IMPROVED METHOD FOR CALCULATING INDUCED CURRENTS ON A LINEMAN ENGAGED IN TRANSMISSION-LINE INSULATOR WASHING

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ABSTRACT

The aim of this paper is to calculate the induced currents on a lineman engaged in transmission-line insulator washing. The method of analysis is based on the charge simulation technique. The lineman is modeled by small sphere for the head and a large sphere for the body. For simplicity, the tower is chosen of the duct type and the insulator of the cylindrical suspension type. The transmission-line conductor is simulated by finite and semi-infinite line charges to account for the nonuniform distribution of conductor charge resulting from the suspension insulator and the supporting tower. As the purity of the washing water is high, the water spray is simulated by a thin dielectric stick extending between the column insulator and the lineman sitting on the crossarm of the tower. This represents a three-dimensional field problem and care has been devoted in the choice of the number and coordinates of charges simulating the tower, the insulator, the conductor, the water spray and the lineman. The induced currents increase as the lineman approaches the insulator with the suspended line conductor. These currents are higher for grounded lineman than those for insulated lineman and may exceed the safe limits.

Keywords: Charge simulation technique, Induced currents, Lineman, Insulator washing.

I. INTRODUCTION

Discharges on the surface of suspension insulators of overhead lines from towers (supports) are often troublesome and source of radio noise and interference with communication networks. The trouble is usually a contamination of the insulator surface. The problem often essentially disappears after it is washed as a part of a maintenance program [1]. The lineman engaged in insulator washing sits on the crossarm of the tower from which the insulators are suspended, to direct the water spray towards the insulators [2].

In the vicinity of ac power lines suspended from the crossarm, a power frequency electric field exists in the space around the line conductors. For a lineman insulated from the crossarm, the body will be charged to a potential depending upon his position in the transmission-line produced field and the field strength. Subsequently, a displacement current enters one side of the body, flows through it and lines of force emanate from the other side to the grounded crossarm. Under these conditions, he will assume a potential other than ground and receive a small disturbing shock with associated short-circuit current when he touches the cross-arm. On the other hand, a grounded lineman during the washing process perturbs the electric field with an enhancement of the field strength in his vicinity. The induced currents in the body due to such enhanced fields may exceed the safe limits.

This paper is aimed at evaluating the distribution of the induced currents on the body of a lineman engaged in insulator washing. The method of analysis is based on the charge simulation technique and takes into account the disturbances of the electric field and potential due to the frame of the tower and due to the presence of the human body and the water spray toward the suspension insulator. This is a pre-requisite for calculating the induced currents in the human body. First of all, the method of calculation is presented. Then, the obtained results are discussed in the light of electric field induction on objects adjacent to AC power transmission lines.

II. METHOD OF ANALYSIS

Figure (1) shows a single-phase conductor-to-plane arrangement where the conductor is suspended from a tower. For simplicity, the tower is chosen of the duct type and the insulator of the column type. The tower has an opening of width W and height H. The thickness of the tower is of T_1 for the legs and T_2 for the crossarm. The insulator has diameter of $2R_i$. The lineman is modeled by a small sphere for the head and a large sphere for the body. As the purity of the washing water is high, the water spray is simulated by a thin dielectric stick extending between the column insulator and the lineman sitting on the crossarm.

In a previous study [3], the water spray was simulated by a thin conducting stick where the potential is constant along the spray. This results in either one of two consequences. The first, is that the potential of the spray is that of the body and a significant potential difference appears between the water spray and the point where the spray meets the insulator. The second consequence is that the potential of the spray is equal to that of the suspension insulator where the spray terminates and a significant potential difference also appears between the body and the water spray where the human grabs the water-spray nozzle. In either of the two consequences, the significant potential difference represents a discontinuity in the potential which should be continuous.

