REDUCTION FACTOR FOR THE GROUND RESISTANCE OF THE FOOT IN SUBSTATION YARDS

Baldev Thapar *Senior Member* **Victor Gerez** *Senior Member* **Harsh Kejriwal** *Student Member*
Montana State University
Bozemen, Montana

Abstract - Limited thickness of the surface layer of gravel in a substation yard decreases the ground resistance of the foot from its value for the infinite thickness of the surface layer, by reduction factor C. The foot is usually represented by an equivalent circular plate of radius 8 cm. This paper presents method and equations to accurately determine the reduction factor for the circular plate. The equations are valid for any depth of the upper layer. The data is presented in the form of graphs. A simple empirical equation for determining the value of C is also presented.

Keywords: Footing Resistance, Grounding, Safety, Body current, Substations.

INTRODUCTION

Ground resistance of the human foot is an important factor in determining the safe value of the touch and step voltage that a person can withstand. A convenient method to estimate the ground resistance of the foot is to consider it equivalent to the ground resistance of a circular conducting disc having a radius of 8 cm and placed horizontally on the surface of the ground.[1]. If the ground is assumed to be homogeneous of resistivity ρ_s, the ground resistance, R_f of a circular conducting plate of radius b on the surface of the ground is given by [1]:

$$R_f = \rho_s /(4b) \tag{1}$$

and for b=0.08 m

$$R_f \approx 3\rho_s \tag{2}$$

In the substation switchyards a surface (upper) layer of gravel, crushed rock or asphalt is usually spread over the surface of the ground. This layer provides a high resistivity medium below the feet of a person in the switchyard area. As compared to the size of the foot, the depth of the surface layer is not large enough to assume that the material is homogeneous in the vertical direction. The ground resistance of the foot in this case is given by:

$$R_f = [\rho_s /(4b)]C \tag{3}$$

where C is the reduction factor due to the limited thickness of the surface layer.

The value of C depends on the depth, h, of the surface layer and the ratio, ρ_s/ρ, which is the resistivity of the surface layer to the resistivity of the soil. With the passage of time, the surface layer in the switchyards collects dirt which is washed by rain to the lower part of the surface layer. In due course the effective thickness of the upper layer may become very small. Asphalt, if used on the pathways in the switchyard area, may have only a small depth. Therefore, it is necessary to determine the value of C for a depth of the upper layer ranging from a fraction of a centimeter to about 30 cm.

93 WM 121-4 PWRD A paper recommended and approved by the IEEE Substations Committee of the IEEE Power Engineering Society for presentation at the IEEE/PES 1993 Winter Meeting, Columbus, OH, January 31 - February 5, 1993. Manuscript submitted June 9, 1992; made available for printing January 6, 1993.

A number of equations and graphs have been proposed to determine the value of C.[1-5]. The equations and graphs given in IEEE Standard 80 are based on the hemispherical electrode for which the value of C is given by [1]:

$$C = 1 + 2 \sum_{n=1}^{\infty} Q \tag{4}$$

$$Q = K^n/[1+(2nh/b)^2]^{1/2} \tag{5}$$

$$K = (\rho - \rho_s)/(\rho + \rho_s) \tag{6}$$

These equations are valid for the hemispherical electrodes and are not justified for the plate electrode representing the foot. These equations give a low value of C particularly when h is less than 10 cm.

Thapar et al [3] have given the equations and graphs based on analytical expressions for rectangular and circular plate representation of the foot. These equations are valid for h>2.8 cm for the rectangular plate representation and for h>16 cm for the circular plate representation.

Dawalibi et al [4] and Meliopoulos et al [5] have given the graphs based on the computer models. Model of the foot used in reference [4] comprises wires of radius 0.1 cm buried at a depth of 0.21 cm. When the depth of the upper layer is small, say less than 2 cm, the model of the foot cannot be considered to be located on the surface of the upper layer as the depth at which it is buried is not negligible as compared to the depth of the upper layer. This can introduce an error in the computed value of C for small values of h. The model of the foot used in reference [5] is a plate electrode at the surface of the upper layer and the values of C obtained are a little lower than the corresponding values obtained by Thapar et al [3]. However, there is a close match in the results presented in the three references, [3], [4] and [5].

This paper presents an analytical method to correctly determine the reduction factor C for a circular plate representing the foot. The equations derived are applicable to any depth of the upper layer. Also, a very simple empirical equation for determining the value of C has been developed and is presented in this paper. Mutual ground resistance between the two feet and the proximity of the energized grid are not considered. In practical cases their combined effect on the ground resistance of the foot is small enough to be considered insignificant in grounding practice [6].

METHOD AND DATA

The reduction factor, C, for a circular plate on the surface of the upper layer is determined with the aid of the following steps.

(a) When a thin circular plate discharges a current I in an infinite medium of resistivity ρ_s, the potential produced at any point is determined in terms of Surface Zonal Harmonics (Legendre Functions of the First Kind). The equations to determine this potential are given in Appendix A.

(b) The potential produced on the plate itself is $(I\rho_s)/(8b)$. Ground resistance, R, of the plate in the infinite medium is, therefore, $\rho_s/(8b)$.[1,7].

(c) The method of images is used to obtain the required boundary conditions at the interfaces between air gravel and soil. The mutual ground resistance between the images and the plate is an important factor and it is determined using only one image at a time. Since the image is parallel to the plate on a common axis, the flow of current from the plate is not appreciably affected by the presence of the image. A little distortion in the flow of current caused by the presence of the image can be ignored for all practical purposes even for a very small distance between the plate and its image.

(d) The potential produced on another similar, parallel, coaxial plate is determined by evaluating the average potential on the surface of this plate. This is done by integration of the potential at the surface of the plate. The mutual ground resistance, R_m, between the two plates is determined by dividing the average potential by the current I. The equations used are given in Appendix A.

