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The Accidental Shock Circuits for Earthing System Design in Electrical Substations

M. Hakan HOCAOĞLU
Gebze Institute of Technology
Gebze-Turkey

A. Turan HOCAOĞLU
Gebze Institute of Technology
Gebze-Turkey

Abstract

In this paper, validity of the safety criteria expressed by the accidental shock circuits of national and international earthing standards is examined. A key problem evident, in some of the standards, is a lack of definition of the components of the accidental equivalent circuit model. Contradictions between definition of touch potentials and how touch potential is applied to the accidental circuit suggest that a clear definition of touch potentials is necessary to prevent misinterpretations of the shock scenario. Additionally, the effect of substation surface chippings is analysed by comparing given analytical formulae with a detailed computer model. The work presented in the paper using the correct Thévenin representation has shown that significant over-estimation can be introduced if the foot resistance is not properly determined.

1. INTRODUCTION

The scope of the paper is to examine the validity of the safety criteria expressed by the accidental shock circuits of national and international earthing standards [1 to 4]. The standards which are considered include British Standard 7354 [1], the UK Electricity Association's Technical Specification 41-24 [2], the draft version of the European standard, CENELEC CLC/TC [3] and IEEE standard 80 [4]. These standards enable earthing designs to be evaluated by calculating the potential rise of the earth electrode system (GPR). Most importantly, the *'step'* and *'touch'* potentials that will appear during faults can be evaluated and are compared to the calculated tolerable limits, which determine whether the earthing design can be considered safe or not.

However, there are contradictions in some of the standards regarding the definition of touch potential and how this potential is applied to the human body accidental shock circuit. Therefore, a clear definition of touch potential is necessary to prevent any misinterpretation of the touching scenario. The incorrect treatment of the *'additional resistances'* [3], which are also called as *'foot'* [4] or *'contact'* [1] resistances, of the accidental circuit is also addressed in this paper. Additionally, the effect of substation surface chippings is analysed by comparing given analytical formulae with a detailed computer model. The methodology of this analysis is similar to the one employed by Dawalibi for mesh potential [5].

2. TOUCH AND STEP POTENTIALS

For earthing design, two different types of shock scenario and related potentials are generally considered, namely *'touch'* and *'step'* potentials. A *'touch potential'* is experienced by a person touching a piece of metalwork bonded to the earth grid that is subject to the full GPR (Ground Potential Rise) of the system, with their feet on the surface of the soil. A 'step potential' is experienced across a person's feet due to potential gradients set up on the surface of the soil due to current flowing from the earth grid. The *'touch potential'* plays the key role for the safety assessment of a substation because in general a touch potential represents the worst shock scenario. Therefore, in this paper, safety assessments will be limited to consideration of this potential only.

Although safety studies [6] and IEC standards [7] specify tolerable limits in terms of the allowable body current level, earthing standards tend to specify the tolerable limits in terms of allowable voltage differences. This is expressed as *'allowable touch'* potentials which are evaluated from assumed tolerable body currents using particular equivalent accidental circuit models. Therefore, definition of the electrocution scenario and its particular equivalent circuit model is fundamental to determining both the actual and the allowable potentials.

The magnitude of touch potential depends on the electrical characteristics of the soil in which buried structure lies, the injected fault current and geometry of the grid. The simple analytical formulae in the standards are based on the evaluation of earth potentials from simplified electrode geometries in homogeneous soils. Each standard employs different techniques for determination of the touch potentials. It has been shown that these formulae may produce different results [8]. The differences between the UK practices and IEEE Std.80 formulae are, mainly, due to their respective approaches to the worst case touch scenario. The worst case touch voltages is defined in the UK practices as the potential difference between the grid and a point in the surface of the ground 1m diagonally out from the corner of the grid. On the other hand, the Std.80 defines the worst touch voltage as the mesh voltage which is the difference between the grid potential and the potential of a point on the surface above the centre of the corner mesh for a uniformly spaced grid.

It is recognised that considerable work has been carried out for accurate determination of these potentials. These efforts have produced much more accurate models for the evaluation of step and touch voltages based on complex electrode geometric representation of realistic earthing systems accommodating multi-layer soil conditions. Several computer program are commercially available for earthing system analysis, such as [9, 10, 11]. Nevertheless for the purpose of this investigation, the scope of the paper will be limited to the homogeneous soil condition with surface chippings, since the main aim is to evaluate more precisely the safety criteria rather than a detailed investigation into the calculation of the touch voltage.

