the insulator. The first insulator has the least amount of Voltage as per the voltage divider. while V4 is 1.65 times the voltage of the last insulator(V_1), V_5 is 2.10 times the voltage of the last insulator.The strength of the Voltage across the 9th insulator is the supply Voltage.

The efficiency of the string is a measure of the utilization of material in the string and is defined as:

$$\text{Efficiency of the string} = \frac{\textit{Voltage across the string}}{n \ X\, \textit{Voltage across the unit holding the line}} \qquad 6.11$$

$$\text{So also Efficiency of string} = \frac{\textit{Spark over voltage}}{n\ X\ \textit{spark over voltage of one disc}} \qquad 6.12$$

The efficiency of the insulator can be calculated by using equation 6.11

$$\text{Efficiency of string} = \frac{132{,}000}{9\ X\ 18{,}181.82}\ \text{X}100 = 80.67\%$$

7.0 CAPACITANCE AND INDUCTANCE OF A TRANSMISSION LINE

Fig 7 shows a transmission line having conductors of phases “a” and “b”, separated by a distance ‘d=D’. The transmission line conductors have a capacitor separating the phases. The conductors of the transmission line act like two parallel plates of a capacitor, and the air in between the conductors acts as a dielectric medium.

To determine the capacitance separating these conductors, we can determine the capacitance. The capacitance and the conductance form the shunt admittance of a transmission line. The line capacitance is proportional to the length of the transmission line. When Voltage is applied across the line, the line capacitance draws a leading sinusoidal current the charging current, which is drawn even when the line is open-circuited at the end[23]

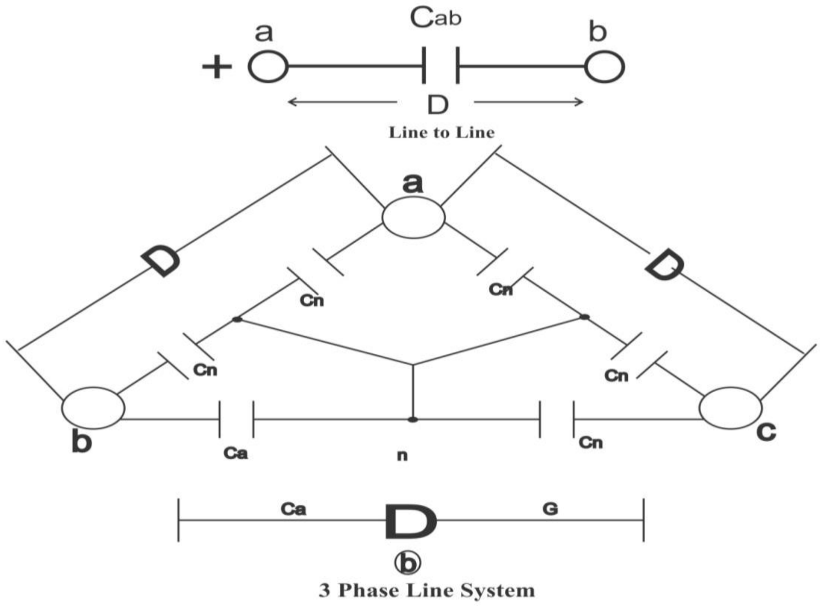

Fig 8. Schematic Diagram of a 3-Phase Line System with Capacitance Between Phases

The potential difference between the conductors “a” and “b”, with a radius “r” as shown in Fig 7 is given as:

$$V_{ab}=\frac{1}{2\pi\varepsilon_0}\left[q_a\, In\frac{d_{ab}}{daa}+q_b\, In\frac{d_{bb}}{d_{ba}}\right] \qquad 7.1$$

Where q_a =charge on conductor “a”;q_b= charge on conductor “b”;V_{ab} = potential difference between “a” and “b”.

$$q_a = -q_b = q$$

$$d_{12} = d_{21} = d, \qquad d_{aa} = d_{bb} = r$$

$$V_{ab} = \frac{1}{2\pi\varepsilon_0}\left(q_a\, In\frac{d}{r} - q_b\, In\frac{r}{d}\right) \qquad 7.2$$

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$V_{ab} = \frac{1}{\pi\varepsilon_0} q_a \text{In}\frac{d}{r}$ 7.3