(e) The ground resistance, R_f, of the plate on the surface of the upper layer is then obtained with the use of the method of images and is given by

$$R_f = 2R + 4 \sum_{n=1}^{\infty} \{K^n R_{m(2nh)}\} \tag{7}$$

where $R_{m(2nh)}$ is the mutual ground resistance between the two similar, parallel, coaxial plates, separated by a distance (2nh).

(f) The reduction factor C is obtained by dividing R_f by, 2R, the ground resistance of the circular plate on the surface of homogeneous soil of resistivity ρ_s. It is given by

$$C = 1 + \frac{16\,b}{\rho_s} \sum_{n=1}^{\infty} \{K^n R_{m(2nh)}\} \tag{8}$$

A computer program was developed to solve the equations for evaluating R_f and C. The infinite series in equations (A3) and (A4) were cut off when absolute value of the term in the series was less than 10^{-7}. The integration in equation (A9) was evaluated with the use of numerical analysis. The disc was discretized into 100 annular rings for integrating the voltages. The infinite series in equations (7) and (8) were cut off at 300th term. It was checked that this cut off did not result in an error of more than 0.01% in the value of R_f. This was done by cutting off the infinite series in equations (7) and (8) at 1000 terms for a few representative cases and comparing the results with those obtained by cutting off the series at 300th term.

R_f and C were calculated for the following range of the variables

ρ = 100 ohm-m.
K = -0.1, -0.2, -0.3, -0.4, -0.5, -0.6, -0.7, -0.8, -0.9, -0.95, -0.98.
h = 0 to 30 cm.
b = 0.08 m.

The results are plotted in Figures 1 to 8.

The slope of the graphs of R_f for h=0, as obtained from the computer data for equation (7), is very closely given by:

$$\frac{\rho_s - \rho}{\pi b^2} \tag{9}$$

and the slope of the graphs of C for h=0, as obtained from the computer data for equation (8), is very closely given by:

$$\left(1 - \frac{\rho}{\rho_s}\right) \frac{4}{\pi b} \tag{10}$$

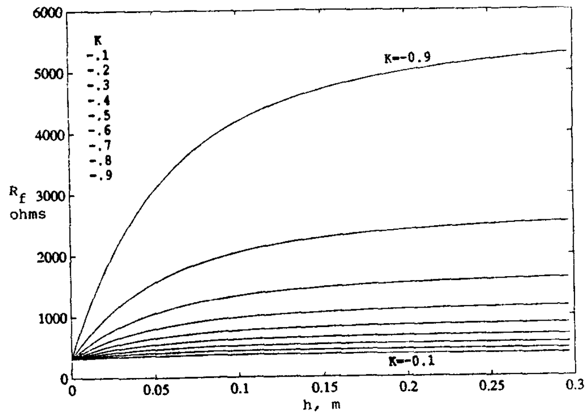


Figure 1 - R_f versus h. (Analytical Method) K = -0.1 to -0.9; h = 0 to 0.3 m.

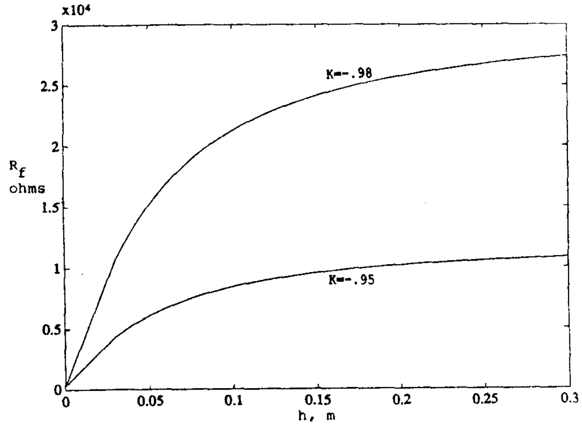


Figure 2 - R_f versus h. (Analytical Method) K = -0.95, -0.98; h = 0 to 0.3 m.

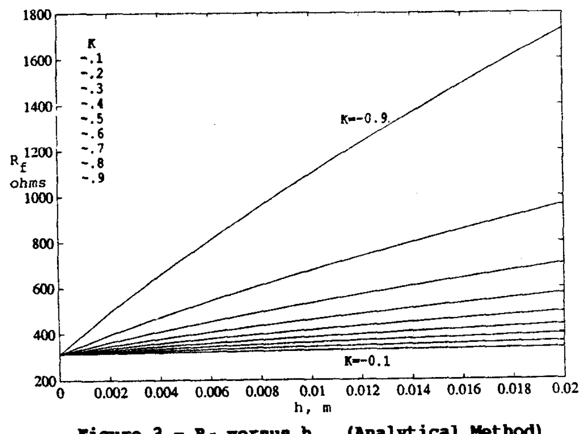


Figure 3 - R_f versus h. (Analytical Method) K = -0.1 to -0.9; h = 0 to 0.02 m.

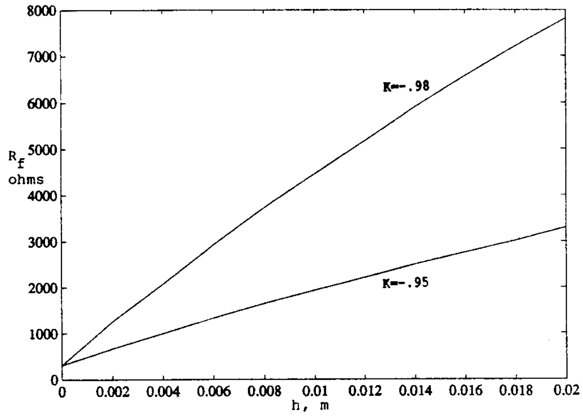


Figure 4 - R_f versus h. (Analytical Method)
K = -0.95, -0.98; h = 0 to 0.02 m.

