Progress in Step and Touch Voltage Equations of ANSI/IEEE Std 80 - Historical Perspective

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Abstract: This paper describes the evolution of safety criteria and the development of basic formuli for evaluation of the step and touch potentials in ac substations, from 1961 to the present time. Refinements proposed for the 1996 edition of ANSI/IEEE Std 80 are presented in a broader context of the continuing development of this popular IEEE Guide. Examples of a typical grounding design illustrate the difference in evaluation procedures given in the 1961, 1986 and 1996 (proposed) editions, and their practical impact on making the design safe.

Keywords: grounding grid, safety criteria, mathematical model, simplification, ac substation.

1. Introduction

Since its first publication in 1961, the IEEE Std 80, Guide For Safety In AC Substation Grounding, has been favorably received by the industry and gained a broad acceptance worldwide [1-3]. With a preparatory work on the 1996 edition well underway, it is therefore useful to stop for a moment and review the proposed improvements in a broader context of the Guide's development to this date.

The purpose of this paper is to assess the evolution of step voltage and touch voltage equations during the 1961-1996 period and document how both the basic safety criteria and the specific formuli comprising these principal equations, progressed under the test of time.

2. Step and Touch Voltage Criteria

The goal of a safe grounding design is to prevent the possibility of situations when a person can be vulnerable to absorbing a dangerous level of electrical shock energy, before the fault is cleared and the system de-energized. Hence,

$$V_{sc} \geq V_c \quad \text{is always required for safety,} \tag{1}$$

where

V_{sc} is safe voltage limit

V_c is voltage of accidental circuit.

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In the **1961** and the **1976 editions,** the safety criteria for step and touch voltages were simply defined as

$$E_{step} = (1000 + 6\,\rho_S)\,0.165 / \sqrt{t} \tag{2}$$

$$E_{touch} = (1000 + 1.5\,\rho_S)\,0.165 / \sqrt{t} \tag{3}$$

where

ρ_S is resistivity of surface material, in ohms-m

t is duration of shock current, in seconds

The choice of resistivity values for a surface layer was left to the reader. The 0.165 constant, divided by a square root of time, t, came from the research of safe body current thresholds, reported by Dalziel in 1960 [4], indicating that 99.5 % of healthy men can be expected to tolerate ac current of 165 mA for one second. A 1000 ohm body resistance hand-to-feet, or hand-to-hand, has been a basic assumption for the safety criteria in all editions of Std 80 to this date.

1986 edition introduced two important changes: i) the safety criteria for touch and step voltages were redefined to accommodate somewhat lower limits for a 50 kg or 70 kg body weight, reflecting the outcome of more recent studies by Dalziel and Lee [5]; and ii) a special corrective factor was added, to account for the effect of a finite thickness of the surface material (which typically consists of 4 - 6 inches of crushed stones forming a protective layer) and for the often great difference in resistivities of the layer and of the soil underneath. In practice, the higher limits for 70 kg body weight are typically used for the areas within the switchyard fence which are not accessible to public.

Proposed 1996 edition retains the 1986 safety criteria without change. Thus both in the 1986 edition and the proposed 1996 edition, the step voltage criteria are given as

$$E_{step50} = (1000 + 6C_s\,\rho_S)\,0.116 / \sqrt{t} \tag{4}$$

$$E_{step70} = (1000 + 6C_s\,\rho_S)\,0.157 / \sqrt{t} \tag{5}$$

and the similar touch voltage criteria, are

$$E_{touch50} = (1000 + 1.5\,C_s\,\rho_S)\,0.116 / \sqrt{t} \tag{6}$$

$$E_{touch70} = (1000 + 1.5\,C_s\,\rho_S)\,0.157 / \sqrt{t} \tag{7}$$

where

C_s is corrective factor reducing resitivity of surface material.

