SAFETY ASSESSMENT OF EARTHING SYSTEMS AT POWER FREQUENCY

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ABSTRACT

Modern earthing system design may be efficiently enhanced by the application of suitable computer models. A key factor is safety, and this is usually assessed in terms of GPR, touch and step potentials under fault conditions.
This work describes an analytical approach which, combined with a comprehensive computer program developed specifically for analysing complex buried structures, enables to carry out parametric studies on "effective" touch and step potentials (i.e. accounting for the presence of the human body) for a given system as a function of the various parameters affecting such values (soil characteristics, parallel return paths for the earth fault current, grid geometry, state of the neutral, etc.).

1 INTRODUCTION

The design of safe earthing systems requires the preliminary assessment (and subsequent verification) of specific quantities such as ground potential rise (GPR), touch potential and step potential.
The permitted values of these potentials are defined by national standards which, although differing from one country to another, are usually dependent upon various influencing factors (protection trip times, surface layer resistivity, human body and foot resistances, etc.). If the calculated values of these potentials in or near the grid exceed the allowed limits, the design of the earthing system need to be improved. This is likely to become a more important aspect

since the trend in new standards is towards making touch and step potentials the basis of the design (Charlton and Griffiths[1]).

Available analytical models (applicable to simple configurations) or more sophisticated computer programs (for complex geometries) usually enable to evaluate the GPR and the so called "undisturbed" touch and step potentials, i.e. without taking into account the presence of the human body. Neglecting to account for the presence of a human body is a conservative measure (undoubtely safer assumption) which may result in eccessive oversizing of the earthing system.

It is well known, however, that the "effective" touch & step potentials actually experienced by a human being may be considerably lower, with respect to the "undisturbed" values, due to the current field distortion caused by its presence. As a matter of fact, italian standards allow to account for such favourable condition at the verification stage, suggesting a suitable circuit arrangement for field measurement of the "effective" touch & step potentials, which results in less stringent, but nonetheless safe, design limitations.

The current field distortion due to the human body can be accurately simulated and accounted for by computer programs (see, for instance Andolfato et al.[2] and Ala et al.[3]); however, this introduces a non-linearity element which considerably increases the time-to-convergence of the solution. Furthermore, since touch & step potentials should be verified at a number of different positions - the numerical method requiring a separate simulation for each position - it follows that the overall computing time becomes extremely onerous.

The computing time may be drastically reduced with the analytical approach presented in this work, making use of suitable correction factors in order to estimate the "effective" touch & step potentials on the basis of the corresponding computed "undisturbed" values. This approach is similar to that suggested by Buccheri et al.[4]), which, however, made use of numerical computation to evaluate the correction factors.

In addition, the analysis is here extended to account for parameters other than soil resistivity and body resistance - characteristics of supply network, state of the neutral, grid geometry, etc. - enabling to efficiently compare different solutions for optimization purposes.

2 REDUCTION FACTORS

In order to measure the "effective" touch & step potentials, the italian standards CEI 11-8 (and the recent guide CEI 11-34) prescribe the use of a 1000 Ω resistance to simulate the human body resistance and the use of two plane electrodes (each of approximately 200 cm^2 surface, corresponding to a disk 8 cm radius) placed at a distance between their axes respectively of 16 cm for touch and 100 cm for step potential measurement (see Figure 1.a). The resistance to earth of the disk electrodes may be computed as (Laurent[5], ANSI/IEEE[6]):

a) in homogeneous soil (resistivity ρ [Ωm])

resistance of 1 disk of radius b [m]	$R_d = \frac{\rho}{4b}$ [Ω]	(1)
mutual resistance between disks placed on ground at a distance d [m] apart	$R_m = \frac{\rho}{2\pi d}$ [Ω]	(2)

b) in a two-layer soil (surface layer resistivity ρ_s [Ωm] and depth h [m], deep layer resistivity ρ [Ωm])