2.1. *Simulation Technique:*

2.1.1 *Tower simulation :*

The tower legs are simulated in the X-Z plane by N_1+N_2 vertical finite line charges of unknown charges q_i ; i = 1,2, ... N_1 for the left leg and q_i ; i = N_1 +1, N_1+2, ... N_1+N_2 for the right leg. The crossarm of the tower in the X - Z plane is simulated by N_3 horizontal finite line charges q_i ; i = N_1+N_2+1, N_1+N_2+2, ... $N_1+N_2+N_3$. The thickness of the tower in the Y-direction is negligible with respect to the HV conductor length which extends very long in that direction. The simulation line charges q_i; i =1,2, ... $N_1+N_2+N_3$ are located along the axis of the tower frame, Figure (1).

2.1.2 *HV conductor simulation:*

The HV conductor is simulated in the X-Y plane by N_c-1 horizontal finite line charges extending along the axis of the conductor in the positive Z-direction with unknown charges q_i;i=$N_1+N_2+N_3+1$, $N_1+N_2+N_3+2$, ... $N_1+N_2+N_3+N_c-1$ as well as one semi-infinite line charge at the end of the conductor. Symmetry of simulation charges about the X-Z plane is considered and the same conductor simulation charges are symmetrically located along the negative Y-direction.

2.1.3. *Water spray simulation*

The water spray, being considered a dielectric stick extending between the human body and the insulator is simulated by N_s finite line charges along the spray axis and N_S ring charges around with unknown charges q_i; i=$N_1+N_2+N_3+N_c+1$, $N_1+N_2+N_3+N_c+2$,...$N_1+N_2+N_3+N_c+2N_s$.

Thus, the total number N_t of the simulation line charges = $N_1+N_2+N_3+N_c+2N_s$,including $N_1+N_2+N_3+N_C+N_S$ - 1 finite line charges, N_S ring charges and one semi-infinite line charge.

2.1.4. *Lineman simulation:*

The lineman is simulated by N_h rings for the head and N_b rings for the body with unknown charges q_i; i = N_t +1, N_1+2, ... N_1+N_H , where $N_H=N_h+N_b$. These ring charges are located along the axis joining the centers of the spheres simulating the head and body of the lineman. The radii of these spheres are small in comparison with the dimensions of the tower.