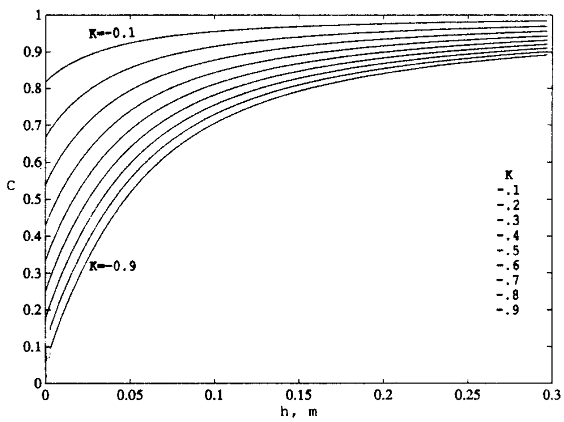


Figure 5 - C versus h. (Analytical Method)
K = -0.1 to -0.9; h = 0 to 0.3 m.

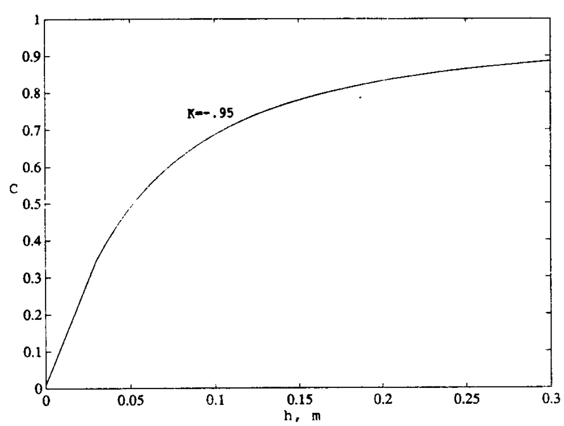


Figure 6 - C versus h. (Analytical Method)
K = -0.95; h = 0 to 0.3 m.

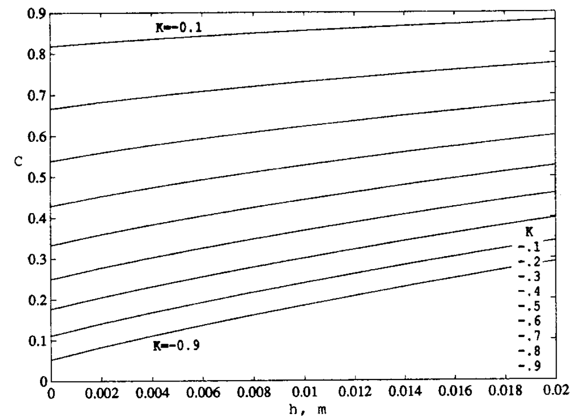


Figure 7 - C versus h. (Analytical Method)
K = -0.1 to -0.9; h = 0 to 0.02 m.

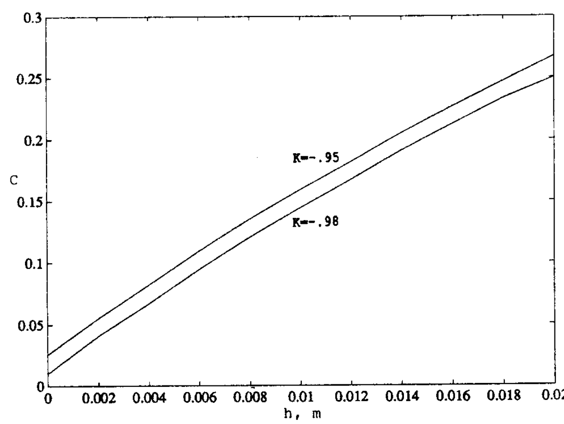


Figure 8 - C versus h. (Analytical Method)
K = -0.95, -0.98; h = 0 to 0.02 m.

Table I - Comparison of the values of C

h		C			
cm	K	TGK	TGE	MXJC	IEEE80
5	-.3	.797	.806	.78	.681
5	-.5	.691	.705	.64	.514
5	-.7	.601	.619	.53	.373
5	-.9	.522	.545	.43	.252
10	-.3	.877	.883	.86	.807
10	-.5	.810	.820	.76	.703
10	-.7	.753	.766	.68	.612
10	-.9	.702	.718	.60	.533
16	-.3	.919	.921	.91	.873
16	-.5	.875	.879	.80	.804
16	-.7	.837	.842	.78	.744
16	-.9	.803	.810	.72	.691
20	-.3	.935	.936		.897
20	-.5	.900	.901		.841
20	-.7	.869	.871		.793
20	-.9	.842	.844		.750

Note: TGK - Thapar, Gerez, Kejriwal. [This paper]
TGE - Thapar, Gerez, Emmanuel. [3]
MXJC - Meliopoulos, Xia, Joy, Cokkinides. [5]. The values are obtained from Figure 12 of the reference.

COMPARISON OF RESULTS

The values of C obtained with the method given in the previous section of this paper are compared with the values of C given by the following:

(a) Thapar et al, (TGE).[3].
(b) Meliopoulos et al, (MXJC).[5].
(c) IEEE Standard 80.

Table I gives the comparison for some representative values of h and K. The values of C given by (MXJC) are somewhat low. The difference which is less than 20% may be due to the computer algorithm and the model of the foot used for the study. IEEE Standard 80 gives values of C which are too low. These values are for a hemispherical electrode and are not valid for the foot which acts like a plate.

