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Analysis and Design of a New Method for Reduction of Touch and Step Voltages for Earthing Systems Using FEM Approach

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Abstract: A new design method for earthing system electrode arrangement and analyzing process using finite element method (FEM) to estimate the solution of the second order laplace type differential equation forced on the proposed system is explained. The surge or earth unbalance current flow in electric power system leads to increased touch and step voltages. Insulating the upper part of earthing system electrodes, proposed in this paper as a new method, causes reduction of touch and step voltages when current flows through the earth as a result of unbalance/surge currents. This is an important safety factor which must be considered for those who work on such electrical sites. Because of independence of the unbalance earth current from the total earth resistance, in high values of ρ it will result in increased touch and step voltages to dangerous values. This research specially refers to the power plants and high voltage substations which have been installed in high resistance soil like rocky earth sites.

Key words: Earthing system, earth rod, finite element method, soil resistivity, step voltage, touching voltage

INTRODUCTION

With ever increasing fault current levels in today's interconnected power systems, there is renewed emphasis on safety (IEEE, 2000, 1986). Since, the early days of the electric power industry, safety of personnel in and around electric power installations has been of a prime concern. A mechanism by which safety of personnel is affected is the ground potential rise of grounded structures during electric power faults and the possibility of humans touching grounded structures and, therefore, subjecting themselves to voltages (Ctci, 1993). A human body coming in contact with an energized grounding system will be normally subjected to a voltage (touch or step). The amount of current through one's body will depend on the body resistance and the parameters of the system at the point of contact (Lee and Meliopoulos, 1999). A 50 or 60 Hz electric current conducted through a human body as a result of an accidental conduct with a grounded structure, under adverse conditions, should be of magnitude and duration below those that cause ventricular fibrillation (Thapar *et al.*, 1993). Electric shock may occur when an individual touches a grounded structure during a fault (touch voltage), walks in the vicinity of a grounding system during a fault (step voltage), touches 2 separately grounded structures during a fault (metal to metal touch voltage), etc.

Safety assessment of grounding systems is a procedure that determines whether the maximum touch and step voltages computed meet the postulated safety criteria (Yauqing, 1999). The safety criterion in IEEE Standard 80 and IEC-479-1 is defined in terms of the allowable body current, that is, the value of electric current that the average person can withstand without danger of electrocution (or the possibility of suffering ventricular fibrillation). The allowable body current is then translated into the allowable touch and step voltages. In other words, safety can be assessed in terms of the touch and step voltages instead of the body current.

In practice, the site selection is often carried out without due attention to the soil electrical resistance property (ρ) (Ctci, 1993; Yauqing, 1999). This will create problem since, for sites with high soil electrical resistance, the flow of unbalance/surge currents will increase the touch and step voltages. This phenomenon usually occurs in dry or rocky soils (Yauqing, 1999). To overcome this problem the earth grid is designed either in 2 layers or its resistance is reduced by adding favorable chemical or replacing the earth soil altogether (Thapar and Gerez, 1991). These methods depending on the hardness and material content of the soil, not only degrade with time but also make the earthing system installation very expensive and hence are considered to suffer from low efficiency in performance (Rong, 1998; Huang and Chen, 1995; Dawalibi and Donoso, 1993; Meliopoulos *et al.*, 1993).

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This study presents a new method to reduce touch and step voltages in the following sites, based on insulation of surface region of grounding electrodes. It will be shown that the proposed method will be very effective and low cost installation.

FINITE ELEMENT

A two and three-dimensional field computer program (http://www.comsol.com) was used in the present study. This program provides automatic mesh generation for solving electrostatic and electromagnetic problems by a differential operator FE method. The computational properties of the FEM LAB 3-D program enabled. Field and potential values at any boundary to be plotted, the integration of field values to calculate charge at a boundary and the display of equipotential and field lines in meshed regions. Detailed description of FE formulation principles and procedures can be found in the user manual of the such packages, or in published literature (Fu *et al*., 2004).