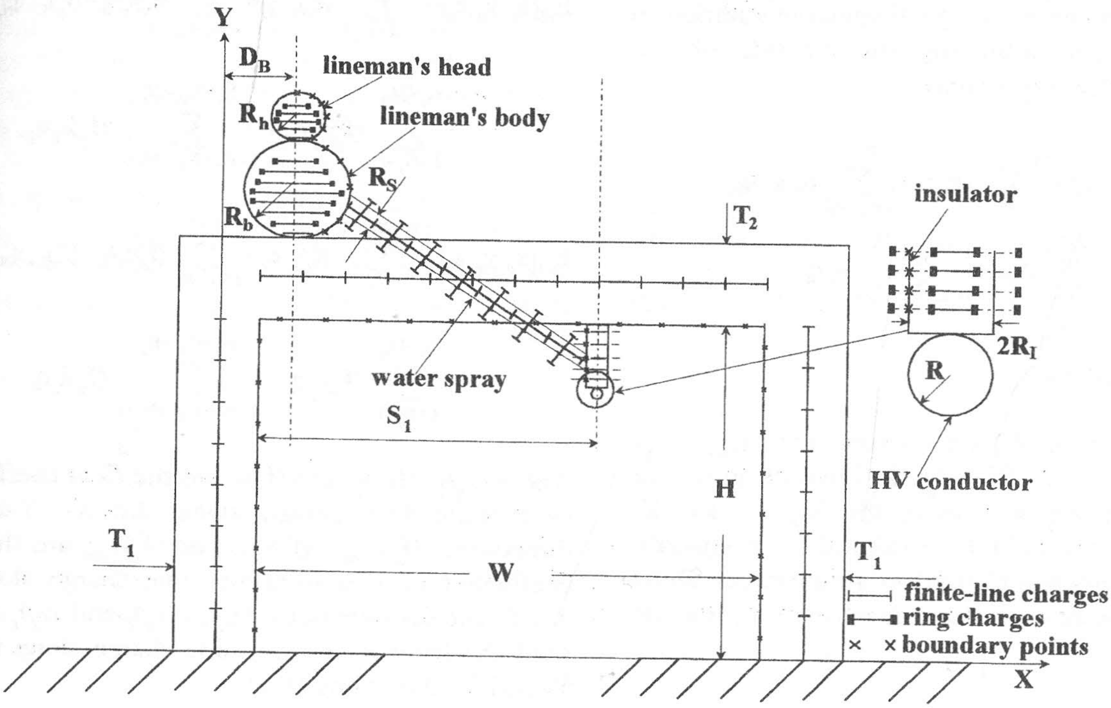

Figure 1. Geometry of the investigated system.

2.1.5. *Suspension insulator simulation*

In the insulator, dipoles are aligned by the applied electric field and compensate each other through the volume of the insulator leaving net charges only on the surface. These charges are simulated by fictitious ring charges inside and outside the insulator volume. The number of simulation charges in the insulator is N_i, the same as that in air N_a and the unknown charges belonging to the insulator are q_i ; $i = N_t + N_H+1, N_t+N_H+2,\ldots,N_t+N_H+N_r$, where $N_r=N_i+N_a$. Subsequently, the total number N_T of simulation charges for the investigated geometry, Figure (1), is $N_t+N_H+N_r$. Of these charges N_H (for the line man), N_S (for the air surrounding the spray) and N_r (for the insulator) are ring charges.

2.1.6 *Ground-plane simulation :*

To maintain zero potential at the ground plane, images of the simulation charges are considered with respect to this plane.

2.2. *Potential Equations :*

The potential f_1 at point P_1 (X_p, Y_p, Z_p) located in the air space is the algebraic sum of potentials due to all finite line charges, one semi-infinite line charge, ring charges of the lineman and ring charges inside the insulator;

$$\phi_1(x_p,y_p,z_p) = \sum_{i=1}^{N_t-N_s-1} P_{iL}\, q_i + P_{L\infty}\, q_{N_t} + \sum_{i=N_t+1}^{N_t+N_H+N_I} P_{ir}\, q_i \quad (1)$$

where P_L , $P_{L\infty}$ and P_r are the potential coefficients of finite-line charge, semi-infinite line charge and ring charge respectively [4-6].

Attention has been made for the symmetry of the conductor charge about the X-Z plane by modifying the potential coefficient expression to accommodate the contribution of the simulation charge and its symmetrical charge.

The potential ϕ_2 at point P_2 (X_p, Y_p, Z_p) located in the insulator volume is the algebraic sum of potentials due to finite line charges, simulating the tower and the HV conductor one semi-infinite line charge and ring charges of the lineman in addition to the ring charges simulating the air side of the insulator and the water spray:

$$\phi_2(x_p,y_p,z_p)=\sum_{i=1}^{N_t-2N_s-1} P_{iL}q_i+\sum_{i=N_t-N_s}^{N_t-1} p_{ir}q_i+q_{N_t}+\sum_{i=N_t+1}^{N_t+N_H} P_{ir}q_i+\sum_{i=N_t+N_H+N_l+1}^{N_t+N_H+N_r} P_{ir}q_i \quad (2)$$

2.3. *Field Equations :*

The electric field E_1 (of components E_{x1}, E_{y1}, E_{z1}) at any point P_1 (X_p, Y_p, Z_p) located in the air space is the algebraic sum of the X-, Y- and Z- components of the field due to all finite line charges, one semi-infinite line charge and ring charges of the lineman in addition to the ring charges inside the insulator;

$$E_{x1}(x_p,y_p,z_p)=\sum_{i=1}^{N_t-1}(f_x)_{i_L}q_i+(f_x)_{L\infty}q_{N_t}+\sum_{i=N_t+1}^{N_t+N_HN_l}(f_x)_{i_r}q_i$$

$$E_{y1}(x_p,y_p,z_p)=\sum_{i=1}^{N_t-1}(f_y)_{i_L}q_i+(f_y)_{L\infty}q_{N_t}+\sum_{i=N_t+1}^{N_t+N_HN_l}(f_y)_{i_r}q_i \quad (3)$$

$$E_{z1}(x_p,y_p,z_p)=\sum_{i=1}^{N_t-1}(f_z)_{i_L}q_i+(f_z)_{L\infty}q_{N_t}+\sum_{i=N_t+1}^{N_t+N_HN_l}(f_z)_{i_r}q_i$$