resistance of 1 disk of radius b [m]	$R_d = \frac{\rho}{4b}\left(1+2\sum_{n=1}^{\infty}\frac{\left(\frac{\rho-\rho_s}{\rho+\rho_s}\right)^n}{\sqrt{1+\left(2n\frac{h}{b}\right)^2}}\right)$ [Ω] (3)
mutual resistance between disks placed on ground at a distance d [m] apart	$R_m = \frac{\rho}{2\pi d}\left(1+2\sum_{n=1}^{\infty}\frac{\left(\frac{\rho-\rho_s}{\rho+\rho_s}\right)^n}{\sqrt{1+\left(2n\frac{h}{b}\right)^2}}\right)$ [Ω] (4)

The equivalent circuits of the measuring arrangements of Figure 1.a are shown on Figures 1.b and 1.c where:

V_{t0} = undisturbed touch voltage between hand and feet
V_{te} = effective touch voltage between hand and feet (V_{A-B})
V_{s0} = undisturbed step voltage between feet (100 cm apart)
V_{se} = effective step voltage between feet (100 cm apart) (V_{C-D})
R_h = human body resistance
R_d, R_m as defined above.

From the above equivalent circuits and definitions it may easily be shown that the desired reduction factors (F_{te} for touch potential and F_{se} for step potential, defined as the ratios between effective and undisturbed potentials), having assumed b=0.08 m, d=0.16 m for touch potential and 1.0 m for step potential, are:

a) in homogeneous soil (resistivity ρ)

$$F_{te} = \frac{V_{te}}{V_{t0}} = \frac{1}{1+2.06\frac{\rho}{R_h}}; \qquad F_{se} = \frac{V_{se}}{V_{s0}} = \frac{1}{1+5.93\frac{\rho}{R_h}} \qquad (5)$$

b) in a two-layer soil (surface layer resistivity ρ_s [Ωm] and depth h [m], deep layer resistivity ρ Ωm])

$$F_{te} = \frac{1}{1+\left[1.56F(12.5h)+0.5F(6.25h)\right]\frac{\rho_s}{R_h}}; \qquad F_{se} = \frac{1}{1+\left[6.25F(12.5h)-0.32F(h)\right]\frac{\rho_s}{R_h}} \qquad (6)$$

where the following function F(X) (ANSI/IEEE[6]) has been introduced:

$$F(X) = \left(1+2\sum_{n=1}^{\infty}\frac{\left(\frac{\rho-\rho_s}{\rho+\rho_s}\right)^n}{\sqrt{1+(2nX)^2}}\right) \qquad (7)$$

Computer simulations have shown that the application of F_{te} and F_{se} is generally valid, but in the proximity of the earthing system the criticity increases with the soil resistivity. In case of high resistivity (1000 Ωm) the threshold distances are about 1 m for F_{te} and 0.5 m for F_{se} (however at such distances touch and step potentials are usually low and not dangerous).
Application becomes also critical in cases where a low resistivity upper layer has a depth of the same order of the burial depth of the earthing system.
If the upper layer soil has a depth greater than 10 m, the effects of different resistivity of the deep soil are negligible and the soil may be considered homogeneous, thus equations (1) and (2) are applicable.
Apart from the above mentioned limitations, application of (1), (2), (3) and (4) provides an accuracy of 2%÷5% with respect to the properly numerically computed values.

3 APPLICATION TO FLOATING NEUTRAL SUPPLY SYSTEMS

3.1 Ground current

In floating neutral networks the single phase to ground current I_f is mainly determined by the shunt capacitances of the supply network and does not vary significantly with the fault position. The single-fase-to-ground fault current is given, with a good approximation, by the following expression

$$I_f = \frac{U/\sqrt{3}}{\sqrt{R_g^2 + X_c^2}} \tag{8}$$

where

- U = rated system voltage,
- R_g = resistance-to-earth of the earthing system,
- X_c =overall capacitive reactance to earth of the supply network.

I_f is relatively small (hundreds of amps) and the contribution of parallel paths (cable sheaths and overhead earth-wires) are usually neglected so that $I_f \approx I_g$ (ground current flowing to earth trough the earthing grid).