The values of C given by (TGE) were obtained when the foot was represented by a rectangular plate. These values are very close to the corresponding values of C for a circular plate reported in this paper. The well established method of images has been used in both the cases but the equations used for the rectangular plate are very different from the equations used for the circular plate. The value of C obtained is almost the same whether the equations for a rectangular plate or for a circular plate are used. The difference is less than 5%. This provides a cross check to the accuracy of the values of C obtained in this paper.

SIMPLE EMPIRICAL EQUATION

Calculation of R_f or C with the analytical method given in this paper requires the sum of the infinite series and the numerical solution of the integral. This is time consuming and not convenient, specially if the calculation of C is to be incorporated as a part of a computer program for the design of the grounding systems. What is needed is a simple equation that gives the values of C very close to the values obtained with the analytical method. From the data generated by the computer the following simple empirical equation for C has been developed:

$$C = \frac{1+K}{1-K} - \frac{4K}{\pi(1-K)}\tan^{-1}(2h/b) - 0.21K^2(e^{-7h}-e^{-30h})$$

$$= \frac{\rho}{\rho_s} + (1-\frac{\rho}{\rho_s})\frac{2}{\pi}\tan^{-1}(2h/b) - 0.21(\frac{\rho-\rho_s}{\rho+\rho_s})^2(e^{-7h}-e^{-30h}) \quad (11)$$

Where h and b are both in meters. This equation is applicable for h varying from 0 to 0.3 m and K varying from 0 to -0.98.

Figures 9 to 12 give the plots of R_f and C as determined from the empirical equation. The graphs of C obtained from the analytical method and from the empirical equation are superposed in figure 13 for the sake of comparison. The error in the empirical equation as compared with the accurate analytical method is small. For most of the range the error in the empirical equation is less than 3%. Equation (11) can further be simplified by ignoring the last of the three terms. In this simplified form, for most of the range the error is less than 10% and at no place it is more than 20%.

CONCLUSIONS

1. The ground resistance of the foot in a substation yard is usually determined by calculating the ground resistance of a circular plate of 8 cm radius on the surface of a very thick top layer of gravel, crushed rock or asphalt. This ground resistance is then multiplied by a reduction factor C which takes into account the limited thickness of the top layer and the resistivities of the top layer and the soil.

2. Analytical method and the equations presented in this paper give an accurate value of C for a circular plate. The equations are valid for any value of the depth of the upper layer.

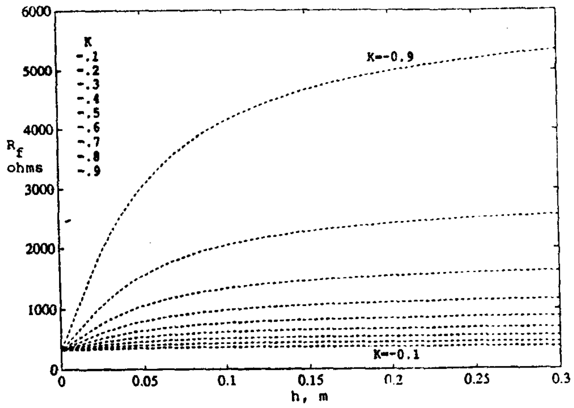


Figure 9 - R_f versus h. (Empirical Equation) K = -0.1 to -0.9; h = 0 to 0.3 m.

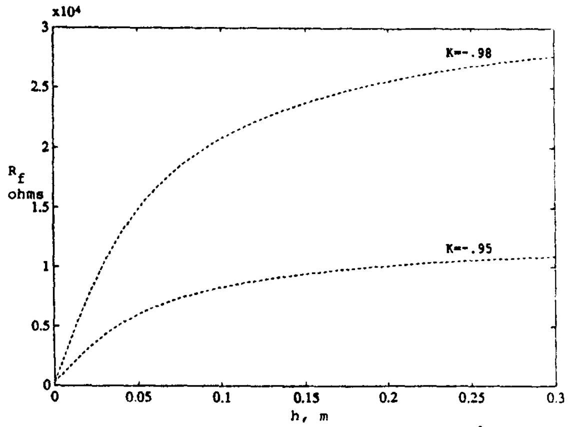


Figure 10 - R_f versus h. (Empirical Equation) K = -0.95, -0.98; h = 0 to 0.3 m.

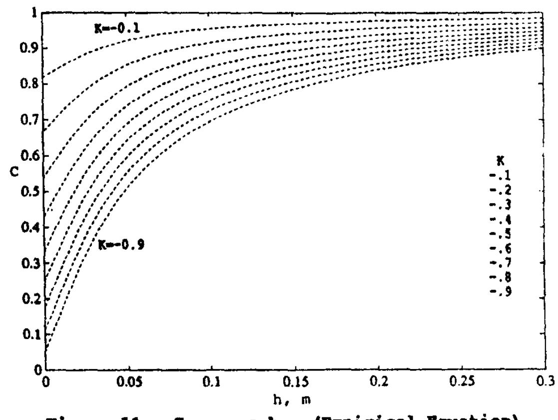


Figure 11 - C versus h. (Empirical Equation) K = -0.1 to -0.9; h = 0 to 0.3 m.

3. The value of C obtained by the analytical method presented in this paper are compared with the corresponding values of C previously reported in the literature. The difference between the values of C determined by the method presented in this paper and those obtained for a rectangular plate is less than 5%.

4. The empirical equation (11) for C gives results which are very close to those obtained from the accurate analytical equations.

5. The graphs and the empirical equation for C given in this paper should be useful to the engineers dealing with the grounding systems.

REFERENCES

1. "IEEE Guide for Safety in AC Substation Grounding", ANSI/IEEE Standard 80, 1986.