The electric field E_2 (of components E_{x2}, E_{y2}, E_{z2}) at any point P_2 (X_p, Y_p, Z_p) located in the insulator volume is the algebraic sum of the X-, Y- and Z- components of the field due to all finite line charges, one semi-infinite line charge and ring charges of the lineman in addition to the ring charges simulating the air side of the insulator and the water spray;

$$E_{x2}(x_p,y_p,z_p)=\sum_{i=1}^{N_t-2N_s-1}(f_x)_{i_L}q_i+\sum_{i=N_t-N_s}^{N_t-1}(f_x)i_rq_i+(f_x)_{L\infty}q_{N_t}+\sum_{i=N_t+1}^{N_t-N_H}(f_x)_{i_r}q_i+\sum_{i=N_t+N_H+N_l+1}^{N_t+N_H+N_r}(f_x)i_rq_i$$

$$E_{y2}(x_p,y_p,z_p)=\sum_{i=1}^{N_t-2N_s-1}(f_y)_{i_L}q_i+\sum_{i=N_t-N_s}^{N_t-1}(f_y)i_rq_i+(f_y)_{L\infty}q_{N_t}+\sum_{i=N_t+1}^{N_t-N_H}(f_y)_{i_r}q_i+\sum_{i=N_t+N_H+N_l+1}^{N_t+N_H+N_r}(f_y)i_rq_i$$

$$E_{z2}(x_p,y_p,z_p)=\sum_{i=1}^{N_t-2N_s-1}(f_z)_{i_L}q_i+\sum_{i=N_t-N_s}^{N_t-1}(f_z)i_rq_i+(f_z)_{L\infty}q_{N_t}+\sum_{i=N_t+1}^{N_t-N_H}(f_z)_{i_r}q_i+\sum_{i=N_t+N_H+N_l+1}^{N_t+N_H+N_r}(f_z)i_rq_i$$

where $(f_x)_L$, $(f_y)_L$ and $(f_z)_L$ are the field coefficients of a finite line charge along the X-, Y-and Z- directions, $(f_x)_{L\infty}$, $(f_y)_{L\infty}$ and $(f_z)_{L\infty}$ are the field coefficient of a semi-infinite line charge along the X-, Y- and Z- directions, $(f_x)_r$, $(f_y)_r$ and $(f_z)_r$ are the field coefficients of a ring line charge along the X-, Y- and Z- directions [4-7]

2.4. *Boundary Conditions :*

The first boundary condition is the Dirichlet condition at the surface of the conducting parts of the investigated geometry, Figure (1), including the HV conductor, the frame of the tower and the lineman. The calculated potential ϕ_1 is equal to (1) the applied voltage at the HV conductor, (2) zero at the surface of the tower frame, and (3) the floating potential picked-up by the lineman if he is insulated from the frame of the tower or zero if the lineman is grounded.

If the lineman is insulated from the tower frame, he will pick-up a potential f_b depending on how thick is the insulation between the frame and the lineman. In this case, the potential f_b is an unknown to be determined among the unknown simulation charges, and the sum of the charges simulating the lineman is equal to zero, i.e.

$$\sum_{i=N_t+1}^{N_t+N_H} q_{ir}=0 \quad (5)$$

As the purity of the spray water is very high and considered as an ideal dielectric no current will be flowing in the spray and the problem remains an electrostatic one.