$C_{ab} = \frac{q_a}{q_b} = \frac{\pi\varepsilon_0}{In\frac{d}{r}}$ 7.4

For a balanced system of Voltage to be applied three-phase-line shown in fig 7b:

$V_{ab} = \frac{1}{2\pi\varepsilon_0}\left(q_a\, In\,\frac{d}{r} + q_b\, In\,\frac{r}{d}\; + q_c\, In\frac{d}{d}\right)$ 7.5

In1=0

$V_{ab} = \frac{1}{2\pi\varepsilon_0}\left(q_a\, In\,\frac{d}{r} + q_b\, In\,\frac{r}{d}\; + 0\right)$ 7.6

The potential difference between conductors a and c

$V_{ac} = \frac{1}{2\pi\varepsilon_0}\left(q_a\, In\,\frac{d}{r} + q_b\, In\,\frac{d}{d}\; + q_c\, In\frac{r}{d}\right)$ 7.7

Adding equations 7.6 and 7.7

$V_{ab} + V_{ac} = \frac{1}{2\pi\varepsilon_0}\left(2q_a\, In\,\frac{d}{r} + (q_b + q_c) In\frac{r}{d}\right)$ 7.8

Since $q_a + q_b + q_c = 0$

$V_{ab} + V_{ac} = \frac{1}{2\pi\varepsilon_0}\left(2q_a\, In\,\frac{d}{r} - q_a In\frac{r}{d}\right)$ 7.9

$V_{ab} + V_{ac} = \frac{1}{2\pi\varepsilon_0}\, \text{X}3q_a\, \text{In}\frac{d}{r}$ 7.10

$\boldsymbol{V_{ab} = \sqrt{3}\;\, V_{ab}\;\, < 30^{o}}$

$V_{ab} + V_{ac} = 3V_{an}$ 7.11

It follows that

$3V_{an} = \frac{3q}{2\pi\varepsilon_0}\, \text{In}\frac{d}{r}$

$V_{an} = \frac{q}{2\pi\varepsilon_0}\, \text{In}\frac{d}{r}$ 7.12

A three-phase conductor's equally spaced capacitance can be represented using the equation.

C= $\frac{2\pi\varepsilon_0}{In\left[\frac{d}{r}\right]}$ F/m 7.13

Where d =$\sqrt[3]{d_{12.}\, d_{23\,.}\;\; d_{31}}$ 7.14

C= capacitance[

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d= equivalent spacing distance

The spacing distance for conductor phase-to-phase spacing is shown in Table 1.0[24]

VOLTAGE	NORMAL SPAN	PHASE-TO-PHASE CLEARANCE	PHASE TO STRUCTURE/ EARTH CLEARANCE
400V	45m	200mm	25mm
11,000V	90m	700mm	180mm
33,000V	90m	1200mm	300mm
132,000V	210m	2400mm	1200mm
330,000V	450m	6000mm	2400mm

TABLE 1 Recommended minimum clearance of Electric line at various Voltage levels.

8.0 ELECTROCUTION ASSOCIATED WITH ELECTRIC AND MAGNETIC FIELD.

8.1 ANALYTICALLY:

A lot of people do not take adequate precautions when working close to or with Medium and High Voltage conductors. This negligence has cost a lot of field workers their lives.

From equation 4.15

$$E = \sqrt{E_+{}^2 + E_z{}^2} = \frac{qd}{4\pi\varepsilon_0}\frac{(3cos^2\theta+1)^{1/2}}{r^3}$$

The Electric field for a 132KV at a distance of 1000mm close to the conductor, at the peak region on the tower, is assumed to be 0^o.

Q=CV

From equation C= $\frac{2\pi\varepsilon_0}{In\left[\frac{d}{r}\right]}$ F/m

ε_0= 8.85x 10^{-12} F/m ,

From Table 1 phase-to-phase clearance = 2400mm, for “d” using Equation 4.14, it follows that d=3023mm. A conductor of 150mm is used for a 132KV transmission line in Nigeria as could be seen in standard cable catalogues.