2. B.Thapar, V.Gerez, A.Balakrishnan, D.A.Blank, "Finite Expression and Models for Footing Resistance in Substations". IEEE Transactions on Power Delivery, Vol 7, 1992, pp. 219-223.

3. B.Thapar, V.Gerez, P.Emmanuel, "Ground Resistance of the Foot in Substation Yards". IEEE/PES 1992 Winter Meeting, Paper # 92 WM 218-8 PWRD.

4. F.P.Dawalibi, W.Xiong, J.Ma, "Effects of Deteriorated and Contaminated Substation Surface Covering Layers on Foot Resistance Calculations". IEEE/PES 1992 Winter Meeting, Paper # 92 WM 221-2-PWRD.

5. A.P.S.Meliopoulos, F.Xia, E.B.Joy, G.J.Cokkinides, "An Advanced Grounding Analysis Method". IEEE/PES 1992 Winter Meeting, Paper # 92 WM 220-0-PWRD.

6. B.Thapar, V.Gerez, V.Singh, "Effective Ground Resistance of the Human Feet in High Voltage Switchyards". IEEE/PES 1992 Winter Meeting, Paper # 92 WM 219-6 PWRD.

7. W.E.Byerly, "Fourier's Series and Spherical, Cylindrical and Ellipsoidal Harmonics". (book), Ginn and Company, Boston, Mass. 1902.

8. Handbook of Mathematical Functions. (book), Dover Publications, Inc., New York, 1972.

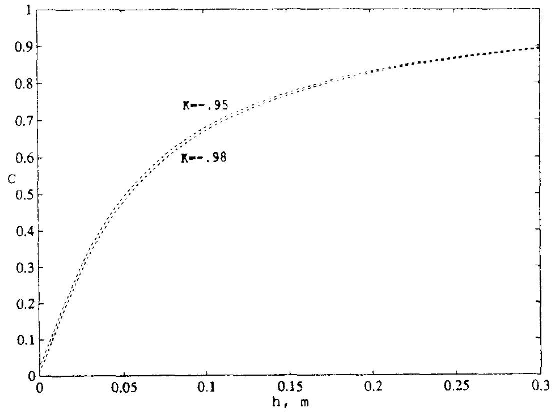


Figure 12 - C versus h. (Empirical Equation) K = -0.95, -0.98; h = 0 to 0.3 m.

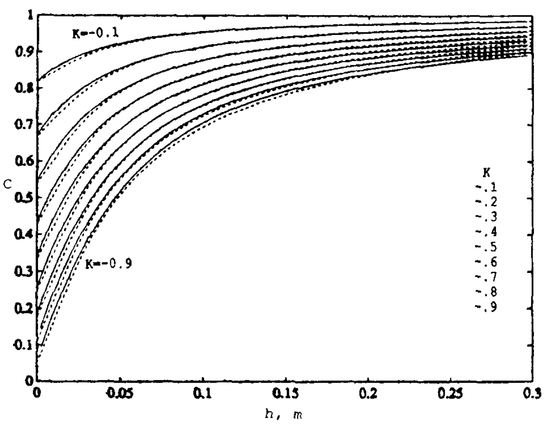


Figure 13 - Comparison of C. Analytical Method ______ ; Empirical Equation ....

APPENDIX A
POTENTIAL AROUND A CIRCULAR PLATE

Consider a thin circular plate, D1, in the x-y plane with the z axis passing through its center. The radius of the plate is b and it discharges a current I in an infinite uniform medium of resistivity ρ_s. Using spherical coordinates the potential at any point (r,θ) is given by the following equations.[7].

$$r = (x^2+y^2+z^2)^{1/2} \quad \text{(A1)}$$

$$\theta = \tan^{-1}(z/r) \quad \text{(A2)}$$

$$V_{r,\theta} = \frac{I\rho_s}{4\pi b}\left[\frac{\pi}{2} + \sum_{q=1}^{\infty} (-1)^q \frac{1}{2q-1}\left(\frac{r}{b}\right)^{2q-1} P_{2q-1}(\cos\theta)\right] \quad \text{(A3)}$$

for $r<b$ and $\theta<(\pi/2)$

and $$V_{r,\theta} = \frac{I\rho_s}{4\pi b}\left(\sum_{q=1}^{\infty} (-1)^{q+1} \frac{1}{2q-1}\left(\frac{b}{r}\right)^{2q-1} P_{2q-2}(\cos\theta)\right) \quad \text{(A4)}$$

for $r>b$

$P_n(\cos\theta)$ is Legendre Function of the first kind and of order n. It is also known as Legendrian of the nth order. Legendrian of the 0, 1st and 2nd order are given by [8]:

$$P_0(\cos\theta) = 1 \quad \text{(A5)}$$

$$P_1(\cos\theta) = \cos\theta \quad \text{(A6)}$$

$$P_2(\cos\theta) = (1/2)(3\cos^2\theta-1) \quad \text{(A7)}$$

Legendrian of a higher order can be obtained from the two legendrians of the next lower order by the following equation.[7].

$$(n+1)P_{n+1}(\cos\theta) = (2n+1)\cos\theta\ P_n(\cos\theta) - nP_{n-1}(\cos\theta) \quad \text{(A8)}$$

Consider another similar plate, D2, placed parallel and coaxial to the circular plate D1 and at a distance z from it. The potential produced on D2 can be determined by evaluating the average potential over the surface of the plate. It is given by:

$$V_{D2} = \frac{1}{\pi b^2}\int_0^b (V_{r,\theta}\, 2\pi x)\,dx \quad \text{(A9)}$$

r and θ are given by (A1) and (A2) respectively for y=0 and $V_{r,\theta}$ is given by (A3) and (A4).