Instead of one boundary condition (Dirichlet condition) at the conducting parts of the investigated geometry, two boundary conditions have to be satisfied at the insulator surface and at the water spray surface; namely.

a) The potential ϕ_1 at any point along the insulator (or spray) surfaces if the point is seen from the air side is the same as ϕ_2, the potential when the point is seen from the insulator (or spray) side, i.e.

$$\phi_1 - \phi_2 = 0 \tag{6}$$

The electric field at any point E_{nI} normal to the insulator or spray at any point on its cylindrical surface if the point is seen from the air side is related to E_{nII}, the normal field when the point is seen from the insulator or spray side as:

$$E_{nI} - \epsilon_r E_{nII} = 0 \tag{7}$$

which is the Neuman's condition

where $E_{nI} = \sqrt{E_{x1}^2 + E_{y1}^2}, E_{nII} = \sqrt{E_{x2}^2 + E_{y2}^2}$ in the plane Y=0, and ϵ_r is the permittivity of the insulator material or water.

2.5. *Boundary Points:*

To satisfy the boundary conditions, boundary points are chosen on all the parts of the investigated geometry, Figure (1).

On the surface of the tower frame, a boundary point is assigned for each finite line charge simulating the tower. The boundary point is located midway between the start and end points of the respective simulation charge. In the same manner, boundary points on the HV conductor are assigned to the finite line charges simulating the conductor along the positive Y-direction. Similarly, boundary points on the water spray are selected, each is assigned to finite line and the surrounding ring charges simulating the spray.

On the lineman, a boundary point is assigned for each simulation ring -charge. The point is located in the same z-level as the respective ring charge. In the same manner, boundary points are selected along the column insulator, i.e. at the same Z-level of the respective simulation ring charges.

2.6. *Determination of the Unknowns:*

With the aid of equations (1) and (2) for the potential, the Dirichlet boundary condition described above is satisfied at the boundary points chosen on the frame of the tower, the HV conductor and the lineman. Also, the continuity of the potential as expressed by eqn. (6) is satisfied at the boundary points chosen on the insulator and spray surfaces.

With the aid of equations (3) and (4) for the field, the Neuman boundary condition expressed by eqn. (7) is satisfied at the boundary points chosen on the column insulator and spray surfaces.

All of this results in a set of simultaneous equations whose solution determines the unknowns.

If the lineman is insulated from the tower, an additional equation is formulated using the boundary condition (5).

Once the unknowns are determined, the electric field at any point and the potential picked-up by the insulated lineman are evaluated.

2.7. *Surface Electric Field, Charge and Induced Current on Lineman:*

The total electric field at the i^{th} contour point on the lineman surface is expressed as:

$$E_n = \sqrt{E_{xi}^2 + E_{yi}^2 + E_{zi}^2} \tag{8}$$

where E_{xi}, E_{yi} and E_{zi} are the x-, y- and z-component of the electric field at the i^{th} point. The total field is normal to the lineman surface being assumed a perfect conductor.

The corresponding charge density on the lineman surface at the i^{th} point is expressed as:

$$\sigma = \epsilon_o E_n \tag{9}$$

where ϵ_o is the permitivity of free space.

At the i^{th} contour point, the induced current density J normal to the surface of the lineman and just inside his surface is expressed as [8]:

$$J = \omega \sigma = \omega \epsilon_o E \qquad (10)$$

where ω is the angular frequency of the voltage applied to the HV conductor.

The induced current just inside the surface of a part of the lineman, say k^{th}, is obtained by integrating J over the surface area S_k of this part:

$$I_k = \int_{S_k} ds \qquad (11)$$

On the other hand, the current density distribution inside the body depends on the material constants assigned to the human organs filling the volume of the body.