3.2 Geometric coefficients

For the sake of simplicity, let us consider homegeneous soil. In this case R_g is directly proportional to the soil resistivity and the undisturbed potential rise at any point on the ground surface ($V_g(x,y)$, where x,y are horizontal coordinates) is proportional to both resistivity and ground current. It follows that these two quantities may be expressed as

$$R_g = k_R \cdot \rho; \qquad V_g(x,y) = k_G(x,y) \cdot \rho \cdot I_g \tag{9}$$

where k_R and $k_G(x,y)$ depend only on the grid geometry (the latter obviously varies with the point position). The same considerations apply to the touch & step potentials; in particular, considering their maximum values, we can define:

$$V_{t0MAX} = k_T \cdot \rho \cdot I_g \quad \text{and} \quad V_{s0MAX} = k_S \cdot \rho \cdot I_g \tag{10}$$

with the coefficients k_T and k_S depending only on the grid geometry.
The above defined geometric coefficients may be computed analytically only for simple geometries. In general, they are evaluated on the basis of R_g and the maximum undisturbed touch & step potentials computed numerically (see for instance Andolfato et al.[1], Ala et al. [2],

Dawalibi and Barbeito[7]). To be noted that k_T should be evaluated on a defined area surrounding conducting structures bonded to the earthing grid, otherwise V_{t0MAX} would alwaye coincide with the GPR.

3.3 Maximum effective touch & step potentials

Combining eq. (5), (8) and (10) the maximum effective touch & step potentials may be expressed as

$$V_{teMAX} = k_T \rho \frac{U/\sqrt{3}}{\sqrt{(k_R \rho)^2 + X_c^2}} \frac{1}{1+2.06\frac{\rho}{R_h}}; \quad V_{seMAX} = k_S \rho \frac{U/\sqrt{3}}{\sqrt{(k_R \rho)^2 + X_c^2}} \frac{1}{1+5.93\frac{\rho}{R_h}} \qquad (11)$$

Eqs. (11) show that both V_{teMAX} and V_{seMAX} are non-linear functions of the soil resistivity. In particular, as can be seen on Figure 4 reporting a practical application of these equations, they are null for $\rho \to 0$ and $\rho \to \infty$, both exibiting a maximum for specific resistivity values. It may easily be shown that these critical resistivity values are given by

$$\rho_{Tcrit} = \sqrt[3]{\frac{R_h X_c^2}{2.06 k_R^2}} \quad \text{and} \quad \rho_{Scrit} = \sqrt[3]{\frac{R_h X_c^2}{5.93 k_R^2}}. \qquad (12)$$

For any given application and boundary conditions, the standards would specify the allowed limit for touch & step potentials (V_{LIM}). Therefore the conditions

$$\boxed{V_{teMAX}(\rho_{Tcrit}) \le V_{LIM} \quad \text{and} \quad V_{seMAX}(\rho_{Scrit}) \le V_{LIM}}$$

are satisfied, then it could be said that the earthing system is intrinsecally safe, independently of the soil resistivity.

If one or both conditions are not satisfied, by intersecting the curves $V_{teMAX}(\rho)$, $V_{seMAX}(\rho)$ with V_{LIM} two restricted resistivity ranges can be identified and appropriate provisions would be required only if the actual soil resistivity is within these ranges.

3.4 Example 1: Earthing grid of distribution substation.

The grid geometry is shown on Figure 2 and consists of a square meshed grid with 4 radial horizontal elements and 4 vertical rods at their extremities, buried in homogeneous soil of 100 Ωm resistivity. By numerical simulation, the undisturbed ground potential distribution has been computed (Figure 3) together with the following grid characteristics:

$R_g = 5.595$ [Ω] $\qquad k_R = 0.05595$ [m^{-1}]
$k_T = 0.009725$ [m^{-1}] $\qquad k_S = 0.009315$ [m^{-1}]

where k_T has been evaluated over a (3m)x(3m) area.