3. ALLOWABLE POTENTIALS

A person will be under risk of electrocution if the current through human body exceeds certain limits. For the determination of the allowable body current limits, all standards except Std.80 employ one of the 'S' shaped probabilistic curves established by IEC 479. Std.80 however evaluates the allowable current limit based on Dalziel's equation. For the calculation of the parameter values of the accidental circuit earthing standards employ some simplifications and neglect some of the components.

The definition of the touch potential is fundamental to the evaluation of safe limits. From the preceding definitions, it might be claimed that the touch potential is the potential difference across the human body where the only impedance in the circuit is the body impedance. However, the standards give different pictorial and verbal definitions. These variations will inevitably lead to different interpretations [5] and accordingly the various definitions are now described here.

3.1 IEEE Standard 80

Std.80 [4] (page 43) defines the touch potential as; "*The potential difference between the ground potential rise (GPR) and the surface potential at the point where a person is standing, while at the same time having his hands in contact with a grounded structure.*" From this definition, it could be concluded that the touch potential is the potential difference across the human body. However, the touch potential circuit in the standard which is shown in Figure 1 suggests that the touch potential circuit also includes additional resistances as well as the human body.

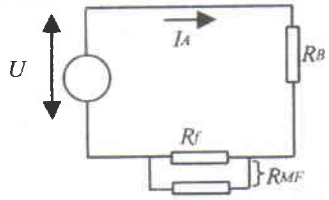

Figure 1 Touch Voltage circuit in Std.80.

U is referred to as the mesh potential. I_A is current thorough the accidental circuit. R_B is resistance of the human body which is lumped and assumed as a constant 1000Ω. R_f is the self-resistance of each foot to remote earth. R_{MF} is mutual resistance between the feet. For practical purposes, this term is ignored and a simple equation is given for the foot resistance (equation 1) where b is the equivalent radius of the foot in metre and ρ is the soil resistivity where

$$R_f = \rho/(4b) \qquad 1$$

when the foot is modelled as a circular plate with a radius of about 8cm (200cm^2) the resistance of the foot approximates to 3ρ. However it is evident from the derivation of equation 1 that this resistance is the resistance to the remote earth. Furthermore, the formula for the touch potential is produced using this circuit.

$$V_T = I_B\,(R_B + R_f/2) \qquad 2$$

Where, I_B is the allowable body current which is function of time. In the first definition, touch voltages refer to potential differences across the human body which is completely different from above figure. Therefore, it might be useful to look at the origins of the standard to understand the bases of this additional resistance, which is named *'foot resistance'*, of the circuit. An AIEE committee report [12], which is accepted as an earlier version of the standard provides an illustration of the somewhere below ground beneath the feet. This pictorial definition is qualified by the following assumptions.

1. Hand contact resistance and the resistance of shoes are uncertain and assumed to be zero.
2. The resistance of under each foot can be calculated assuming an equivalent area of circular plate.
3. Any change in the pre-existing voltage by reason of the current diverted through body can be neglected.
4. The body impedance is lumped (1000Ω) without any consideration of voltage dependency.
5. The tolerable voltage between any two points of contact in the above network can be calculated. This voltage may act as a Thévenin's voltage source.

Although, the accidental *'touch voltage circuit'* in Std.80 differs from that in [12], it fulfils the listed assumptions. Hence, it may be concluded that the accidental circuit model has not changed since the publication of [12].

3.2 The UK Standards

The touch potential in [2] is defined by the statement; "*a person standing on the ground 1 metre away and touching the structure will be subject to the 'touch potential'.*" The standard does not provide any equation for the calculation of allowable limits, however, states that "*Touch and step potentials involve additional insulation of footwear and surface coverings.*" A value of 4000Ω per shoe is cited for the footwear resistance. For surface chipping 2000Ω per foot is assumed. Using these values, statistically safe touch potential curves are derived using IEC 479 safe body current curve (curve c1). BS 7354 [1] gives a formula to calculate the allowable touch voltages as;

$$V_T = I_B\,(R_B + (R_c + R_{fw})/2) \qquad 3$$

Where R_B is the body resistance which is assumed to be constant as 1000Ω. The recommended allowable current limit I_B is that of curve c2 in IEC 479. R_{fw} is the footwear resistance and BS 7354 assumes 4000Ω for each foot. R_c is defined as the *'contact resistance'* and is the same as equation 1. Hence it can be concluded that the same assumptions made in std.80 have also been made.

