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Safety Considerations Untransposed Overhead Transmission Lines.

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SAFETY CONSIDERATIONS
IN
UNTRANSPOSED OVERHEAD TRANSMISSION LINES

BY

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ABSTRACT:

For untransposed H.V. T.L. the electro magnetic and electrosratic effects are so large that affecting the balance of T.L. phase impedances. So, if an ungrounded object in the near by of such lines, induced voltage will appear on it causing a flow of current from the object to ground through the object's capacitance.

This paper presents formulae for predicting the induced currents passing through an object in the vicinity of such lines.
Also, formulae for predicting the voltage gradient are developed.

1- INTRODUCTION:

For an ungrounded object in the nearby of extra high voltage transmission line, induced voltages appear on it due to the electromagnetic and electrostatic induction, causing a flow of current from the object to ground through the object's capacitance to gound which will be energised.

These induced voltages are more severe in the vicinty of untransposed transmission lines.

If a low impedance such as a person's body shorts the object to ground, there will be an initial pulse of current to discharge the energy stored in the object's capacitance to ground. This discharge may be painful or ev[illegible] to humans.

2- Induced Current In An Object:-

For the object X of length A_x i[illegible]
(1), in the nearby of a set of con[illegible]

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V_1, ..., V_i, ..., V_n and carrying charges Q_1, ..., Q_i, ..., Q_n then the object will has an induced voltage V_x, and will carry a charge Q_x.

The voltage equations can be written as:

$$\begin{bmatrix} V_1 \\ V_2 \\ \\ V_n \\ V_x \end{bmatrix} = \begin{bmatrix} P_{11} & \cdots\cdots & P_{1x} \\ \\ \\ P_{n1} & \cdots\cdots & P_{nn} \\ P_{x1} & \cdots\cdots & P_{xx} \end{bmatrix} \cdot \begin{bmatrix} Q_1 \\ \\ \\ Q_n \\ Q_x \end{bmatrix} \qquad \ldots\ldots\ldots(1)$$

Simbolically,

$$[V] = [P] \cdot [Q] \qquad \ldots\ldots\ldots(2)$$

Generally, the current flow from the i th conductor to the object is,

$$I_{ix} = J\, w.\, C'_{ix} \cdot (V_i - V_x) \cdot A_x \quad \text{amps} \qquad \ldots\ldots\ldots(3)$$

where,

C_{ix} = is the mutual capacitance between i th conductor and object X in the absence of the other conductors.

So, the total current flow to the object from n-conductors is,

$$I_x = \sum_{i=1}^{n} I_{ix} = J\, w.\, A_x \cdot \sum_{i=1}^{n} C'_{ix} \cdot (V_i - V_x) \ldots\ldots(4)$$

If the object is grounded; ($V_x = 0$) therefore,

$$I_x = J\, w.\, A_x \cdot \sum_{i=1}^{n} C'_{ix} \cdot V_i \qquad \ldots\ldots\ldots(5)$$

$$(-1)^{i+(n+1)} \cdot \frac{\text{cofactor } P_{ix}}{\text{determinant of } P} \ \text{Farad/meter}$$

To simplify the expression of C'_{ix} . a new set of voltages (V'_i) may be introduced as:

$$[V'_i] = [P_{ii}] \cdot [Q_i]$$

or in expanded form,

$$\begin{bmatrix} V'_1 \\ V'_2 \\ V'_n \end{bmatrix} = \begin{bmatrix} P_{11} & & \\ & P_{22} & \\ & & P_{nn} \end{bmatrix} \begin{bmatrix} Q_1 \\ Q_2 \\ Q_n \end{bmatrix} \qquad \ldots\ldots\ldots\ldots(6)$$

Solving eqn.(6) for $Q_1, Q_2, \ldots\ldots, Q_n$ and substituting in eqn.(1) gives:-

$$\begin{bmatrix} V_1 \\ V_2 \\ V_n \end{bmatrix} = \begin{bmatrix} 1 & P_{12}/P_{22} \ldots\ldots P_{1n}/P_{nn} \\ P_{21}/P_{11} & 1 \quad \ldots\ldots \\ P_{n1}/P_{11} & \ldots\ldots\ldots\ldots\ 1 \end{bmatrix} \begin{bmatrix} V'_1 \\ \\ V'_n \end{bmatrix} \qquad \ldots\ldots\ldots(7)$$