The mutual ground resistance, $R_{m(z)}$, between the two plates is given by:

$$R_{m(z)} = (V_{D2})/I \qquad \text{(A10)}$$

Baldev Thapar (M'60, SM'62) was born in India on Sept. 1, 1930. He received the B.Sc.(Honours) degree from Banaras Hindu University, M.S. and Ph.D. degrees from Illinois Institute of Technology, in 1953, 1960 and 1963 respectively, all in electrical engineering. From 1953 to 1955 he was with Punjab Public Works Department, India, working in Power System Operation. In 1955 he joined the faculty of Punjab Engineering College, Chandigarh, India, where he was Professor, Electrical Engineering from 1966 to 1985. In 1985-86 he was a Visiting Professor at Louisiana State University. At present he is a Professor in the faculty of Electrical Engineering Department, Montana State University, Bozeman.

Dr. Thapar is a Fellow of Institutions of Engineers (India). He is a member of Eta Kappa Nu, Tau Beta Pi and Sigma Xi. His research interests are in electric power system analysis, protection and grounding.

Victor Gerez (SM) was born in Santander, Spain, on April 11, 1934. He received his Engineering degree from National University of Mexico and his M.S. and Ph.D. degrees from the University of California at Berkeley in 1958, 1969 and 1972 respectively, all in electrical engineering.

From 1958 to 1965 he was an electrical design engineer in several Mexican companies. From 1966 to 1973 he was a member of the technical staff of Mexico's National Utility. In 1973 he became chairman of the Mechanical-Electrical Engineering Department at the National University of Mexico. In 1977 he was named director of the power system division in Mexico's Electric Research Institute. He joined the Electrical Engineering Department at Montana State University in 1983 and became chairman in 1984.

Dr. Gerez is the author of several articles on system and power engineering and co-author of six electrical and system engineering textbooks widely used in Spanish speaking countries.

Harsh Kejriwal is currently a graduate student working on his MS degree in Electrical Engineering at the Montana State University. He received his BE in Instrumentation Engineering from Bombay University, India in 1991. In 1990-91 he worked for the Society for Applied Microwave Electronics Engineering and Research, Tata Institute of Fundamental Research, Bombay.

Discussion

J. G. SVERAK (DECON, Bad Homburg, Germany): Renewed interest in persons' safety near the energized electrical facilities seems to be reflected in the recent avalanche of papers zeroing on the ground resistance of a human foot in a switchyard and the evaluation of a reduction factor for protective layers. [2-6, 9]

Realizing that in such a fertile environment it is possible to overlook some trees in the forest and especially not to see some little one sitting a notch below the grass level, I would like to point out that the small print on page 41 of Std 80-1986 contains a formula which should have been of interest to the authors. The formula is a part of a footnote to the infinite series defining the reduction factor curves, shown in Fig. 8 of the Guide [1]. The footnote says:

Simple alternative approaches based on the equivalent hemisphere concept, such as

$$C \approx 1 - a[(1 - rho/rhos)/(2hs + a)] \qquad a = 0.106\ m \qquad (D1)$$

which avoids the infinite summation series, are also possible; refer to pp. 14-15 of [B100] and to Jackson's discussion of Sverak's equations on p. 19 of the same reference.

This formula is simpler than the proposed Eq. (11) and yet it is not empirical, in spite of avoiding completely the infinite summation series. And, referring to [4] of the authors' reference list, recently Dawalibi et al. verified that this "footnote" formula actually performs much better than the infinite series expression of Std 80 which it has been supposed to approximate.

In 1984, I developed the basic form of (D1) as equation (61) of [B100], viewing it only as an intermediate step in a series of equations leading to a simple expression for estimating the foot resistance in the presence of an energized grid. It was Mr. D. W. Jackson's thoughtful suggestion to change the sign of the a-term in the denominator of (61) for thin layer applications, that led to the idea to put such a modified expression into the Guide, as alternative means for estimating the reduction factor C.

However, in the eighties, the curves in Fig. 8 of [1] were believed to contain less approximation errors than D1, which showed a positive bias with respect to the former. That's why the formula was put in the footnote.

Predictably, now there is not much difference between the curves corresponding to (D1) and those obtained by Eq. (11), since the latter approximates the C curves that do not contain the error imbedded in those of the Std 80 (caused by adapting the Shiau's formula for a deep-buried antenna wire to a shallow depth problem).

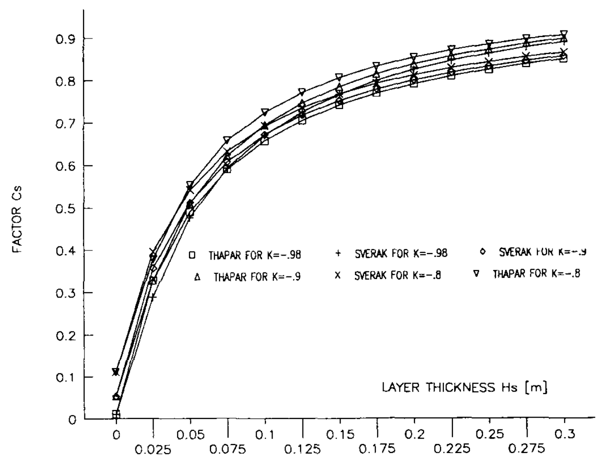
As shown below, (D1) is just a bit more conservative than Eq. Eq. (11).