The rated system voltage is U = 10 kV and the overall system capacitive reactance $X_c = 50$ Ω.

From eqs. (11), the maximum effective touch and step potentials result

$$V_{teMAX} = \frac{56.148\rho}{\sqrt{(0.05595\rho)^2 + 2500}} \frac{1}{1+2.06\frac{\rho}{1000}}; \quad V_{seMAX} = \frac{53.783\rho}{\sqrt{(0.05595\rho)^2 + 2500}} \frac{1}{1+5.93\frac{\rho}{1000}}$$

These two curves are plotted on Figure 4 together with the maximum allowed limit (Vmax=144.5 V according to the italian standards CEI 11-8 having considered a protection trip time of 0.55 sec.).
From Figure 4 it can be seen that the grid satisfies the step potential requirements for any resistivity values, and is safe for resistivity values outside the range 180 - 2700 [Ωm]. If the soil resistivity lies within that range, than a high resistivity surface layer is required.

4 APPLICATION TO EARTHED NEUTRAL SUPPLY SYSTEMS

4.1 Ground current

In earthed neutral supply systems the single-phase-to-ground fault current levels are much higher (1 to 2 order of magnitude) than those typical in floating neutral systems, and vary significantly with the position of the faulted section within the electrical system. In addition, parallel earth return paths may significantly reduce the effective ground current flowing through the grid thus dumping dangerous potentials. I_g can be calculated by detailed modeling of the surrounding electrical system or may be estimated, as a first appoximation, using simplified approaches (which, however, should account for the electric system characteristics and any parallel earth path).
As an example, considering the simplified circuit of Figure 5, representing an overhead line with earthwire connecting the supply system to the faulted section, where:

- U = rated system voltage,
- R_g = resistance-to-earth of the earthing system,
- R_s = equivalent resistance-to-earth of the supply system,
- Z_c = phase conductor longitudinal impedance,
- Z_f = earthwire longitudinal impedance,
- Z_m = phase conductor - earthwire mutual impedance,
- I_f = fault current,
- I_g = ground current,
- I_p = parallel path return current,

it may be shown that

$$\dot{I}_g = \frac{\dot{U}/\sqrt{3}}{R_g\left(1+\frac{\dot{Z}_c-\dot{Z}_m}{\dot{Z}_f-\dot{Z}_m}\right)+R_s+\dot{Z}_m+\dot{Z}_f\frac{\dot{Z}_c-\dot{Z}_m}{\dot{Z}_f-\dot{Z}_m}} \quad (13)$$

whose modulus may be written, keeping in evidence R_g, as

$$I_g = \frac{U/\sqrt{3}}{\sqrt{\alpha R_g^2+\beta R_g+\gamma}} \quad (14)$$

where α, β and γ are all function of the electric system impedances.
In order to contain the size of the earthing grid, it is desirable to reduce I_g, which can be done by acting on the electric system parameters (i.e. increasing α, β and γ) or increasing the earth resistance R_g.

4.2 Geometric coefficients

The geometric coefficients are the same as defined above in par. 3.2.

4.3 Maximum effective touch & step potentials

As outlined in par. 3.3, combining eqs. (5), (8) and (14) the maximum effective touch & step potentials may be expressed as

$$V_{teMAX} = k_T \rho \frac{U/\sqrt{3}}{\sqrt{\alpha (k_R \rho)^2 + \beta k_R \rho + \gamma}} \frac{1}{1 + 2.06 \frac{\rho}{R_h}}; \quad V_{seMAX} = k_S \rho \frac{U/\sqrt{3}}{\sqrt{\alpha (k_R \rho)^2 + \beta k_R \rho + \gamma}} \frac{1}{1 + 5.93 \frac{\rho}{R_h}} \tag{15}$$

Similarly to the above, it is possible to define critical resistivity values in correspondence of which the earthing system exibits the maximum effective touch & step potentials.