Symbolically:

$$[V] = [H] \cdot [V']$$

$$\therefore [V'] = [H]^{-1} \cdot [V] \qquad \ldots\ldots\ldots\ldots(8)$$

where,

$$H_{ii} = 1$$

and $H_{ij} = P_{ij}/P_{jj}$

So , the voltage of conductor i is:-

$$V_i = \sum_{j=1}^{n} \frac{P_{ij}}{P_{jj}} \cdot V'_j \qquad \ldots\ldots\ldots\ldots(9)$$

$\therefore$ substituting in eqn. (5)

$$\therefore I_x = J\,W.\,A_x \sum_{i=1}^{n} C'_{ix} \cdot V'_i \qquad \ldots\ldots\ldots\ldots(10)$$

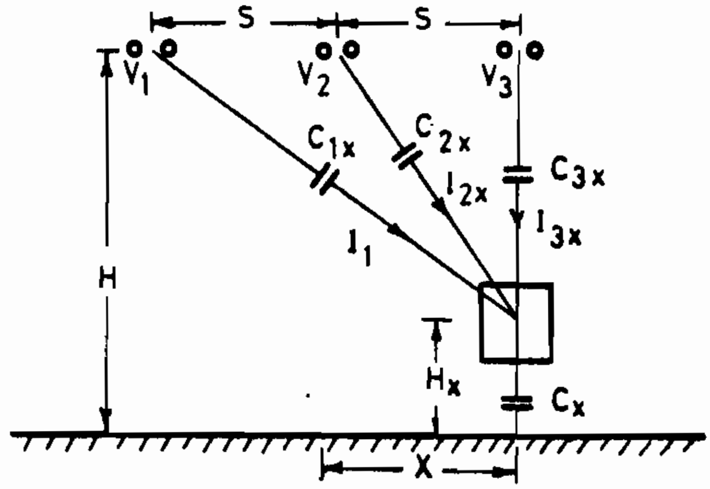


FIG (1): OBJECT IN VICINITY OF OVER HEAD TRANSMISSION LINE

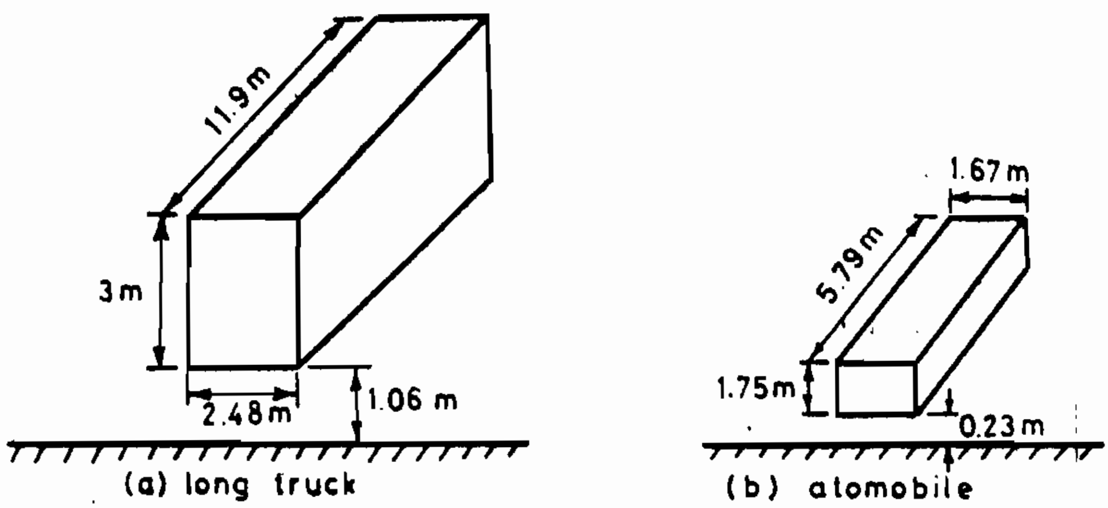


FIG.(2): OBJECTS CONSIDERED FOR APPROXIMATE INDUCED CURRENT FORMULA where,

C_{ix} can be approximated to a high degree of accuracy as:-

$$C_{ix} = \frac{P_{ix}}{P_{ii} \cdot P_{xx} - P_{ix}^2} \qquad \text{Farad/meter.}$$