III. RESULTS AND DISCUSSION

3.1. *Accuracy of the simulation technique:*

The accuracy of the simulation technique is assessed by calculating the potential at check points selected between the boundary points. The deviation of the calculated potential from the value applied to the HV-conductor and from zero for the frame of the tower did not exceed 0.4%. A slight increase of the potential deviation was observed at the ends of the tower legs and may be attributed to the effect of the cross-arm at one end and the ground plane at the other end. On the other hand, the potential deviation (expressed as a percentage of the applied voltage) along the positive Y- direction of the HV-conductor is about 0.1%. However, an increase (up to 4%) took place at the ends of the conductor. This is at the effect of the frame of the tower at Y=0 and the discontinuity at the end of the line where the line, being simulated by finite line charges, is replaced by a semi-infinite line charge.

The larger the number of the simulation charges N_1 and N_c, the smaller is the deviation of the calculated potential from the applied voltage value and the higher is the accuracy of the simulation. Throughout the course of the present results, N_1 is kept constant at 20 line charges. The number of simulation charges N_2 and N_3 are chosen equal to N_1. The number of simulation charges of the conductor is also maintained at 20 charges. The number of ring charges (N_h, N_b) simulating the head and body of the lineman are assigned values of 5 and 10 respectively. The number of ring charges (N_i = N_a) simulating the insulator was kept at 10 charges. The number of finite-line/ring charges simulating the water spray was chosen 30. The relative permittivity of the suspension insulator is 4 and that of water spray is 80.

3.2. *Potential Distribution along the spray cloud:*

Table (I) shows how the potential ϕ along the spray changes from ϕ_b, the potential acquired by human body to ϕ_i , the potential where the spray meets insulator surface. l is the distance measured along the spray length starting at the lineman side and L is the spray length.

3.3. *Induced field, charge and current-density on lineman:*

Figure (2) shows the distribution of the electric field around the head and body of the lineman. The electric field, being normal to the profile of the lineman, is plotted radially as shown in Figure (2). The electric field assumes a step change at the angle q which defines the direction of the water spray where the lineman grasps the insulated spray-nozzle by his hands. However, the present calculated field values, where the water spray extends, are higher than those reported before [3]. This is simply ascribed to the changing nature of the water spray from a conducting stick [3] to a dielectric stick as described before.

Integration of the current density, eqn. (11), over the surface of the lineman gives the induced current. The latter depends on the relative position of the lineman sitting over the tower cross-arm with respect to the HV-conductor. Also, the induced currents depend on how high is the position of the lineman above the cross-arm.

Figure (3) shows how the induced current in grounded and isolated lineman increases as the lineman approaches the HV conductor. It is clear that the previous calculated induced current [3] remains almost constant up to 5 meters from the conductor and starts to increase at 4.5 meters.

Table I. The potential ϕ along the water spray.

Normalized distance along the spray (l/L)	0%	20%	40%	60%	80%	100%
Potential (ϕ/V)100%	0.035	0.076	0.097	0.173	0.202	0.316

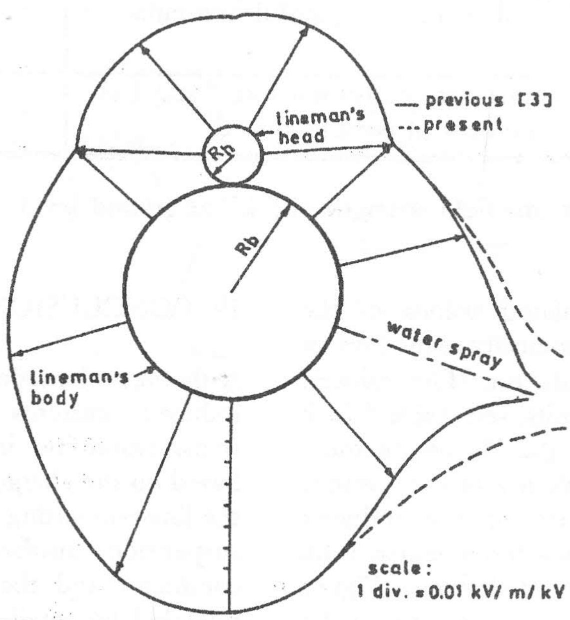

Figure 2. Calculated surface electric field around the profile of the lineman.