In this case, however, it is economically unrealistic to refer to intrinsecally safe systems, given the high ground current levels involved. Nevertheless, eqs. (15) may still be applied for quikly comparing the efficiency of different design solutions. In practice, considering that both electric system and soil characteristics are given, it is possible to act only on the grid geometry (and thus the geometric coefficent k_R, k_T and k_S).

As a thumb rule, the costs of the earthing installation can be considered inversely proportional to k_R. From eqs. (15), an incease of k_R would seem to reduce V_{teMAX} and Vs_{teMAX}; however, care should be taken since k_T and k_S will also increase. Generally, a grid optimization criterion would be the maximization of the ratios k_R/k_T and k_R/k_S.

4.4 Example 2: Earthing grid of a gas-insulated substation.

The specification of the system are:

- soil resistivity = 100 Ωm;
- fenced area = (28m)x(68m);
- insulated surface area = (30m)x(70m);
- fault current I_f = 15 kA;
- reduction coeff. for parallel earth path = 0.5;
- protection trip time = 0.8 sec.

The corresponding specification for the earthing grid are

- ground current I_g = 7.5 kA;
- max allowed GPR = 10 kV;
- max effective touch potential (1 m from earthed structures) = 80 V;
- max effective step potential (anywhere) = 80 V.

Given the above requirements, a conventional grid design (meshed grid with peripherical vertical rods) would necessitate a rather wide surface area to be covered with a high resistivity layer (insulated area), mainly in order to contain the step potentials.

The solution suggested in this case, determined with an iterative optimization procedure, is shown on figure 6. Here the criteria adopted have been to contain the insulated surface area up to 1 m from the fence border and to maximize k_R (i.e. to achieve a GPR just below the maximum allowed value).

The resulting ground potential distribution (shown on figure 7) has a rather deep gradient in correspondence of the grid. This, however, does not affect safety since that area has a surface insulation; outside the insulated area, the step potentials are well below the allowed limits (see figure 8). The computed grid characteristics are:

R_g = 1.287 [Ω] $\qquad$ k_R = 0.01287 [m^{-1}]

k_T = 0.008246 [m^{-1}] $\qquad$ k_S = 0.000106 [m^{-1}]

where k_T should be reduced by a factor F_{te} of about 10^{-2} over the insulated area (to account for the high resistivity surface layer) and k_S evalated in the region of interest, i.e. outside such area.

5 CONCLUSIONS

The use of reduction factors and the analytical approach described in the paper, combined with the appropriate numerical simulation program, may provide an efficient tool for assessing effective touch and step potentials.

It has been shown that any earthing system may be characterized by two critical resistivitiy values in correspondence of which the highest touch and step potentials may occur. Given the

characteristics of the electric supply system and of the earthing grid, these critical resistivity values may be computed and, if the grid is safe for such values, it may be considered as intrinsecally safe.
This concept, however, may be practically applicable only to floating neutral electric systems. For earthed neutral electric systems, the procedure may still be useful for grid design optimization.

6 REFERENCES

1 Charlton, T.E. and Griffiths, H.:'Electric earth grid performance', Proc. ERA Conference "Earthing Systems - Which Path to Follow?", paper 3.3, Manchester (UK), 1993

2 Andolfato, R., Fellin, L. and Turri, R.:'Analisi di impianti di terra a frequenza industriale: confronto tra indagine sperimentale e simulazione numerica', L'Energia Elettrica, Vol. 74, n.2, 1997.

3 Ala, G., Buccheri, P. and Mangione, S.:'Recenti sviluppi nello studio di elettrodi interrati a mezzo di programmi di calcolo', L'Energia Elettrica, n.11 pag. 463- ,1992.

4 Buccheri, P., Mangione, S., Parise, G.:'A General Method to Evaluate Human Body Effects on Dangerous Voltages in Earthing System - Interferenza a frequenza industriale e ad alta frequenza negli impianti di terra' L'Energia Elettrica", Vol. LXV, n. 5, 1988.

5 Laurent, P.G: 'Guide sur le calcul, l'exécution et la misure des prises de terre, Revue Générale de l'Életricité, Vol.81, n.7/8, pp 453-472, 1972.