3. Energy Stored:

The energy stored in the object's capacitance to ground is:

$$SE_x = \tfrac{1}{2} C_x \cdot V_{xp}^2 \quad \text{joules} \qquad \ldots\ldots\ldots\ldots(11)$$

where,

V_{xp} is the object's peak open circuit voltage.

If R_x is the leakage resistance, V_{xp} is given by:

$$V_{xp} = 2\, I_x \cdot R_x / (1 + R_x \cdot J\, w \cdot C_x) \quad \text{volts} \qquad \ldots\ldots\ldots(12)$$

The current I_x can be calculated from eqn.(10) and the value of C_x (the object -to- ground capacitance) can be approximately computed(5) as:

$$C_x = \left(\frac{A_x}{3.048} - 1\right) \cdot 1000 \quad \text{picofarads} \qquad \ldots\ldots\ldots\ldots(13)$$

4. Voltage Gradient(3):

At the vicinity of an O. H. T. L., the voltage gradient is given by:

$$E_x \doteq \frac{1}{2\pi\epsilon_0} \sum_{i=1}^{n} \frac{Q_i \cdot 2\, H_i \cdot 10^{-3}}{H_i^2 + S_{ix}^2} \quad \text{KV/m.} \qquad \ldots\ldots\ldots(14)$$

$$\text{and} \quad [Q] = [P]^{-1} \cdot [V] \qquad \ldots\ldots\ldots\ldots(15)$$

where:-

H_i is the phase bundle height above ground in meters.

S_{ix} is the distance in meters from the i th bundle to the point of interest.

n is the number of phase bundles.

Q_i is the charge of phase bundle in coulombs.

ϵ_o is the permittivity of free space = $8.854 \cdot 10^{-12}$ F/m.

5. Approximate Formulae For Predicting Electrostatic Effects[5]:-

5.1. Induced Current:

For a long truck and an automobile of dimensions as shown in Fig.(2), Formulae are developed to have the maximum induced current I_{xp}, the cutt-off current I_{xc}, the cutt-off distance L_c (the distance from the center phase to where this current level exists), and the slope α_{xc}.

For T.L. with horizontal configurations, different phase spacing, different operating voltages, and different heights, the induced current defined by eqn.(10) can be evaluated and plotted as a function of the distance Fig. (3).

Imperically the maximum r.m.s. induced current is given by:-

$$I_{xp} = a \cdot (KV) \cdot (V_{p.u.}) \cdot \sqrt{S} \cdot h^{-b} \quad mA \qquad \ldots\ldots(16)$$

where,

- a is constant, depends on the line voltage and object size.
- KV is the nominal line -to- line voltage of the transmission circuit.
- h is the height in meters of the flat conductor configuration above the ground.
- b is constant which depends also on line voltage and object size.
- S is the phase spacing in meters.
- $V_{p.u.}$ is the per unit operating voltage of the line.

Table (1-A) gives the constants a and b for predicting maximum r.m.s. induced current I_{xp}.

The cutt-off distance L_c was found to be a function of phase spacing S. It can be calculated as:-

$$L_c = C \cdot S + d \qquad \ldots\ldots\ldots\ldots(17)$$

where, constants C & d are given in Table (1-B)