The formulation of the generalized Laplace's equation with a Dirichlet boundary condition has zero current on the boundary. Let ϕ_i be the shape function for the ith node, such that $\phi_i = 1$ at node i and zero elsewhere, by replacing the test function v by the shape functions ϕ_i, for all nodes and expanding the voltage as

$$u = \sum_j u_j \phi_j$$

where, u_j is the voltage at node j, then the FEM formulation becomes:

$$\int_\Omega (\nabla \phi_i)^T \sigma \nabla u = \sum_j u_j \int_\Omega (\nabla \phi_i)^T \sigma \nabla \phi_j = 0 \qquad (1)$$

which can be split into boundary $\partial\Omega$ and interior $\Omega\backslash\partial\Omega$ vertices:

$$\sum_{j \in \Omega\backslash\partial\Omega} u_j \int_\Omega (\nabla \phi_i)^T \sigma \nabla \phi_j = -\sum_{j \in \partial\Omega} u_j \int_\Omega (\nabla \phi_i)^T \sigma \nabla \phi_j \qquad (2)$$

It was computed as:

$$Au = 0 \qquad (3)$$

where, A is the system matrix and u is the potential on all vertices. Thus, by dividing the system matrix into blocks for the interior and exterior vertices

$$Au = \begin{pmatrix} A_{11} & A_{12} \\ A_{21} & A_{22} \end{pmatrix} \begin{pmatrix} u_{\Omega\backslash\partial\Omega} \\ u\partial\Omega \end{pmatrix} \qquad (4)$$

Since, $u\Omega\partial$ are the boundary conditions, the interior potential was solved as:

$$A_{11} u_{\Omega\backslash\partial\Omega} = -A_{12} u_{\partial\Omega} \qquad (5)$$

SYSTEM EQUATIONS

The calculation of electric potential and electric fields, where the environment is homogenous, linear and isotropic and where there is no spatial charge, requires the solution of laplace's equation (IEEE, 2000):

$$\nabla^2 \Phi = 0 \qquad (6)$$

Laplace's equation is required for the determination of both the electric potential $\Phi(x)$ and the electric field:

$$E = -\nabla\Phi \qquad (7)$$

Within a three-dimensional domain Ω, where x is the coordinate vector. Furthermore, $\Phi(x)$ has to attend the contour conditions:

$$\Phi(x) = \Phi_\Gamma(x), \quad x \in \Gamma \qquad (8)$$

Over the Γ boundary of domain. For insulation boundary we have Newman boundary condition:

$$\frac{\partial\Phi}{\partial x} = K \text{ if insulated fully } \Rightarrow K=0 \qquad (9)$$

in earth surface that we have full insulation and has the most important area for the research area we should have Newman condition with K = 0.
And for others we have Dirichlet boundary condition:

$$\begin{aligned} \Phi(a) &= \Phi_a = A \\ \Phi(b) &= \Phi_b = B \\ &\vdots \end{aligned} \qquad (10)$$

SYSTEM MODELING

The proposed earthing system as shown in Fig. 1, consists of an array of insulated earth rods. The length of insulated area for every rod depends on its place in the array. The final shape of insulated area is like a coin. This structure causes the earth currents be led to depth of the earth comparing with common earth rods array.

The structure of every earth rod and cross section (AA') of the first arrangement is shown in Fig. 2. The