3.3 CENELEC Standard

The recent draft version the standard [3] distinguishes between *'source potentials'* and *'touch potentials'*. This provides a better formulation of the problem. The touch potential is defined as "*The part of the earth potential rise due to an earth fault which can be picked up by a person, assuming that the current is flowing via the human body hand to feet.*" The source voltage for the prospective touch voltage is clearly defined as "*The voltage which appears during an earth fault between conductive parts and earth when these parts are not being touched.*" The touch potentials is calculated using

$$U_{STp}(t_f) = U_{Tp}(t_f) + (R_{a1} + R_{a2})I_B \qquad 4$$

U_{STp} is the source potentials and U_{TP} represents the touch potential across the human body. I_B is current flowing through the human body with reference to IEC 479 curve c2. Z_B is impedance of the human body taken from the respectively. The footwear resistance is pronounced as 1000Ω and R_{a2} is given as a function of *'resistivity of the ground near the surface.'* In the standard, there is not any satisfactory explanation about the origin of the R_{a2}. This implies that resistance of feet to remote earth is being employed as done by previous standards.

4. ANALYSIS OF ACCIDENTAL CIRCUITS

Meliopoulos [13] discusses the safety problem and develops a different approach. He defines the touch potential with a pictorial way and differs from one in Std.80. This definition is similar to that in the CENELEC standard and introduces a new term, *'equivalent internal circuit resistance'*. Regarding that, he states *"the equivalent internal resistance (r_{eq}) between the points of contact can be accurately computed with numerical techniques."* However he employs a simple technique assuming an equivalent resistance which is equal to resistance of the foot to the remote earth as given in the standards. Thus it can be concluded that misrepresentation of accidental circuit in reference [12], inherently affects all subsequent approaches.

It is clear from the preceding discussion that the accidental circuit should include not only foot resistance but also the other impedances in the current path. Therefore a detailed generic accidental circuit model is proposed, in Figure 2, to facilitate a realistic analysis. The circuit is similar the one presented in [5].

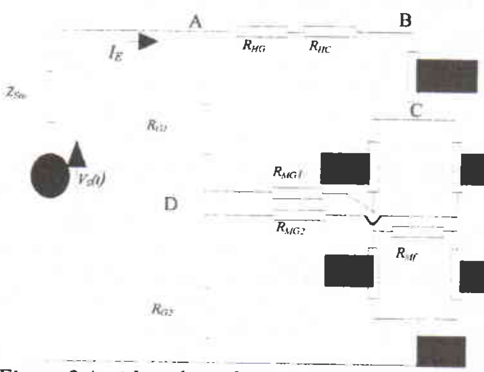

Figure 2 Accidental touch circuit.

Where,

$V_S(t)$ = Short circuit voltage.
$Z_S(t)$ = Short circuit impedance.
I_E = Earth return fault current.
R_{HG} = Glove resistance.
R_{HC} = Hand contact resistance.
$Z_B(V)$ = Body impedance which is dependent on voltage.
R_{G1} = Part of the grid resistance which caries the touch potential.
R_{G2} = Rest of the grid resistance.
R_{fw1} & R_{fw2} = Footwear resistances.
R_{f1} & R_{f2} = Resistances of each foot to the remote earth.
R_{Mf} = Mutual resistance between feet.
R_{MG1} & R_{MG2} = Mutual resistan between feet and point D.

The mutual resistances between grid and feet are the most significant differences in this circuit model compared to the previous circuits from the standards. If this resistance is assumed to be very high the accidental circuit given in the standards become satisfactory by accepting that listed assumptions is also true. The source impedance is relatively higher than the grid resistance especially for the transmission system and hence its effect on the circuit is negligible. Consequently source impedances are not considered in this study. Also hand contact and glove resistances are neglected.

To analyse the safety problem and quantify the significance of the additional equivalent resistances a series of simulations have been carried out. An arbitrarily chosen earthing system is modelled with an earthing system analysis package (viz. CDEGS [11]). The earth grid is assumed to have a rectangular (20x10m) shape and buried at 0.6m. The soil is assumed to have a uniform resistivity. The touch voltage scenario has been utilised by modelling feet 1m diagonally out from the edge of the grid. The feet are placed 30cm apart from each other and modelled as rectangular shaped (0.3x0.1m) meshed copper conductors and buried near to the surface. The total area of the feet model is greater than the model employed by the standards. However the model employed here is considered to be more realistic.