A=150mm^2 ;A=πr^2 it follows that: $r^2=\frac{A}{\pi} = \frac{150}{3.142}$ =47.74 ; r= 6.90mm

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C= $\frac{2\ X\ 3.142\ X\ 8.85\ X10^{-12}}{In\ \frac{3023}{6.9}}$ = $\frac{55X10^{-12}}{6.1}$ = 9.0 X 10^{-12} F/m

It follows that q= 9.0 X10^{-12} X 132,000 =11.88 x10^{-7}C

E= $\boldsymbol{\frac{11.88\ X\ 10^{-7} X\ 2.4}{4\ X3.142X8.85\ X10^{-12}}}$ **x** $\boldsymbol{\frac{2}{1}}$**= 52KV/m (132KV line)**

The Electric field within 1 m close to 132 KV is 55KV/m.This far exceeds the recommended safety exposure limit for field workers and linesmen.

For 33KV:

C= $\frac{2\ X\ 3.142\ X8.85\ X10^{-12}}{In\frac{1511.90}{6,9}}$ =$\frac{55\ X10^{-12}}{5.39}$ =10.20 X 10^{-12} F/m

Therefore: q= 9.0 x10^{-12} X 33,000 =297 X10^{-9}C

$\boldsymbol{E_{33}}$ =$\boldsymbol{\frac{297\ X\ 10^{-9} X\ 1.2}{4\ X\ 3.142\ X8.85X10^{-12}}}$ **X** $\boldsymbol{\frac{2}{1}}$ **=** $\boldsymbol{\frac{712.8\ X10^{-9}}{111\ X\ 10^{-12}}}$ **=6.42KV/m (33KV line)**

The Electric field within 1m close to 33KV is 6.42KV/m.This value is greater than 5KV/m for public exposure and less than 10KV/m for occupational exposure. All precautions should be taken, as it is extremely dangerous to work around the field for a prolonged time. Remember that the exposure time for workers in the field was stated as:

t = $\frac{80}{6.42}$ =12.46 Hours

The human body is made up of fluids(blood and limbs). The body fluids are good conductors of electricity. The body fluids acquire charges(when the body is within the electric field) and move to the surface of the body. These fluids alternate charges as the transmission line repeatedly alternates between the positive and negative in each cycle. The negative charges induced in the upper part of the body in half of a cycle flow into the lower part of the body in the second half of the cycle[15].

The power frequency of the electric field induces current in the body, as well as charges on the surface. If the worker is not well shielded from the Electric field with safety regalia, such a worker would be in danger of electrocution. The normal human body resistance is 2KΩ. The maximum body current induced by the electric field from a transmission line is much greater than the body current.

The magnetic field varies with the current flowing through the line. As the current increases, the magnetic field increases as well. Magnetic induction occurs in a body due to the force electric fields exert on the electric charges in the body. The induced currents flow in loops through the human body. The effect of the magnetic field is equally, affected by the distance from the magnetic field[25].

This will be analyzed in detail as we progress

Electrocution from electromagnetic waves could come in various forms, namely:

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8.2 ELECTROCUTION FROM ARCING:

The breakdown Voltage is the threshold required to break down an insulator. Air is an excellent insulator when the electric field is at its highest, air can gradually begin to break down and become partially conductive across a short distance.

Breakdown voltage in the air is a function of gap length and pressure. This can be represented as:

Breakdown voltage= gap length X pressure 8.1

$$V = f(pd) \quad 8.2$$

This equation is known as Paschen's law. p = gas(air) pressure; d= gap length.To account for the effect of temperature, Paschen's law is generally stated as

$$V=f(Nd), \quad 8.3$$

where N is the density of the gas molecules. The pressure of gas changes with temperature, according to gas law:

$$pv = NRT \quad 8.4$$

where v = volume of the gas, T= temperature and R= constant.

The breakdown potential of air is given as a power function(pd), as per results from experiments[26]

$$V=24.22\left[\frac{293\,pd}{760T}\right] + 6.08\left[\frac{293\,pd}{760T}\right]^{1/2} \quad 8.5$$

If p=760 torr T= 293K

$$\text{Electric field} = \frac{V}{d} = 24.22 + \left[\frac{6.08}{\sqrt{d}}\right] \quad 8.6$$

At 1cm gap E = 30KV/cm, this is the breakdown strength of air.

From equation 5.6 The electric field is inversely proportional to the distance for arcing to take place. This means at a closer distance to the Voltage source arcing is likely to take place.

For safety purposes, The Occupational Safety and Health Administration (OSHA), has established a safe working distance should be maintained from the Voltage source. Failure to maintain these safe working distances might lead to electrocution initiated by arcing. Table 2 below shows the recommended clearance for various Voltages [27].