Application of C_s Factor in 1986 Edition: Without the use of computer, C_s is rather tedious to evaluate, especially when a protective surface layer of small thickess, h_s, is covering the switchard and its resitivity is greater than that of the underlying soil. A set of curves, was therefore provided, Fig. 1. The curves were based on the following formula:

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

where

$K = (\rho - \rho_s)\,/\,(\rho + \rho_s)$ and $b = 0.08$ m.

As a footnote option left to readers' discretion, the 1986 Guide also suggested a very simple semi-empirical equation for alternative estimate of C_s, shown here as $C_{s\,est.}$ in (10).

However, analytical studies done in the nineties [6,7,8] have revealed that (8) contains a minor error. The error stems from a less than perfect adaptation of Shiau and Genge's equation for a deeply buried wire [9], to a shallow depth problem. The shape of derating curves is symptomatic of this oversight: There is an initial convex-to-concave curvature for depths between 0 and 0.04 m, which causes that values of C_s are too conservative for $h_s < 0.15$ m.

On the other hand, as also documented by Dawalibi et al. in [7], the seemingly unsophisticated (10) - which was adapted from Sverak [10] just for the mentioned "footnote approximation" - has proven itself to yield not only reasonably correct results, but quite unexpectedly, for very thin layers to do so within a smaller error range than other formulas.

Application of C_s Factor in 1996 Edition: In view of the above described findings, it is likely that the following equations will be included in the 1996 edition, giving the value of C_s with very good accuracy:

$$C_s = C_1 - C_2 \tan^{-1}\left(\frac{2h_s}{b}\right) - C_3\left[e^{-7h_s} - e^{-30h_s}\right] \qquad (9)$$

where

$C_1 = (1+K)\,/\,(1-K)$; $\quad C_3 = 0.21\,K^2$

$C_2 = 4K\,/\,[\pi\,(1-K)]$

h_s and b are in meters, and $\tan^{-1}$ is in radians

$$C_{s\,est.} = 1 - a\left(1 - \frac{\rho}{\rho_s}\right) / \,(2h_s + a); \quad a = 0.106 \qquad (10)$$

Equation 9 has been derived as a polynomial fit by Thapar et al. [12], to give values of C_s very close to the results obtained with their accurate but rather complex analytical method. The error is less than 5%. This equation is applicable for h_s varying from 0 to 0.3 m and K varying from 0 to -0.98. A set of C_s curves for $b = 0.08$ m will also be provided, Fig. 2, replacing Fig. 1.

The older (10) is more accurate for very thin surface layers between 0.005 m and 0.02 m, and for the rest of parameter range is about 2 - 5 % more conservative than (9).

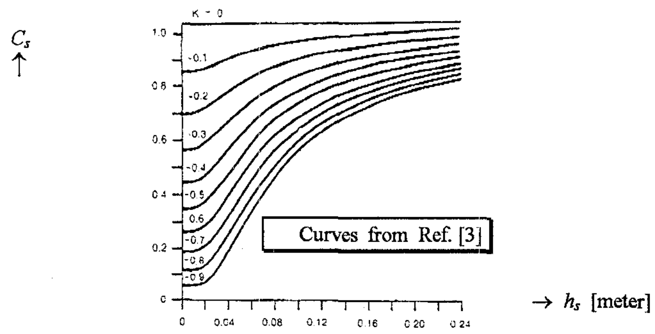

Fig. 1. Reduction factor C_s (1986 curves).

Ultimately, using the factor 1/0.96 from (8), makes its results practically identical to those of (9). Thus,

$$C_s = C_{s\,est.}\,/\,0.96 \qquad (10a)$$

Example. A surface layer of crushed stones with an average wet resistivity of 2000 ohm-m and thickness of 0.1 m (4 in), covers homogeneous soil with resistivity of 222 ohm-m. For these parameters and $b = 0.08$ m, it follows that