The aim of this study is to determine the total impedance, R_{eq}, as seen from the over-bridging human body. This is achieved by determining the open circuit voltage (touch potential) and the short circuit current which flows when a solid connection between the model feet and grid is established. The grid was energised by using a current source with infinite source impedance. Open and short circuit studies were carried out and the total equivalent impedance R_{eq} which is seen from the prospective over-bridging body was calculated by using 5.

$$R_{eq} = V_{open\text{-}circuit}/I_{short\text{-}circuit} \qquad 5$$

Therefore, a Thévenin equivalent circuit is established and body current I_B can be calculated from this circuit, where V_{eq} is the open circuit voltage and R_{eq} is given in 6.

$$I_B = V_{eq}/(R_{eq} + Z_B) \qquad 6$$

Since the equivalent voltage in above equation is equal to the touch potential, the equivalent resistance in this equation should be equal to additional resistance of the standard's formulae. Thus it can be concluded that the equation given in the standards is an approximation as claimed by Meliopoulos. Therefore the question is how good the approximation is. Also, most importantly whether they err on the safe side as is always claimed. In Figure 3 the *'foot resistance'* calculated by the formula given in equation 1 and the equivalent resistance are compared for soil resistivities ranging from 100Ω-m to 5000Ω-m.

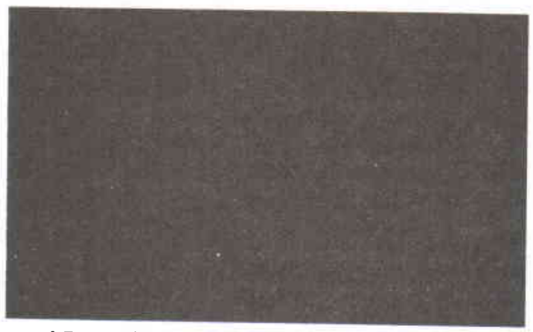

Figure 3 Dependence of soil resistivity.

It can be seen from Figure 3, standards over-estimate the *'equivalent resistance'*. The difference in two values is approximately 25 percent for all soil conditions. This could result in an under designed earthing systems.

5. EFFECT OF GRAVEL LAYER

In general the surface of the soil has different resistivity due to gravel or crushed rock layers used in the substation. These layers provide extra protection from hazard. The treatment of surface resistivity and the calculation of equivalent models differs between the standards. BS 7354 and std.80 calculate a factor called the reflection or reduction factor which depends on the resistance and the thickness of the layers. On the other hand, the CENELEC standard considers only surface resistivity to calculate the resistance of the foot. BS 7354 and std.80 give different formulae. However both standards utilise the reflection coefficient K,

$$K = (\rho - \rho_s)/(\rho_s + \rho) \qquad 7$$

Where, the terms ρ_s and ρ represent the surface (usually chipping) and underlying soil resistivity, respectively. Normally K will be negative since its function is to provide an insulating layer. Std.80 calculates the foot resistance by using surface resistivity with conjunction of a reduction factor, C_s which is a function of the reflection factor K, and the thickness of the gravel layer. This factor is calculated by following infinite series

$$C_s = \frac{1}{0.96}\left[1 + 2\sum_{n=1}^{\infty}\frac{K^n}{\sqrt{1+(2n\,h/b)^2}}\right] \qquad 8$$

Where, h represents the thickness of upper layer and b is the equivalent radius of the human foot. Also, a simple formula, based on a hemispherical equivalent of the human foot, is given in the standard which avoids the infinite summation of above series. However it has been reported that [14] calculation of resistance using the approximate equation will result in an inconsistent resistance value depends upon the thickness of gravel layer. Accordingly usage of exact formulae has been encouraged by providing a series of look-up graphs in the standard. On the other hand an inconsistency in the IEEE curve in the region from zero to eight centimetres has been noticed and attracted attention [5, 15]. Revisions in the form of analytical [16, 17], empirical [9] or semi-analytical [18] formulae have been proposed to estimate more accurately foot resistance. However, these formulae are still calculations of the resistance of the foot to the remote earth, For example, Thapar et al employs a semi-analytical method and calculates the reduction factors by following equation [18].

$$C = \frac{\rho}{\rho_s} + (1 - \frac{\rho}{\rho_s})\frac{2}{\pi}\tan^{-1}(2h/b) - 0.21\left(\frac{\rho - \rho_s}{\rho + \rho_s}\right)^2\left(e^{-7h} - e^{-30h}\right) \qquad 9$$

The term h is the thickness of the surface layer and b is the equivalent radius of the human foot both in metres. It is claimed that this equation is valid for the thickness up to 0.3m. It has been shown [19] that these new approaches yield similar results. However it has been reported on a recent IEEE paper [20] that, a revision on Std.80 is on the agenda and equation 9 proposed by Thapar et al [18] is likely to be employed.