Line clearance for Power lines	
Voltage	**Distance from Power lines**
≤50KV	10 feet
200KV	15 feet
350KV	20 feet

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500KV	25 feet
650KV	30 feet
800KV	35 feet

Table 2 Line clearance for Power lines.

The Safe working distance can be calculated using the formula below:

Line clearance distance= 10 feet + (0.4 Inches)(Voltage over 50KV) 8.7

An electric field can arc over to an object that is at a very short distance from it. When a field worker holding an object such as a screwdriver, plier, spanner, etc gets close to a distance where the electric field is at its peak(highest), it can draw an arc up to several feet before it can get extinguished. This occurs due to the breakdown of the air, especially during harmattan, when the air is dry and fully charged with electrostatic charges.

The body doesn't require sustained contact with the conductor to get electrocuted. The breakdown voltage of the human skin is 500V. At a minimum Voltage of 500V, the outer layer of the skin is damaged by high energies.

Two incidents of electrocution from arcing are mentioned below:

(1) **Engineers working on 33KV Panel**: Pauma Engineering was assigned to upgrade the size of the 7.5MVA transformer to 15MVA.The project requires upgrading the 33KV Panels as well. One of the senior Engineers with Pauma Engineering was unaware that the indoor SF6 breaker was faulty. He opened the breaker through the push button. The power supply in the power room went off, but unknowing to him one of the phases was still making contact with the system. Mr. Emmanuel opened the 33KV panel to inspect and work on the breaker. He was holding a screwdriver and a plier, on getting close to the breaker, stretching his hands(not putting on a hand glove), even before touching the breaker, there was a massive explosion inside the power control room.

Mr Emmanuel was seen lying on the floor, despite wearing safety boots and standing on an insulation mat before the accident. He suffered serious burns, with his clothes burnt and a puncture on the backside. The Voltage traveling through the body,because of the body resistance, the current heats up and burns the body. Luckily, he survived and was revived after a week in the hospital.

After a careful analysis of the accident, we concluded that the accident occurred due to arcing as his hands were not yet close to the breaker. Air can become conductive across gaps(close distance) due to the breakdown voltage of the air.

(2) Electrocution of workers working on street lights at NNPC drive in Kaduna:

In 2019 two men were electrocuted while maintaining streetlights along NNPC Drive. These workers were working using metallic scaffolds to reach the height of the street light pole. While working carrying the scaffold, they got too close to the 33KV line, and suddenly, an explosion was heard. When people got to the scene of the accident, two men were seen lying lifeless after the explosion.

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One of the colleagues of the dead workers argued that the scaffold did not make contact with the 33KV line as can be seen from the scaffold position. He, however, said he saw spark-like lighting in a flash and then the explosion that was heard.

If truly, the scaffold did not make contact with the 33KV overhead line. The spark he saw in a flash, can only be arcing. Since the scaffold was not isolated, the electric field, went through the scaffold to the earth, thereby forming a complete circuit.

The picture of this accident is attached as shown in Fig 9 below.

Fig 9 photo of electrocuted workers along refinery drive in Kaduna (source of the picture: by *Samuel on Tue 09th Jul 2019 - tori. ng)*

8.3 ELECTROCUTION FROM FLASHOVER VOLTAGE

When a 33KV power line, passes under 132KV or 330KV if proper precaution or preventive measures were not put in place during the construction flashover Voltage from the high Voltage line can likely occur to the 33KV line.

Lighting, Switching, or any other reasons can cause abnormal Voltage on the Transmission line. This abnormal Voltage can damage the 132KV or 330KV insulator. Damage to the insulators means a Phase-to-earth fault or Flashover Voltage will likely occur.

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In 1999, I was on an internship with Pauma Engineering. Pauma Engineering was Consulted to investigate the Cause of an accident in Farakwai, that took place on January 16, 1999, in Kaduna State. As was reported by the Daily Trust newspaper some years later, “13 people died instantly, while 53 sustained injuries and several properties went up the flame”[Daily Trust newspaper, Saturday 24, April 2, 2010].

Upon Investigation by our team, the villagers revealed that they had earlier seen: a flash of traveling wave along the 132KV transmission line, that later returned after a short period. This resulted in an explosion and the subsequent death of Villagers, staying inside their houses. The survivors reported that the walls and floor of their homes were shocking as they acquired very high potential[24].

8.4 Technical Observations:

The breakers of the 132KV and 33KV failed to trip, due to a fault on the protection relays.