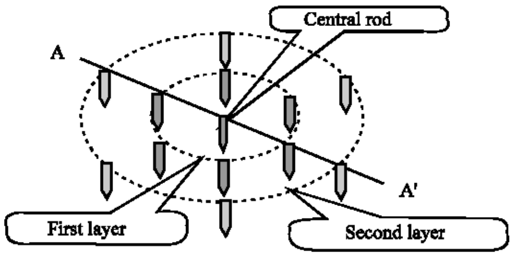

Fig. 1: Earth rods array with 2 layers

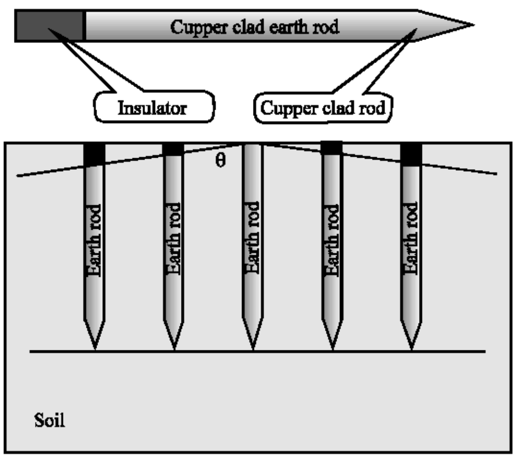

Fig. 2: Earth rods arrangement with linear surface insulation

arrangement can be made in several layers so that the desired earth resistance can be achieved.

Although, this arrangement of rods is very economic and has low installation costs as well as high step and touch voltages reduction effects, however it will be shown in the next section that this structure will cause a low unwanted increment in total earth resistance (under 10%); that is a disadvantage of this arrangement (as discussed in section). But this structure is suitable for sites with high rating in touch or step voltages and no total earth resistance problem.

To solve this problem the authors suggest another structure that results in lower earth resistance plus major reduction in touch and step voltage as shown in the Fig. 3.

This structure does not reduce the active interconnected surface of the rods, so every rod depending on its place in the array should be hammered to the specified depth under ground and then be connected to other members by an insulated wire.

It is very important to achieve the insulation level that supplies the standard step and touch voltages (IEEE Standard 80 and IEC-479-1). By the suggested technique, we can find an optimum solution for every

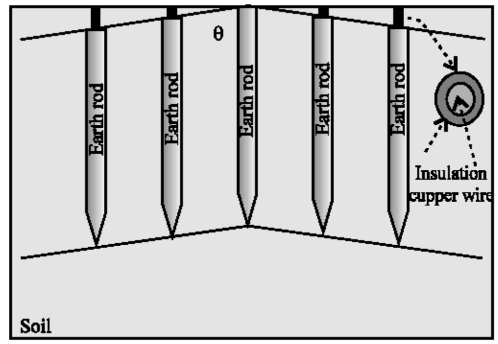

Fig. 3: Earth rods arrangement with constant active surface of rods

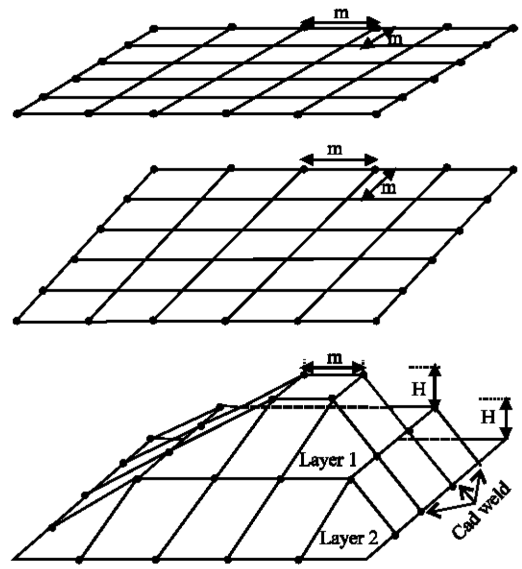

Fig. 4: Proposed structure for two layer earth grid

defected substation corresponding to its ρ and present touch and step voltage. More requirement for improving in touch and step voltages results in more insulation level for earth rods (reduction in θ in Fig. 2 and 3). However, for first structure this factor will increases total earth resistance (Rg), so insulation should be limited only to the necessary depth for step and touch voltages.

For systems with two parallel horizontal layers in earth grid (usually in high voltage substations with ρ>250 Ω-m) the proposed arrangement can be installed as shown in Fig. 4.

This structure like structure explained in Fig. 3 reduces step and touch voltages plus the total earth resistance (Rg).