Using (9) or Figure 2:	Using (10):	Using (10a):
$C_s = 0.725$	$C_s = 0.692$	$C_s = 0.721$
$1.5\,C_s\,\rho_S =$ 2175 ohm	$1.5\,C_s\,\rho_S =$ 2076 ohm	$1.5\,C_s\,\rho_S =$ 2163 ohm
$6.0\,C_s\,\rho_S =$ 8700 ohm	$6.0\,C_s\,\rho_S =$ 8304 ohm	$6.0\,C_s\,\rho_S =$ 8652 ohm

3. Simplified Equations for Mesh and Step Voltage

In 1959, a small working group led by Stevens [13] developed a practical mathematical model, allowing to approximate the performance of grounding grids in terms of the maximum step and touch voltages in the critical area of a corner mesh. For its time, this was a remarkable achievment.

The model, which so far has been used in all editions of the Guide, is based on a simple abstraction of n parallel conductors in depth h. The mesh voltage, in volts, is obtained as

$$E_m = \frac{\rho \cdot K_m \cdot K_i \cdot I_G}{L_M} \qquad (11)$$

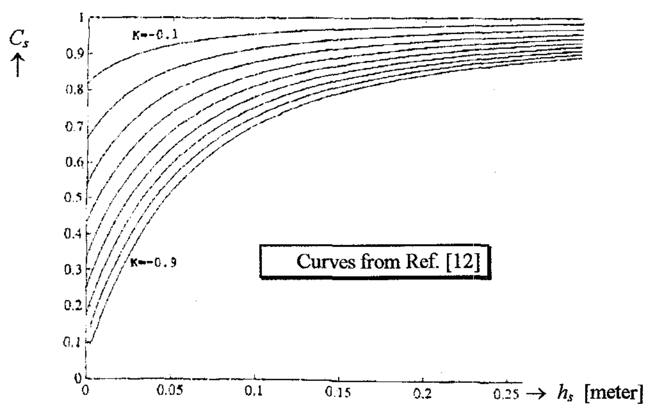

Fig. 2. Reduction factor C_s (proposed 1996 curves).

An analogous formula for calculation of the maximum step voltage, E_s, in volts, is

$$E_s = \frac{\rho \cdot K_s \cdot K_i \cdot I_G}{L_S} \tag{12}$$

Note: A formal distinction between $L = L_S$ and $L = L_M$ indicates that the effective buried conductor length may be defined differently for the step and the touch calculations.

In either formula, the calculated voltage is obtained as a product of the soil resistivity ρ, of an average current density per unit of the effective buried length, I_G/L_M or I_G/L_S, and of two factors:

K_m or K_s, characterizing the grid geometry, and

K_i, an irregularity factor, which accounts for some of the errors introduced by the assumptions made in deriving K_m and K_s.

The effective length of buried conductors includes ground rods connected to the grid. The entire grounding system is energized and conducts current I_G into the earth. A homogeneous soil of uniform resistivity is assumed.

1961 and 1976 Editions: Assuming a square grid consisting of n parallel conductors evenly spaced D apart and an undetermined number of cross-connections, K_m, K_s and K_i were defined as follows [1,2]:

$$K_m = \frac{1}{2\pi} ln\left(\frac{D^2}{16hd}\right) + \frac{1}{\pi} ln\,(\lambda) \tag{13}$$

$$K_s = \frac{1}{\pi}\left\{\frac{1}{2h} + \frac{1}{D+h} + \frac{1}{2D} + \frac{1}{3D} + \ldots + \frac{1}{(n-1)D}\right\} \tag{14}$$

$$K_i = 0.65 + 0.172\, n \tag{15}$$

where

n is number of parallel grid conductors in one direction
D is spacing between parallel conductors, m
d is diameter of grid conductor, m
h is depth of grid burial, m
λ is a finite series (3/4)(5/6)(7/8) ... ((2n - 3)/(2n -2)

The effective buried length, L, used both in (11) and (12), was simply defined as

$$L = L_c + L_r \tag{16}$$

where

L_c is total length of grid conductors including cross-connections, m
L_r is total combined length of all ground rods, m

Factors K_m, K_s and K_i perform the necessary corrections due to the difference in geometries of a configuration of n parallel conductors representing the grid and of the actual grounding system. K_m simulates the influence of currents flowing in n - 2 conductors of the n conductor model, upon the current density in two most outward parallel conductors representing the corner mesh, whereas K_i compensates for the difference in performances of the whole model and of a complete grid.