6 'Guide for measuring earth resistivity, ground impedance and earth surface potentials of a ground system', ANSI/IEEE, Std. 81, 1983.

7 Dawalibi, F. and Barbeito, N.:'Measurements and Computations of the Performance of Grounding Systems Buried in Multilaier Soils', - IEEE Transactions on Power Delivery, Vol. 6, No. 4, October 1991.

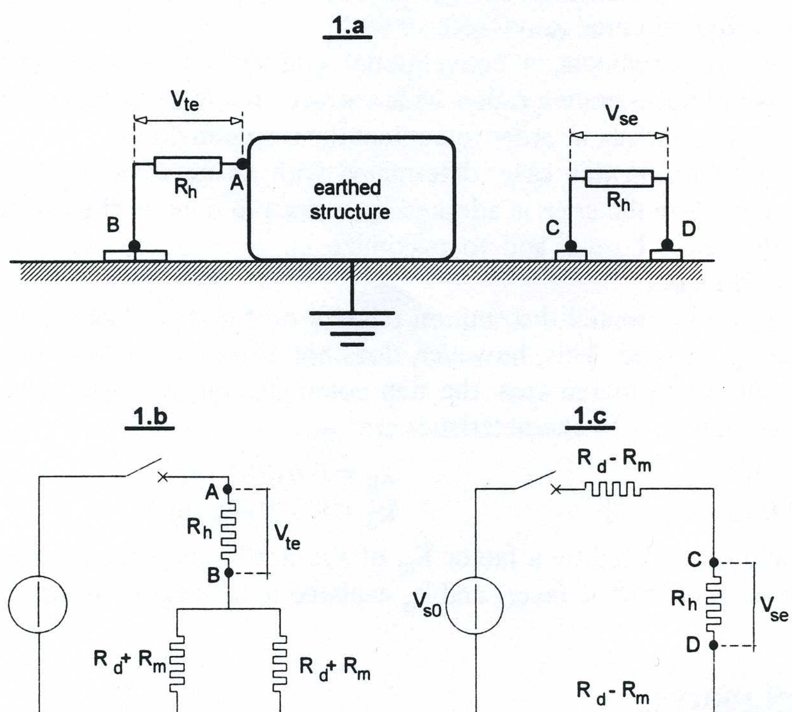

FIGURE 1. a) Schematic arrangements for effective touch and step potential measurement;
b) Equivalent circuit for effective touch potential measurement;
c) Equivalent circuit for effective step potential measurement.

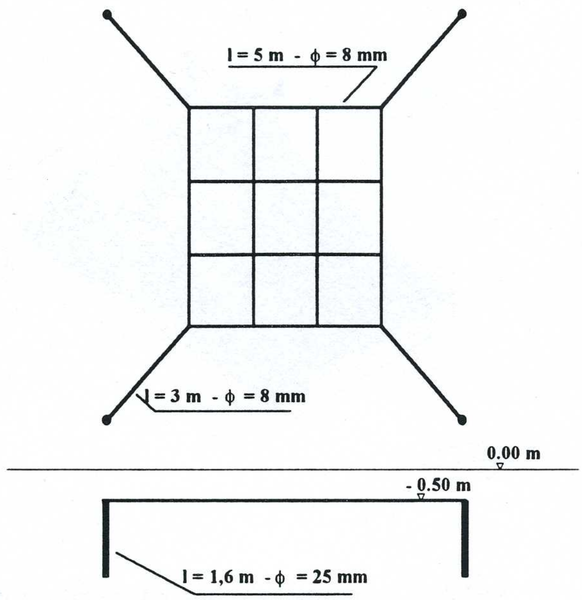

FIGURE 2. Example 1: meshed earthing grid with 4 radial elements and 4 vertical rods