D1/STD 80

HS -->	0	0.05	0.1	0.15	0.2	0.25	0.3
K	0.106	0.206	0.306	0.406	0.506	0.606	0.706
K = 0	1	1	1	1	1	1	1
-0.1	0.818181	0.906443	0.937017	0.952530	0.961911	0.968196	0.972701
-0.2	0.666666	0.828478	0.884531	0.912972	0.930171	0.941694	0.949952
-0.3	0.538461	0.762509	0.840120	0.879499	0.903314	0.919268	0.930703
-0.4	0.428571	0.705963	0.802054	0.850809	0.880293	0.900047	0.914204
-0.5	0.333333	0.656957	0.769063	0.825944	0.860342	0.883388	0.899905
-0.6	0.25	0.614077	0.740196	0.804187	0.842885	0.868811	0.887393
-0.7	0.176470	0.576242	0.714725	0.784989	0.827481	0.855950	0.876353
-0.8	0.111111	0.542610	0.692084	0.767925	0.813790	0.844517	0.866540
-0.9	0.052631	0.512519	0.671826	0.752657	0.801539	0.834288	0.857760
-0.98	0.010101	0.490634	0.657093	0.741553	0.792629	0.826849	0.851374

EQUATION (11)

K = 0	1	1	1	1	1	1	1
-0.1	0.818181	0.920888	0.955018	0.969123	0.976639	0.981272	0.984400
-0.2	0.666666	0.852770	0.915500	0.941852	0.956060	0.964877	0.970844
-0.3	0.538461	0.792643	0.879753	0.917024	0.937386	0.950109	0.958741
-0.4	0.428571	0.738360	0.846565	0.893812	0.919988	0.936463	0.947669
-0.5	0.333333	0.688349	0.815051	0.871608	0.903406	0.923570	0.937320
-0.6	0.25	0.641429	0.784543	0.849956	0.887295	0.911152	0.927462
-0.7	0.176470	0.596697	0.754534	0.828507	0.871390	0.898996	0.917918
-0.8	0.111111	0.553453	0.724627	0.806990	0.855487	0.886938	0.908549
-0.9	0.052631	0.511141	0.694511	0.785192	0.839423	0.874848	0.899247
-0.98	0.010101	0.477662	0.670096	0.767434	0.826368	0.865081	0.891794



Ultimately, I believe that the influence of an energized grid should have been taken into account. The authors dismissed the need for doing so by making reference to their previous paper [6]. In my opinion, that paper conveys misleading information: It stipulates that "the presence of the energized grid in practical situations decreases the ground resistance of the feet", which translates into a negative value of the mutual resistance between the grid and the feet.

This contradicts both one's logic and the physical reality. Since the energized grid is an active electrode which is simultaneously discharging fault currents into the soil at a full GPR potential, the mutual resistance must be positive, to account for the reduction of an accidental current flow through the feet into the ground due to the counter-influence of the fault currents emanating from the grid, which saturate the soil between the surface and the grid to such an extent that the soil potential under the point of foot contact is elevated to a GPR minus mesh voltage level, or higher. The net result is that the presence of an energized grid forces the current flowing from the feet into the ground to spread wide; an effect similar to that caused by an impenetrable barrier, except that the barrier is electrical, as no current will flow from the point of lower potential (feet) to that at the maximum potential (grid at GPR). In this respect, the model experiments described in [6] were rather ill-conditioned and the results inconclusive enough to lend credence to a wrong conclusion, which is projected into this paper.

Additional references:

[9] F. P. Dawalibi, R. D. Southey and R. S. Baishiki, "Validity of Conventional Approaches for Calculating Body Currents Resulting from Electric Shocks", IEEE Trans. on PWRD, Vol. 5, No. 2, April 1990, pp. 613-626.1

[B100] J. G. Sverak, "Simplified Analysis of Electrical Gradients Above a Ground Grid; Part I - How Good is the Present IEEE Method?", IEEE Trans. on Power Apparatus and Systems, Vol. PAS-103, No. 1, January 1984, pp. 7-25.

Manuscript received March 4, 1993.

BALDEV THAPAR, VICTOR GEREZ, HARSH KEJRIWAL: The authors thank the discusser for his comments and appreciate the interest shown by him. There is an obvious mistake in the nomenclature used for the graphs for K=-.98 in the figure given in the discussion. The correct nomenclature should be:
□ SVERAK FOR K=-.98 + THAPAR FOR K=-.98

The discusser has raised two points:
1. Footnote in IEEE Standard 80-1986.
2. Presence of the energized grid.
The authors shall address both these points and show that the results and conclusions presented in this paper are based on sound scientific principles and are correct.

1. The authors are aware of the footnote on page 41 of IEEE Standard 80-1986 which is reproduced in the discussion. Development of equation (D1) as given in reference [B100] is anomalous because of the following:

(a) The gravel-soil and the air-gravel interfaces are taken care of by considering only one image. It is an established fact that the two interfaces will give rise to an infinite number of images.

(b) The equivalent hemispherical electrode is considered to be wrapped in a hemispherical layer of gravel, forming a concentric shell of thickness equal to twice the depth of the gravel. There is no scientific justification for this modelling.

(c) Radius of the hemispherical equivalent conductor is taken as 0.106 m. It represents two feet in parallel having the ground resistance of 1.5ρ in uniform soil. When the ground resistance of the two feet in parallel is 1.5ρ, the distance between the feet may be more than the depth of the gravel. As such two feet cannot be adequately represented by only one hemisphere. If each foot is represented by a hemisphere, the radius of the equivalent hemisphere that gives a ground resistance of 3ρ in uniform soil is 0.053 m. If this radius is used in equation (D1) then the error in the equation is large as shown in Figure C1. This figure shows the graph of C versus h for the following parameters:

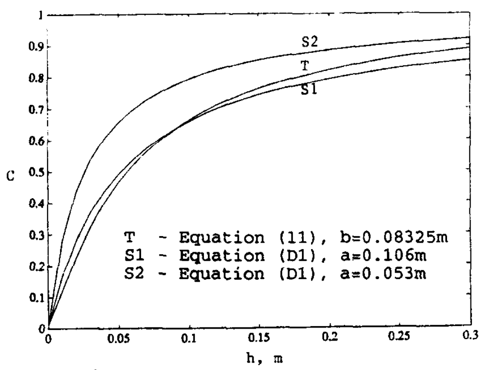


Figure C1 - C versus h, K=-0.98

K = -0.98
a(for equation (D1) of the discussion) = 0.106, 0.053 m.
b(for equation (11) of this paper) = 0.08325 m. This is the radius of the plate that is equivalent to a hemisphere of radius 0.053m.