TOUCH AND STEP VOLTAGES CRITERIA

Definition: Electric shock may occur when an individual (1) touches a grounded structure during a fault (touch

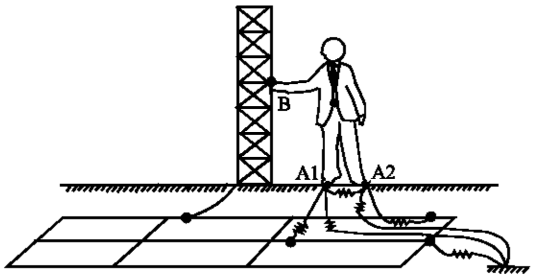

Fig. 5: Definition of the touch voltage (between B and A1 or A2)

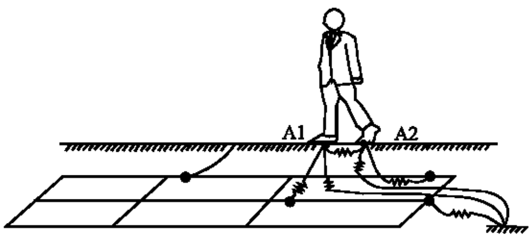

Fig. 6: Definition of the step voltage (between A1 and A2)

voltage), Fig. 5, Eq. (2) walks in the vicinity of a grounding system during a fault (step voltage), Fig. 6, Eq. (3) touches two separately grounded structures during a fault (metal to metal touch voltage), etc.

The touch and step voltage criteria are derived from the permissible body current, which is premise of the standard. The allowable body current and step and touch voltages in the IEEE standard 80 (IEEE, 2000) for a 50 kg person is defined with Eq. (11-13):

$$i_{b,allowable,50} = \frac{0.116}{\sqrt{t_s}} A \tag{11}$$

$$V_{touch,50} = (1000 + 1.5C_s.\rho_s)\frac{0.116}{\sqrt{t_s}} \tag{12}$$

$$V_{step,50} = (1000 + 6C_s.\rho_s)\frac{0.116}{\sqrt{t_s}} \tag{13}$$

Where, t_s is the electric shock duration in seconds. C_s is the surface layer derating factor and ρ_s is the surface material resistivity and 1000 appearing in Eq. (12) and (13) is human body resistance. To ensure safety for a person in vicinity of a substation, the actual touch-and-step voltages should be less than the maximum permissible touch and step voltages (IEEE, 2000).

Profile of voltage: The shape of voltage profile for common earth rods system in two layers on the surface of the earth is as shown in Fig. 7.

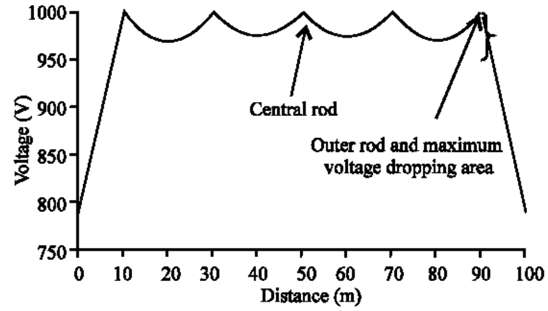

Fig. 7: Voltage Profile for common Earth rods arrangement

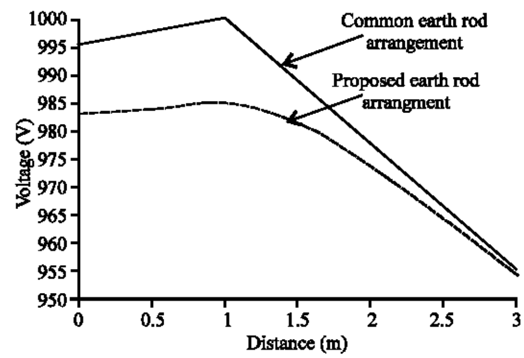

Fig. 8: Voltage profile for common arrangement and insulated surface (to the depth 1.1 m) for last rod

Because for the last rod there is no voltage overlap, voltage dropping is sever and the maximum touch and step voltage occur in the vicinity area of the last layer of the rods and for other inner layers there are some potential holes with less amount in touch and step voltages.

After insulation the earth rods layers (introduced in the previous section) based on the rules which will be discussed later, the profile will change as shown in Fig. 8. it can be seen that there is a significant improvement in touch and step voltages and the derivative of voltage appears to have less slope than common arrangement of earth rods.