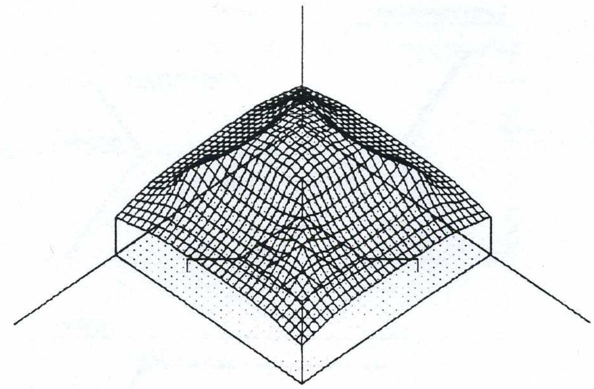

FIGURE 3. Example 1: computed undisturbed ground potential distribution

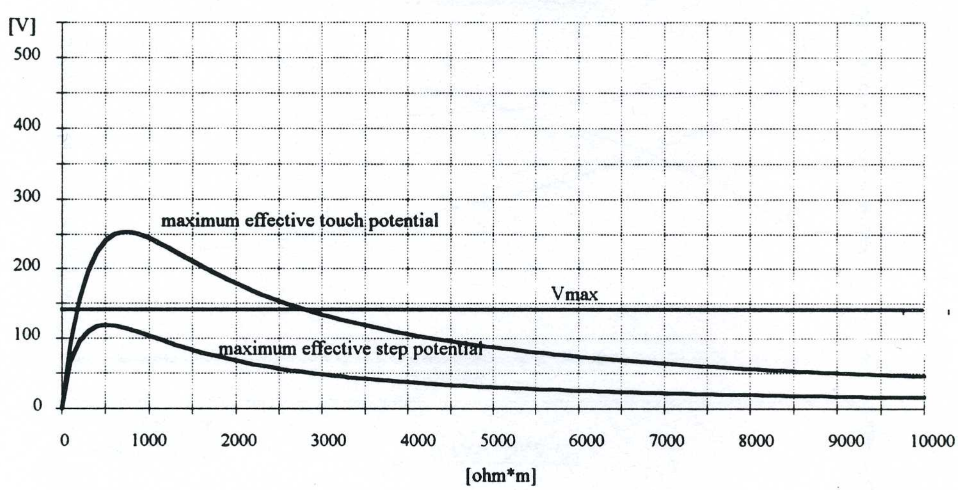

FIGURE 4. Max effective touch&step potential as a function of soil resistivity for the grid of figure 2

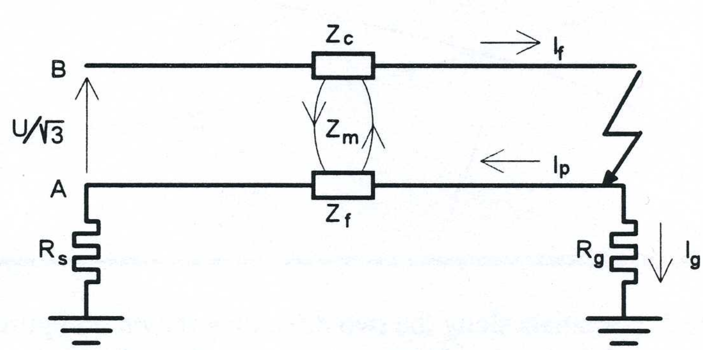

FIGURE 5. Equivalent circuit of OH line with earthwire connecting the faulted section to an earthed neutral supply system.