There was a 33KV distribution line passing under the 132KV line. Guard wire was not used in between the crossing points. The traveling wave upon returning due to the failure of the 132KV breaker to trip, shattered the 132KV insulator, due to the high Electromagnetic field flashover to the 33KV line. This subsequently, was transformed in the 33/0.415KV sub-station near the incident. This transformed high Voltage, leading to complete insulation breakdown.

This flashover Voltage occurred due to the ionization of the air, which led to the breakdown potential of the air.

The fault on the 132KV line was caused by a red and blue phase line to the ground fault. Due to the failure of the protective device to sense and disconnect the faulty system, the fault lingered on. This fault resulted in a traveling wave [24].

8.5 Mathematical analysis:

The flashover Voltage of the 132KV Transmission line with 9 insulators is 485KV as shown in Table 3 below:

No of Units	Flashover Voltage(Dry)	Flashover Voltage(Wet)	Impulse flashover Negative	Impulse flashover Positive
9	485	320	775	760
11	635	395	1090	1040

Table 3 Flashover Characteristic[24]

The traveling wave damaged a phase Insulator, it follows that the flashover voltage given as 485KV from the table is considered on a single phase;

V_{132} = 485KV (flashover Voltage)

The efficiency of the disc insulator can be calculated using equation 6.12

$$\text{Efficiency of string} = \frac{Spark\ over\ voltage}{n\ X\ spark\ over\ voltage\ of\ one\ disc}$$

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From equation 6.15

V_9=7.26 V1 ; V_9=485KV, V_1= 66,804V

Efficiency of string =80.67%.Same as using equation 6.11. This follows that the voltage distribution along the insulator is the same at both the normal working voltage and under fault conditions. However, the fault condition voltage would lead to the breakdown of the insulating properties of the insulator, which would lead to the eventual damage of the insulator and subsequent flashover voltage.

The Electric field generated from this Voltage can be calculated using equation 1.15

$$E=\frac{qd}{4\pi\varepsilon_0}\frac{(3cos^2\theta+1)^{1/2}}{r^3}$$

Also, using equation 4.13

$$C= \frac{2\pi\varepsilon_0}{In\left[\frac{d}{r}\right]} \text{ F/m}$$

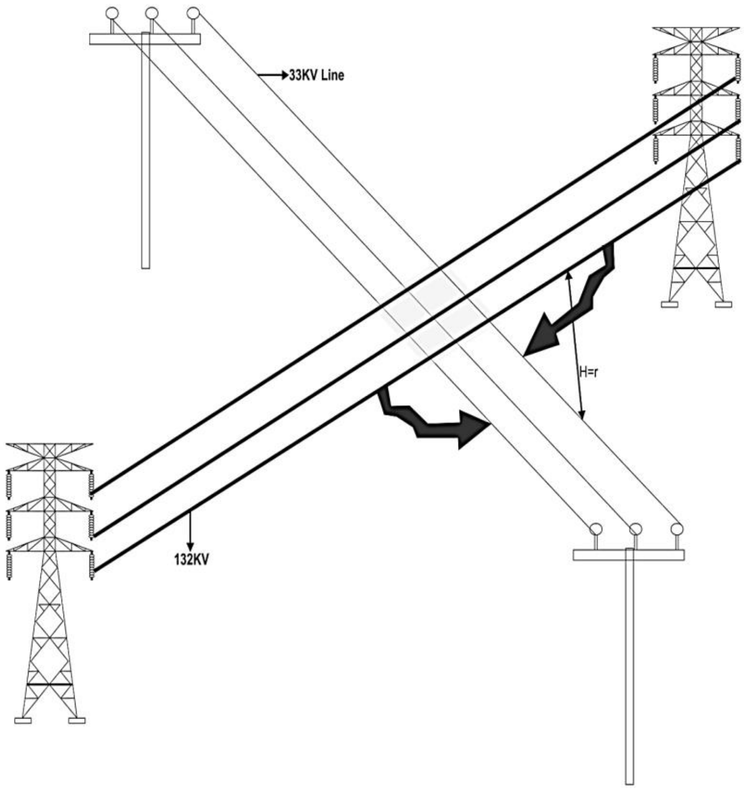

Fig 10 Flashover Voltage from 132KV Line to 33KV line

The Flash-over Voltage from the 132KV line to the 33KV line can be computed by subtracting the height of the 33KV line from the height of the 132KV tower. The Height of the 9 Dics insulator is approximately 1.9m; the tower arm separation layer is approximately 3.7m. The minimum sag is approximately 2m (a function of the span of towers).