Equation (D1) is not based on scientific accepted principles and is in large error when used for an equivalent hemisphere for one foot. It is by chance that for a = 0.106 m equation (D1) gives values of C which are not very different from the correct values. As such equation D1 is just another empirical equation. Equation (11) of this paper is simple and gives better results which are very close to the analytically calculated values.

2. The effective ground resistance of the feet is the resistance offered by the soil to the flow of the current from the two feet when the fault current is flowing through the grounding system and a person is exposed to the touch voltage. In reference [6] of this paper Thevenin equivalent circuit approach is used to determine the effective ground resistance of the feet. It can also be obtained from the basic circuit equations as follows.

Figure C2 shows the fault current I_f, being discharged to the ground by the grounding system of the station and a person touching a grounded metallic structure at H. I_b is the current flowing from H through the body of the person to the ground at F and I_g is the current that flows through the grounding system of the station. Let V be the voltage at H and use the following nomenclature which is the same as used in reference [6] of this paper.

R_b = Resistance of the body.
R_g = Ground resistance of the grounding grid.
R_{2fpg} = Ground resistance of the two feet in parallel when there is no fault current and the grid is not energized.
R_m = Mutual ground resistance between the grounding grid and the two feet.

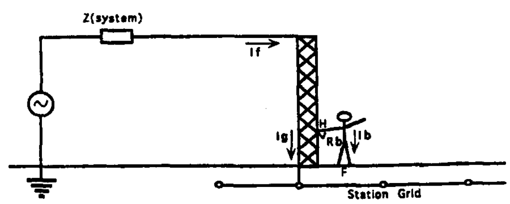


Figure C2 - Exposure to touch voltage.

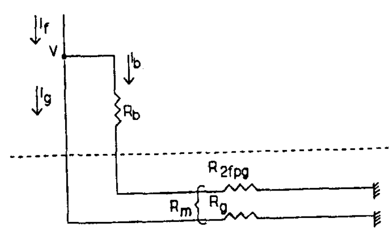


Figure C3 - Equivalent circuit.

Figure C3 shows the equivalent circuit of Figure C2 and following are the basic equations for this circuit.

$$V = I_bR_b+I_bR_{2fpg}+I_gR_m \quad (C1)$$
$$V = I_gR_g+I_bR_m \quad (C2)$$
$$I_f = I_g+I_b \quad (C3)$$

From equations (C1) and (C2)

$$I_b=\frac{V}{R_b+R_{2fpg}+\frac{(R_b+R_{2fpg})R_m-R_m^2}{R_g-R_m}} \quad (C4)$$

If the grid is not energized (I_g=0), then from equation (C1)

$$I_b=\frac{V}{R_b+R_{2fpg}} \quad (C5)$$

Comparison of equations (C4) and (C5) shows that the effect of the energized grid in this case is to increase the ground resistance of the feet from R_{2fpg} to

$$R_{2fpg}+\frac{(R_b+R_{2fpg})R_m-R_m^2}{R_g-R_m}$$

Perhaps this is what the discusser has in mind when he thinks that the effect of the energized grid is to increase the ground resistance of the feet. But this is not the way the body current I_b is determined in IEEE Standard 80. The equation used in the Standard to calculate I_b is [equation (25) page 46, IEEE Standard 80-1986]

$I_b=E_{touch}/\{R_b+$(ground resistance of the feet)$\}$ (C6)

Where E_{touch}= Touch voltage.

Note that the driving voltage used to determine the current I_b is E_{touch} and not V.

From the basic equations (C1) to (C3)

$$I_b=\frac{I_fR_g-I_fR_m}{R_b+R_{2fpg}+R_g-2R_m} \quad (C7)$$

I_fR_g is the ground potential rise (GPR) and I_fR_m is the potential on the surface of the ground at the point where the person would be standing before he/she comes in the circuit. Therefore, ($I_fR_g-I_fR_m$) is equal to E_{touch} and from equation (C7)

$$I_b=\frac{E_{touch}}{R_b+R_{2fpg}+R_g-2R_m} \quad (C8)$$

In practical grids E_{touch} is of the order of 10% of the GPR which means that R_m is of the order of 90% of R_g. Therefore, (R_g-2R_m) is negative.

Comparison of equations (C6) and (C8) shows that the effective ground resistance of the feet when the station grid is energized is ($R_{2fpg}+R_g-2R_m$) which is less than R_{2fpg}. This effective ground resistance of the feet is same as in equation (15) of reference [6] of this paper.

It should be clear from the basic equations that the effect of the energized grid on the ground resistance of the feet will depend on the driving voltage that is used to evaluate the body current. The effect will be to decrease the ground resistance of the feet when E_{touch} is the driving voltage.

The discusser has overlooked that IEEE Standard 80 uses E_{touch} as the driving voltage and this seems to have caused his unsubstantiated doubts about the validity of the results given in reference [6] of this paper. The fact is that the analog model experiments, Thevenin approach and the basic circuit equations as given above, all give the same results for the effective ground resistance of the feet. Therefore, it can be said with confidence that the results and the conclusions presented in this paper and in reference [6] of this paper are correct.

Manuscript received April 1, 1993.