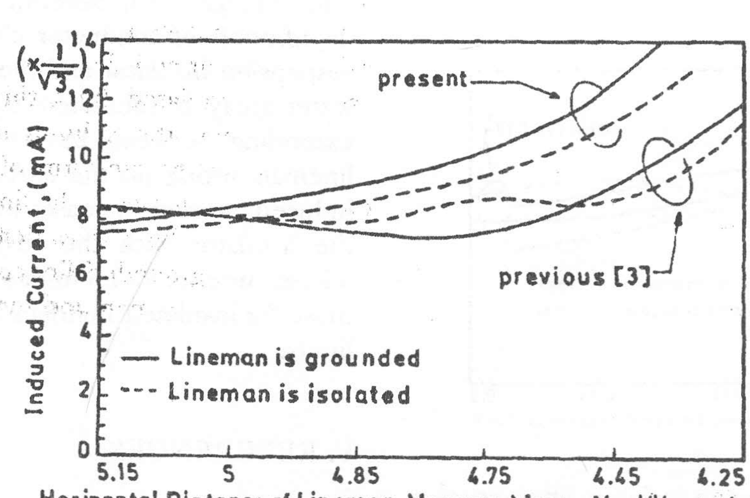

Figure 3. Induced current in grounded and isolated linemen as a function of the distance from the HV-conductor (V=66/$\sqrt{}$3kV).

Table II. Physiological effects and thresholds for body currents and shock currents [9].

	Currents in Milliamperes 60 Hz rms	
	Men	Women
1. Estimated dc interception and ac induced currents.	0.08*	--
2. No sensation on hand.	0.4	0.3
3. Slight tingling. "Threshold of perception" level.	1.1	0.7
4. Shock, uncomfortable, but not painful, muscular control not lost.	1.8	1.2
5. Painful shock; muscular control not lost. "Safe Let-Go" level for 99.5 percent of persons tested.	9.0	6.0

* Assumes 60 Hz rms field strength of 5 kV at ground level.

However, the present calculated values of the induced current increase monotonically as the human approaches toward the HV conductor. The induced current may exceed the safe limits, see Table (II), if the lineman becomes closer to the HV conductor.

Figure (4) shows the dependency of the present and previous calculated values of the induced current on the height of the isolated lineman from the frame of the tower. The trend shown in Figure (4) is self-explanatory and depicts a decrease of the induced current with the increase of the lineman height above the tower.

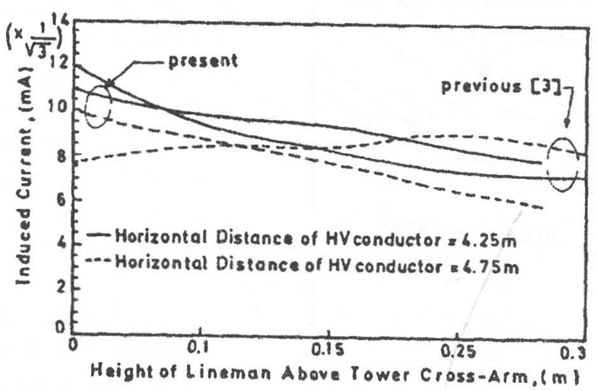

Figure 4. Induced current in isolated linemen as a function of the height above the tower frame (V=66/√3kV).

IV. CONCLUSION

A theoretical model is proposed for calculating the induced currents on a lineman engaged in transmission-line insulator washing. The model is based on the charge simulation technique applied to the lineman sitting on the crossarm of the tower, the suspension insulator, the tower frame, the line conductor and the water spray. The lineman is modeled by small sphere for the head and a large sphere for the body. The transmission-line conductor is simulated by finite and semi-infinite line charges to account for the nonuniform distribution of conductor charge resulting from the suspension insulator and the supporting tower. The water spray is simulated by a thin dielectric stick extending between the column insulator and the lineman sitting on the crossarm of the tower. The induced currents increases as the lineman approaches the insulator with the suspended line conductor. These currents for grounded lineman are higher than those for insulated lineman and may exceed the safe limits.

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