To assist the reader in choosing a convenient square grid representation of rectangular or L-shaped grids and in interpreting the results, a figure was provided for six different grid spacing patterns, depicting the distribution of mesh voltages within each grid. These auxiliary data reflected the outcome of Koch's measurements on miniature grid models in an electrolytic tank [14]. A complementary example, describing the development of a grounding design for an L-shaped grid from a rough idea to a viable concept, was also provided. Otherwise, implicitly assuming the presence of one's good engineering sense and prudent judgment, no explicit applicability limits were mentioned.

In practical use, however, some deficiencies emerged. It has been found that the application of K_m, as defined by (13), causes optimistic errors in the calculated values of the mesh voltage and, for very dense grids with high n and D approaching the order of h parameter, the result becomes negative. In contrast, K_s defined by (14) often yields overly conservative values for grids buried deeper than 0.25 m below the earth surface. In 1979, Crawford et al [15] presented a result of computer calculations, showing that the sample evaluation of the L-shaped grid given in Appendix II, did not lead to a sufficiently safe design.

1986 Edition: In order to remedy these shortcomings and to improve the accuracy of calculations for a broad class of rectangular grids with and without ground rods, Sverak [10] reassessed the effect of simplifying assumptions used in [1] and established a different modeling approach, to develop new simplified equations for K_m and K_s, which corrected most of the deficiencies of the previous equations. The development was later summarized in Appendix A of the Guide [3]. Salient points of his analysis were:

- In the relationship between K_m and E_m, the modeling assumptions made for the perimeter conductors versus those for the inner conductors, are critical for determining the current density in both conductors representing the corner mesh.

- The root of problems associated with the application of (13) has been the fact that the original simplification process led to a highly asymmetrical model, where only one perimeter conductor was modeled exactly in depth h, whereas n - 1 conductors were in zero depth; Fig. 3.

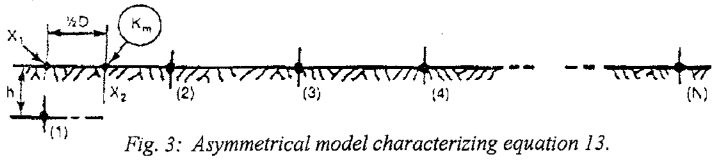

Fig. 3: Asymmetrical model characterizing equation 13.

K_m *Model:* For the purposes of the 1986 edition, in 1984 Sverak therefore developed a symmetrical model, in which the representation of first two conductors is exact and the position of remaining n-2 conductors is fairly approximated to be in depth h; Fig. 4.

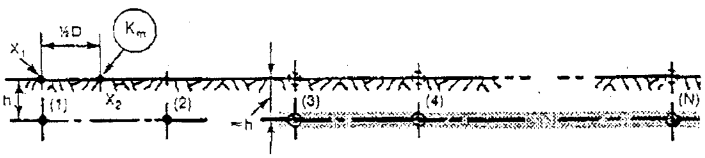

Fig. 4. Symmetrical model characterizing equation 17.

Given below as (17), the resulting equation for K_m is more accurate and versatile than the previously used (13):

$$K_m = \frac{1}{2\pi}\left\{ ln\left[\frac{D^2}{16hd} + \frac{(D+2h)^2}{8Dd} - \frac{h}{4d}\right] + \frac{K_{ii}}{K_h} ln\left[\frac{8}{\pi(2n-1)}\right]\right\} \quad (17)$$

where, in addition to symbols D, d, and h described earlier,

$$K_h = \sqrt{1+\frac{h}{h_0}}\ ; \quad h_o = 1\text{m (grid reference depth)}$$

and

$K_{ii} = 1$ for grids with ground rods along perimeter or with ground rods both in the grid corners and inside the grid area, or

$K_{ii} = \dfrac{1}{(2n)^{\frac{2}{n}}}$ for grids with a few inner ground rods, or no rods.