Furthermore, BS 7354 calculates the effective soil resistivity by employing following equation

$$\rho_{eff} = \rho_s\left[1 + \frac{K}{20}h\right] \qquad 10$$

Where, $_s$ represents the surface resistivity. K is the reflection factor and it is stated that *'usually it is negative'*. However, a closer look at the above equation suggests that something is fundamentally wrong with it. According to this equation effective soil resistivity would decrease as the thickness of the crushed rock layer is increased.

Figure 4 has been produced by assuming 5000Ω-m chipping resistivity and considering four different reflection factors which are -0.6, -0.7, -0.8 and -0.9.

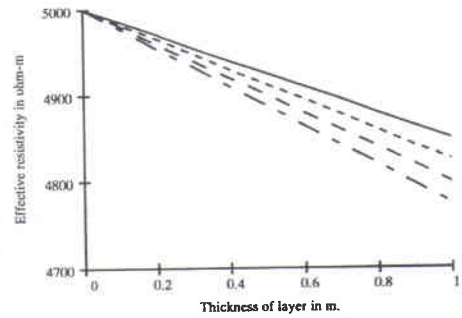

Figure 4 Decrement in the BS7354 formula.

Quite apart from the fact that effective resistivity decreases with layer thickness, this formulae suggest that effective resistivity tends towards the top layer resistivity value as the layer thickness tends to zero. BSI has been contacted and confirmed there has been no amendment regarding this formula. However the safe touch potential curves in BS 7354 and TS 41-24 does not appear to be derived from that equation. BS 7354 provides three curves for 100, 500 and 1000Ω-m soil resistivity and 8cm chipping. TS 41-24, on the other hand, gives a curve considering 4000Ω footwear resistance and 2000Ω chipping resistance for 15cm of thickness.

The effects of surface resistivity is presented in Figure 5. The substation is assumed to be covered by a 0.15 m of gravel layer whose resistivity has been varied and changes in the equivalent resistance is presented. The single value, cited in TS 41-24, is also included for comparison.

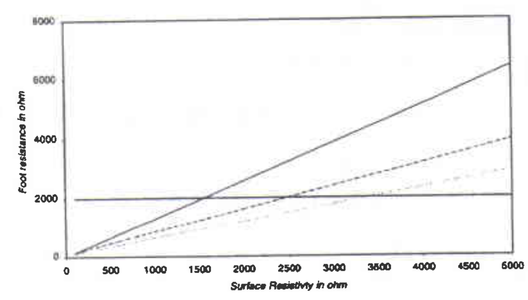

Figure 5 Effects of surface resistivity

IEEE and CENELEC, over-estimate the foot resistance or equivalent resistance of the accidental circuit. Therefore the resulting allowable touch voltages are under estimated. This will result in an under-designed earthing system and possibly put people's lives at risk. The over-estimation of the *'foot resistance'* for IEEE varies between 23% up to 33% and for the CENELEC between 45% up to 80%.

The thickness of the surface layer also plays an important role, therefore, resistivity of the layer kept constant as 5000Ω-m and thickness of the layer varied from 0 to 0.3m. Results are presented in following Figure 6. Since no consideration has been observed in CENELEC standard regarding effect of varying surface layer thickness, it is excluded from the study. The single value, which is cited by TS 41-24 is also presented for 0.15m thickness.

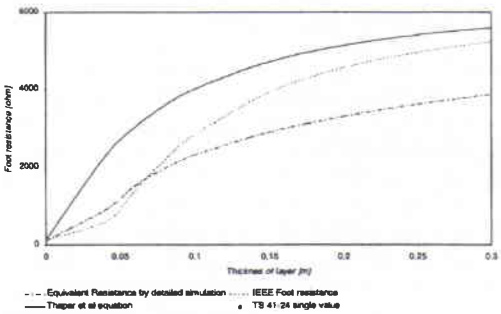

Figure 6 Effect of thickness

The foot resistance or equivalent circuit resistance calculated by the IEEE standard 80 is over-estimated for the higher surface thickness. The Thapar et al equation [18] over-estimates the foot resistance for the whole thickness range.

6. CONCLUSIONS

The definition of touch potential in IEEE standard 80, BS 7354 and EA TS 41-24 is misleading. The new CENELEC standard defines this potential correctly. However this standard does not treat the foot resistance of the accidental circuit correctly and assume a foot resistance to remote earth. The simulations carried out in this work using the correct Thevenin representation have shown that significant over-estimation can be introduced if the foot resistance is not properly determined. The errors are considerable at high soil resistivity conditions.

Further over-estimate of the foot resistance is apparent in the standards' treatment of gravel layers.

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