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Height of 132KV tower =28.22m

Lowest conductor point=13.22m=28.22 – ((3X 3.7m)+ 1.9 +2)

Height of 33KV Pole =8.5m

Flashing point Height=H_{132} - H_{33} =13.22 − 8.5 = 5.3m

At the point the 33KV line crosses under the 132KV line.θ is at its maximum.

Summary:

The flashover voltage occurred due to the ionization of the air, which resulted in arcing across the two lines. As stated earlier the complete ionization of air is 30KV/cm. The flashover voltage occurred when the insulator was completely broken down, at a flashover voltage of 485KV. From Table 3 above, the flashover voltage for a 9-disc insulator is 485KV. An electric field is generated in the 132KV line which subsequently, is induced in the 33KV line via flashover voltage. This very high voltage in the 33KV line resulted in a short circuit in the 33KV line with a high electromagnetic field. This short circuit resulted in a break in the aluminum conductor which dropped on the 415V. The 415V line was connected to their homes. A dangerous High voltage got distributed into their homes, which damaged the insolation of most electrical equipment.

This dangerous high Voltage got into their homes through the 415V conductor. This then generated a strong electromagnetic field in their homes. This resulted in a high potential, where the floors and walls were shocking.

The voltage flashover from the 132KV line to the 33KV line could have been averted using a "Guard wire ". Guard wires are required to be used at points where high voltage line crosses power lines, rail lines, roads, and telecommunication lines and have to be earthed at all points.

9.0 ELECTROCUTION FROM STEP VOLTAGE:

A step potential is the potential difference between two points on the earth's surface, separated by a distance.

When a power line touches the ground, a phase-to-earth fault occurs. During the phase-to-earth, the fault current is very high, and a high potential is generated within the vicinity. The potential is distributed in a concentric circle waveform on the ground. Walking or standing near the accident can be as dangerous as touching the line conductor. Accidents that are occasioned by walking within the concentric circle potential, are referred to as "electrocution from step potential.

Step potential occurs when the two feet are in two voltage zones as shown in the diagram above. This difference in voltage causes current to flow through the body. The greater the difference between both feet the more electricity would flow through the body. The potential difference created by separating the two feet flows through the body. The average internal human impedance has been estimated to be 500 in humans. The voltage difference flowing through the body, causes a high current to flow through the body. Electrical current from an electric shock can cause instant death and burning of the body when it is orders of magnitude greater than acceptable physiological current.

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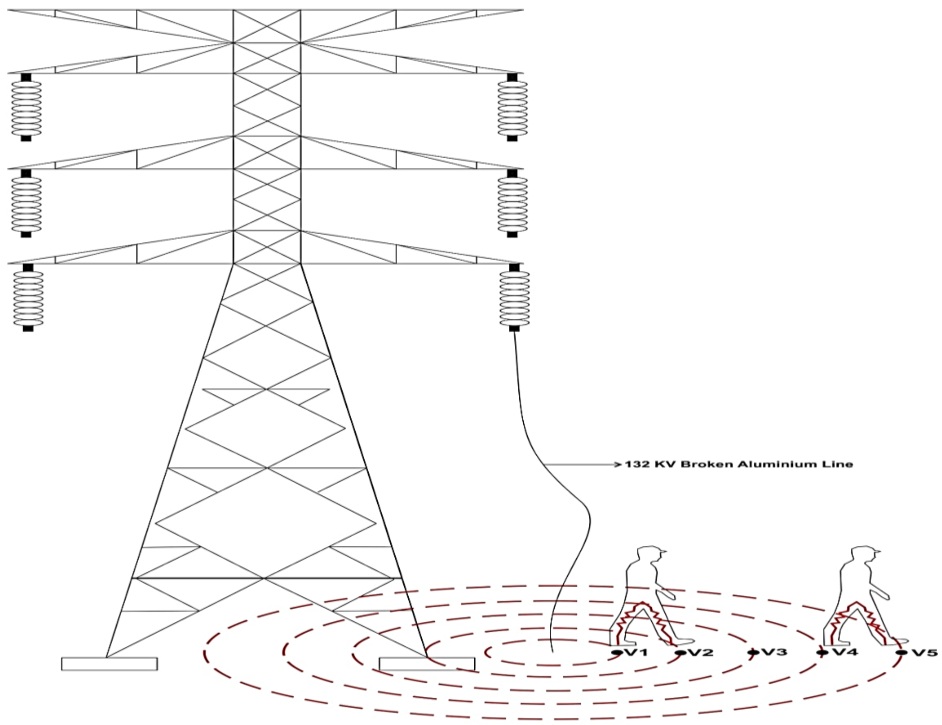