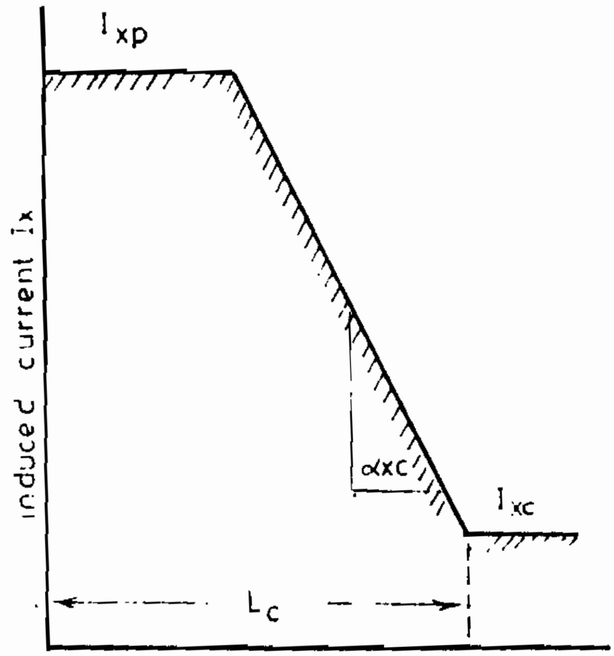
The cutt-off current I_{xc} depends on line voltage and object size

$$I_{xc} = V_{p.u.} \cdot I_{xco} \quad mA \qquad \ldots\ldots\ldots\ldots(18)$$

where,

I_{xco} is the cutt-off current at nominal voltage.

Table (1-C) gives the values of I_{xco} for a long truk and an automobile.



FIG(3) ZONE BOUNDARIES FOR INDUCED CURRENT

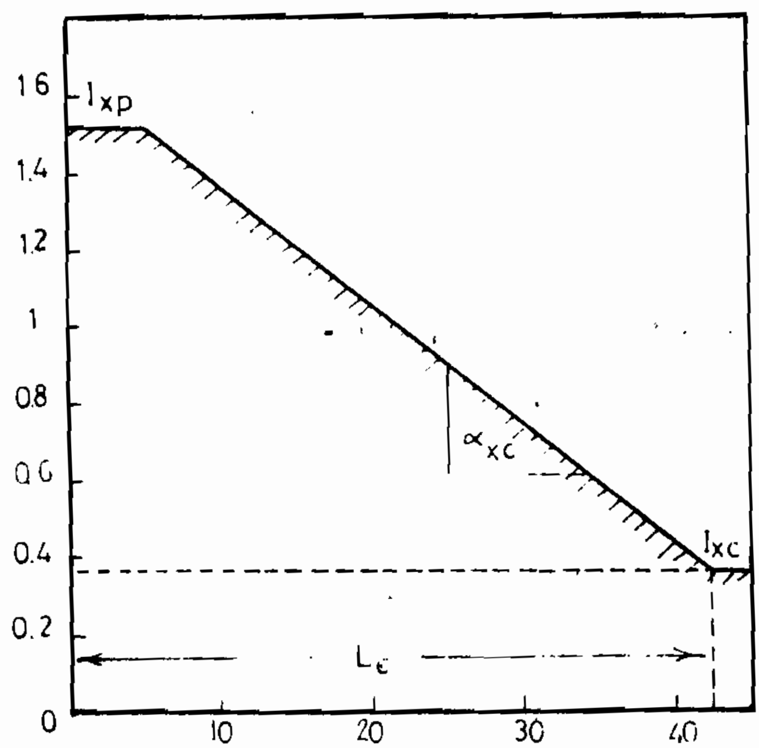


FIG.(4):ZONE BOUNDARIES FOR THE NUMERICAL APPLICATION

The slope α_{xc} is the greatest slope of a straight line through the cutt-off point, defined by L_c and I_{xc}, and tangent to the induced current curve. It is a function of conductor height and is given by:-

$$_{xc} = g \cdot h^{-2} \quad mA/m \qquad \text{..........(19)}$$

where,

g is a function of line voltage and object size, and given in Table (1-D)

5.2. Voltage Gradient:

Similarly, the maximum r.m.s. voltage gradient is given by the following formula:

$$E_{xp} = m.(KV) \cdot (V_{p.u.}) \cdot \sqrt{S} \cdot H^{-n} \quad KV/m \text{ .....(20)}$$

where, m and n depend on line voltage and are given in Table (2-A) for various voltages.