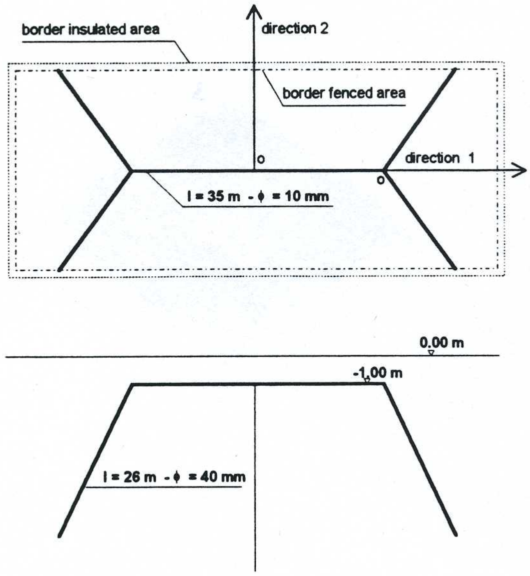

FIGURE 6. Example 2: substation earthing grid

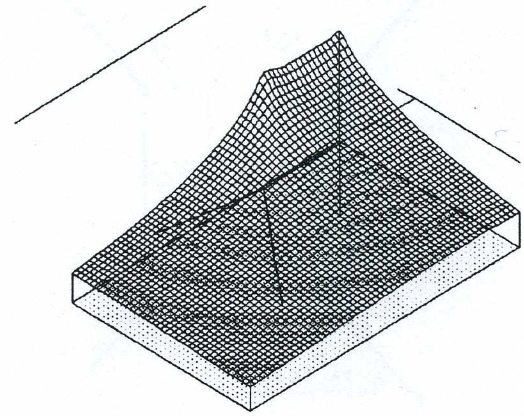

FIGURE 7. Example 2: computed undisturbed ground potential distribution

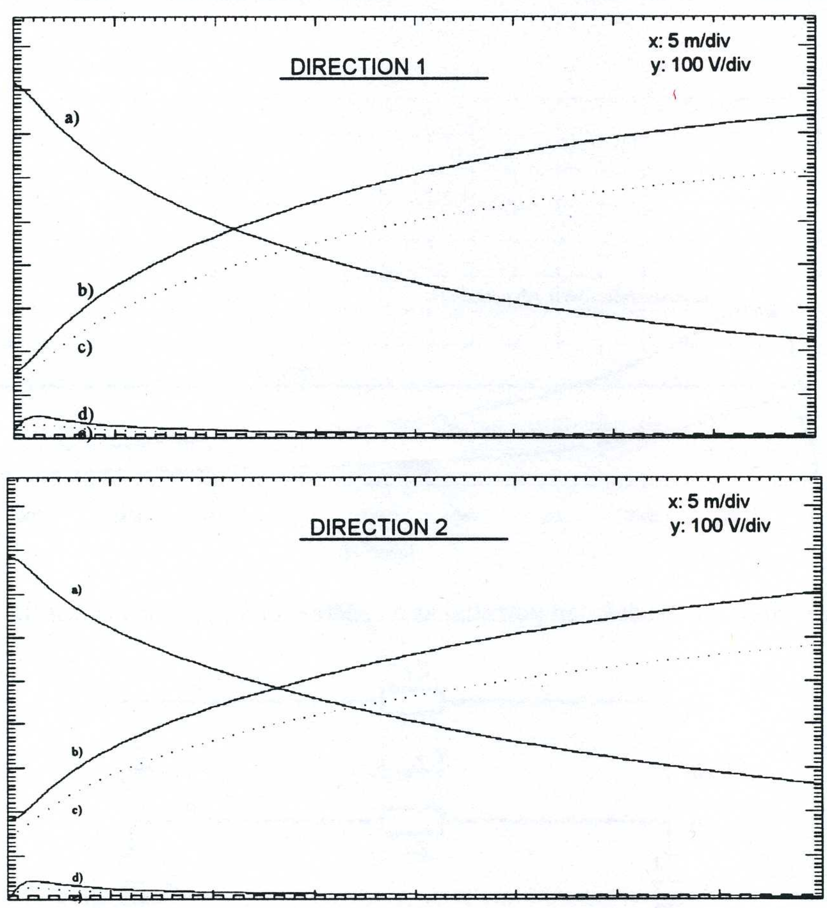

FIGURE 8. Example 2: potentials along the two directions shown on figure 6 (computed before considering the high resistivity surface layer in the insulated area).

a) ground potential ; b) undisturbed touch potential; c) effective touch potential; d) undisturbed step potential; e) effective step potential