Fig 11. Step voltage

Step voltage can be calculated using the formula below:

$$S.V = \left(\frac{I \; X \; \delta}{2 \; X \; \pi}\right) X \left(\left(\frac{1}{L_1}\right) - \left(\frac{1}{L_1 + L_2}\right)\right) \qquad 9.1$$

S.V = Step Voltage

δ = 150Ωm (Soil electrical resistivity varies from place to place depending on the nature of the soil)

I= Earth fault current

L_1 = Distance from a person to the point where the wire touches the ground

L_2 = step distance (applies equal 0.5m-1m)

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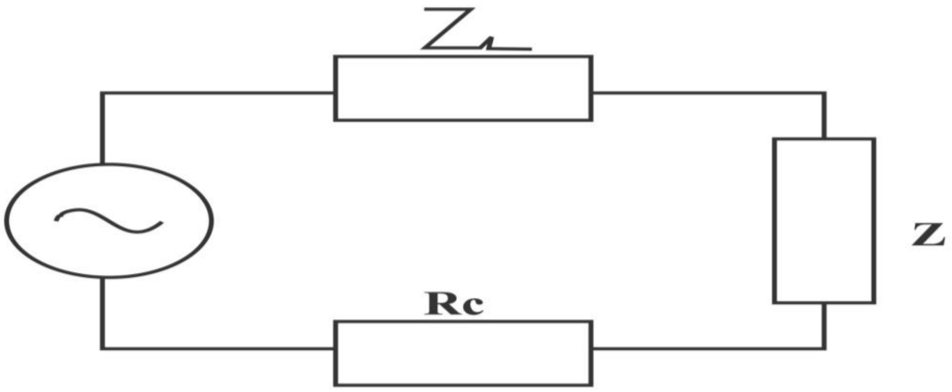

Fig 12. Equivalent circuit diagram.

I = $I_f = \frac{V_{phase\ to\ ground}}{Z_L + Z_{PEN} + R_C}$ 9.2

Z_L = Impedance of the phase conductor

figI = I_f = Earth fault current

Z_L = Impedance of the phase conductor

Z_{PEN} = Impedance of the PEN conductor

R_C = contact resistance at the fault location

$V_{phase\ to\ ground} = \frac{V_{LL}}{\sqrt{3}}$

V_{LL} = Phase Voltage

The magnetic field generated around, the conductor due to the short circuit is:

H= $\frac{I}{2\pi r}$

H= Magnetic field (A/m)

I =Earth fault current.

Electrocution from step Voltage can be avoided by observing the following precautions:

(1) Avoiding the fault area.

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(2) Walking with the two legs closed or jumping and landing with both legs closed. If a field worker's feet are in two separate voltage zones, these differences in voltage cause current to flow through the body and shock the person.

(3) When inside the car, it is advisable to remain inside the vehicle, unless, there is a fire outbreak. In such a situation, the person jumps down from the car with both feet landing on the ground at once. Such a person should continue to move with both legs joined together.

(4) Vehicles should be parked at least 30m from the accident scene.

CONCLUSION

Electric and Magnetic fields exist in all power conductors carrying electric voltage and current. Electric fields “E” are measured in V/m and magnetic field are measured in A/m. Electric fields decrease with an increase in distance. The electric field strength is at its peak at the tower base and dips at the center of the lines. The field decreases away from the tower on either side. Working with High voltage requires special precaution as this may prove fatal, especially when the worker is not putting on personal protective equipment for safety. A lot of people do not consider it dangerous to work in an Electric power electric field. A person inside an electric field, electric charge is distributed on the surface of the body. In the body, there are electric currents and a weak electric field. The magnetic field induces an electric current or weak electric field in the body. The ICNIRP guidelines emission limit of an electric field is 5KV/m and the magnetic field is 200μT. Professionals working inside electric fields and magnetic above the safe limit could risk their lives.

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