This phenomenon occurs because the less-demanded of earth current flows and results in potential lines distributed on the earth's ground have more distance from each other comparing with common earth rods arrangement as shown in Fig. 9 and 10.

Because the highest step and touch voltage rating, the most significant area for touch and step voltage research is in the vicinity of the last earth rod layer and in direct with radius arrow, so all simulations were done for this area.

Touch voltage: Results of the simulations done using FEM on the proposed system and in the distance

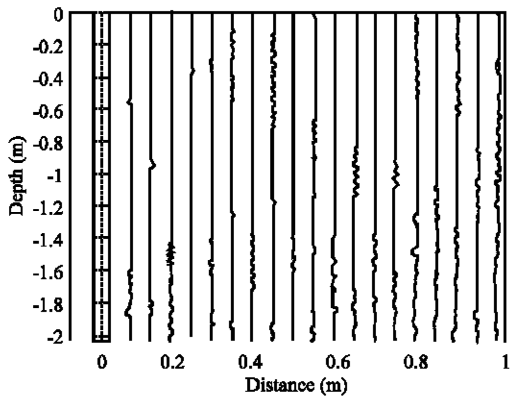

Fig. 9: Potential lines distributed in the depth and surface of the earth for common earth rod (for the last rod)

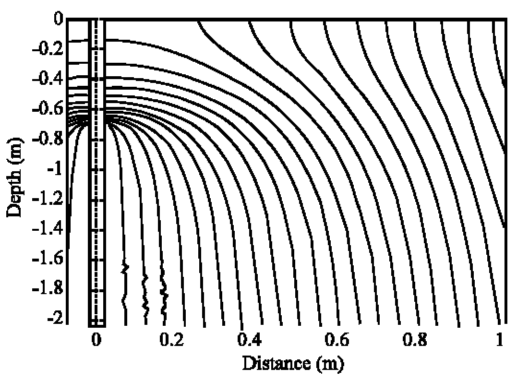

Fig. 10: Potential lines distributed in the depth and the surface of the earth for insulated earth arrangement (for the last rod)

L = 0.6 m from the last layer for measuring touch voltage have been given in Table 1. These results show that for proposed earthing systems there is a significant relationship between amount of insulation level of rods (respecting to introduced structure in Fig. 2 and 3) and decrement rating of touch voltage, as shown in Fig. 11.

There is an exponential equation that is derived from the fitting curve in Fig. 11 and relates new touch voltage to the old one corresponding to insulation depth in last rod of the array:

$$V_{touch} = V_{touch,0}\left(2.8e^{-\left(\frac{x+1.21}{1.057}\right)^2} + 0.665e^{-\left(\frac{x+84.77}{85.86}\right)^2}\right) \quad (14)$$

Calculating V_{touch} from standards (IEEE, 2000, 1986) and existing defected voltage ($V_{touch,\ 0}$) and from above equilibrium, a minimum necessary depth for insulation the rods in the last layer will be derived. Additionally because the insulation is considered in a linear form, using triangular relationships, other insulation levels will be derived for inner layers easily.

Table 1: Step and touch voltage changing with increment in insulation level (step = 0.1 M)

Insulation length (m)	Step voltage (V) %	Touch voltage (V) %
0.0	100	100
0.1	92	87
0.2	83	73
0.3	74	61
0.4	68	52
0.5	61	45
0.6	56	39
0.7	51	35
0.8	47	33
0.9	45	31
1.0	42	28
1.1	39	26

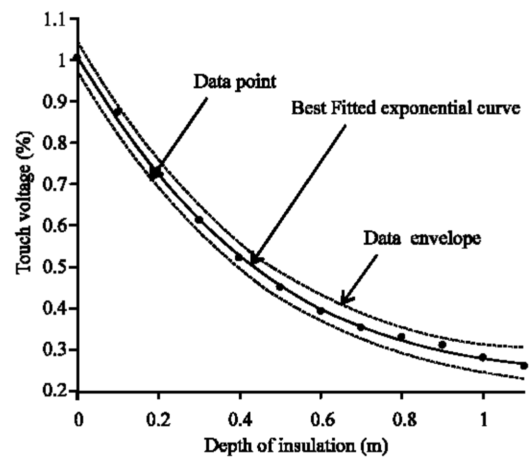

Fig. 11: Relationship between last rod insulation level and touch voltage reduction percentage