The cutt-off distance M_c is given by:-

$$M_c = p.S + q \quad \text{meters} \qquad \text{..........(21)}$$

The values of p & q are given in Table (2-B) for various values of line voltage.

The slope β_{xc}, is given by:-

$$\beta_{xc} = R.H^{-2} \quad KV/m/m \qquad \text{..........(22)}$$

where Table (2-C) determines the values of R for various voltages.

The cutt-off voltage gradient, E_{xc} is given by

$$E_{xc} = V_{p.u.} \cdot E_{xco}$$

where,

E_{xco} is the cutt-off gradient at nominal voltage and given in Table (2-D).

6. Numerical Application:

If an automobile with dimensions shown in Fig.(2) in near-by a 765 KV line having a phase spacing S = 15 m., conductor height h = 15 m., two 46 m.m. diameter conduotors per bundle and subspacing of 0.49 m. The line was assumed to be operating at 800 KV. It is required to establish areas along the right -of- way at which electrostatic effects may be a problem.

Solution:-

From Table (1-A), for an automobile, and at 765 KV,

∴ $a = 0.0497$ & $b = 1.635$

Substituting in eqn. (16)

∴ $I_{xp} = (0.0411) \cdot (765) \cdot (\frac{800}{765}) \cdot \quad 15 \quad \cdot (15)^{-1.635}$

$= 1.52$ m.A.

From Table (1-B)

∴ $C = 1.491$ & $d = 20.20$

Substituting in eqn. (17)

∴ $L_c = (1.491) \cdot (15) + 20.20$

$= 42.56$ m.

From Table (1-C)

∴ $I_{xco} = 0.364$ m.A.

Substituting in eqn.(18)

∴ $I_{xc} = (\frac{800}{765}) \cdot (0.364) = 0.38$ m.A.

From Table (1-D)

∴ $g = 12.97$

Substituting in eqn.(19);

∴ $\alpha_{xc} = (12.97) \cdot (15)^{-2} = 0.057$

∴ So, we can plot the zone boundary values from the foregoing results as shown in Fig. (4).

Substituting in eqn.(13) to have the automobile's capacitance to ground,

∴ $C_x = (\frac{5.79}{3.048} - 1) \cdot 1000 = 899.6$ picofarad assuming that its leakage resistance is infinite, and substituting in eqn.(12) So,

$$V_{xp} = \frac{2 \cdot (1.25 \cdot 10^{-3}) \cdot R_x}{2 \cdot (50) \cdot R_x \cdot (899.6 \cdot 10^{-12})} = 6254.97 \quad \text{volts.}$$

Substituting in eqn.(11) to have the discharge anergy,

∴ $SE_x = ½ (899.6 \cdot 10^{-12}) \cdot (6254.97)^2$

$= 17.59$ milli-joules.

Table (1)

Line-to-Line Voltage KV	A				B		C		D	
	Automobil (5.79 m)		Long Truck (11.9 m)		Automobile & Long Truck		I_{xco} (mA)		Autom-obile	Long Truck
	a	b	a	b	c	d	Autom-obile	Long truck	g	g
345	0.0453	1.652	0.217	1.763	2.055	12.22	0.173	0.609	4.35	16.98
500	0.0506	1.689	0.211	1.743	1.504	17.89	0.230	0.773	7.60	25.10
765	0.0497	1.635	0.194	1.669	1.491	20.20	0.364	1.272	12.97	47.03
1100	0.0404	1.545	0.157	1.579	1.640	17.01	0.600	2.060	19.57	68.98

Table (2)

Line-to-Line Voltage KV	A		B		C	D
	m	n	p	q	R	E_{xco} (KV/m)
345	0.2550	1.6923	2.055	12.21	23.34	0.89
500	0.3068	1.7425	1.604	17.89	47.04	1.18
765	0.3076	1.6819	1.491	20.20	72.98	2.00
1100	0.2532	1.5876	1.640	17.01	115.57	3.35

7. Conclusions:

Formulae for predicting the maximum induced current in an object in the vicinity of EHV and UHV lines have been presented which enable the designer to establish the zone at which the electrostatic effects may be a problems.

Also, Formulae for predicting the voltage gradient at ground level have been developed.

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