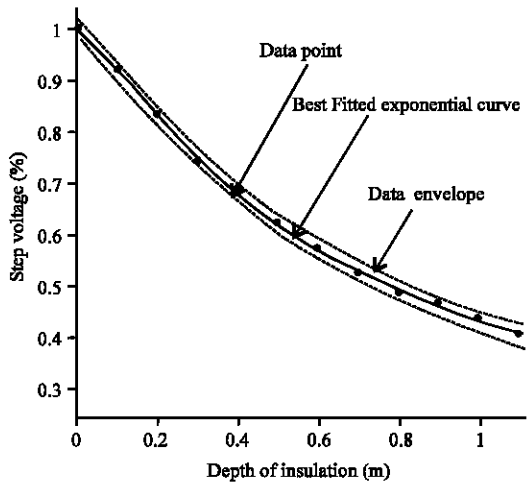

Fig. 12: Relationship between last rod insulation level and step voltage reduction percentage

Step voltage: Based on the data of Table 1 and for L = 1.0 m there is a major decrement in quantity of step voltage (even more than reduction rate for touch voltage) and only with 40 cm insulation level, the step voltage will decrease to 70% of its original value. Approximation curve for step voltage is as shown in Fig. 12.

The proposed equation for step voltage is given in Eq. 15:

$$V_{step} = V_{step,0}\left(0.29e^{-\left(\frac{x+0.154}{0.464}\right)^2} + 1.271e^{-\left(\frac{x+2.29}{3.113}\right)^2}\right) \quad (15)$$

Where,

V_{step} : Value of step voltage after insulation process.
$V_{step,0}$: The common value of step voltage.
x : Insulation level under ground in meter.

The reason for using two exponential parts in Eq. 15 for more accurate estimation of step voltage (error <0.05).

EARTH RESISTANCE CRITERIA

It is certain that insulating top area of the earth electrodes as introduced in Fig. 2 will increased the total earth resistance (Rg) as shown in Fig. 13. But for the second proposed arrangement which was explained in second structure based on Fig. 3 drawing, we see that this structure reduces the total earth resistance of the system plus major reduction in touch and step voltages.

In some earthing systems (specially for substation installed in rocky substrate or mountain) it is needed to decrease the step or touch voltage only without any requirement for reduction in total earth resistance. For these sites first structure (or a similar one) will be very useful especial if compared with nowadays earth structure that use two parallel layers in two different depth to improve electrical safety characteristics of the earthing system, consumes in required installation money more than 50%.

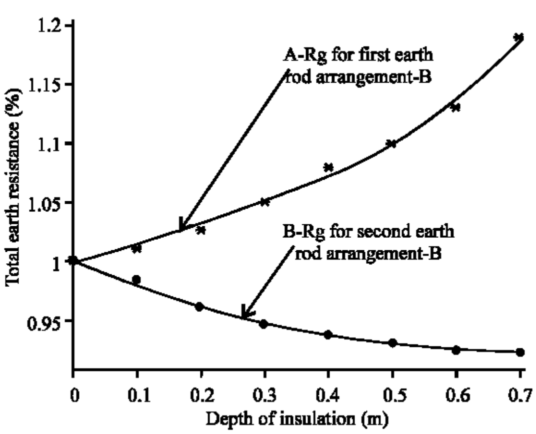

Fig. 13: Relationship between last rod insulation level and earth resistance percentage, A-for first structure, B-for second structure

CONCLUSION

A new method for major reduction in touch and step voltage which are the most important safety factors in high voltage substations and other electrical sites using linear insulation of the top area of every earth electrode depending on its place in the array have been discussed. Method consists of two different structure that in the first one total earth resistance increases a little and in other one resistance and step and touch voltages reduce both together but more expensive to install.

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