The approximation of a current density distribution pattern includes two weighing terms, K_{ii} and K_h. The first term adjusts the influence of n - 2 conductors upon the current density in the first two conductors forming the corner mesh, according to the presence (K_{ii} = 1), or the absence (K_{ii} = $2n$ exp -$2/n$) of peripheral grounding rods. The second term, K_h, corrects for non-zero depth of the remaining n - 2 conductors. The finite series $\lambda = (3/4)(5/6)$ ... etc., which had been previously used in (13) to represent these conductors, is replaced by an asymptotic sum.

K_s *Model:* For the calculation of step voltages, two versions of factor K_s were used:

- The older formula (14), applicability of which was limited to shallow depths between 0 and 0.25 m; and
- Sverak's formula below, applicable to depths greater than 0.25 m.

$$K_s = \frac{1}{\pi}\left[\frac{1}{2\cdot h} + \frac{1}{D+h} + \frac{1}{D}\left(1-0.5^{n-2}\right)\right] \quad (18)$$

Other Changes: Compared to (15), the value of a starting point in the definition of irregularity factor K_i was slightly adjusted, yielding exactly K_i = 1 for a singular mesh (n = 2);

$$K_i = 0.656 + 0.172\, n \quad (19)$$

An important novel detail in the application of K_m and K_s was a more precise definition of parameter n for rectangular grids, characterized by an actual number of the parallel conductors in each direction, n_A , n_B . For the calculation of mesh voltages,

$$n = \sqrt{n_A n_B} \quad \text{(rounded to the nearest integer).} \quad (20)$$

For the calculation of step voltages,

$$n = \text{Max.}\ (n_A\ ,\ n_B\ ). \quad (21)$$

Only one value of the effective buried conductor length, L, was used both in the general formuli for mesh and step voltage, that is, $L_M = L_S = L$. However, it was defined differently for grids with peripheral ground rods and for other grids. For grids with ground rods predominantly around perimeter

$$L = L_c + 1.15\, L_r \quad (22)$$

The use of older definition (16), that is, of $L = L_c + L_r$, was restricted to grids with no ground rods, or with only a few rods located in inner parts of the grid, away from the perimeter.

Finally, the following conservative applicability limits were recommended for square and rectangular grids:

$n < 25$ $\qquad$ $D > 2.5$ m
$d < 0.25\, h$ $\qquad$ 0.25 m $< h < 2.5$ m

Proposed 1996 Edition: To extend the applicability of simplified calculations to T-shaped, L-shaped and triangular grids, as well as to further improve the overall accuracy of results, it is proposed to introduce a new definition of parameter n, which will broaden the applicability of existing mesh voltage and step voltage equations

Additional minor refinements concern various empirical co-factors in definitions of the effective conductor length and an adjustment of K_i formula, reflecting the result of bench-mark tests performed by the Working Group. The specific refinements, are:

1. *Equation 17:* For calculations of the mesh voltage, retain without change the formulation of K_m itself, but broaden its applicability by a new definition of parameter n.

2. *Equation 18:* For calculations of the step voltage, retain without change this more recent formulation of K_s itself (as given for grids buried in depths ≥ 0.25 m), but broaden its applicability by the new definition of parameter n,

3. *Equation 14:* Abandon this older version of K_s, which has been already limited by the 1986 edition to grids in a shallow depth < 0.25 m.

4. Using four grid shape components developed by Thapar et al [16], the newly extended formulation of parameter n, is:

$$n = n_I \cdot n_{II} \cdot n_{III} \cdot n_{IV} \tag{23}$$

where

$n_{II} = 1$ *for square grids*
$n_{III} = 1$ *for square and rectangular grids*
$n_{IV} = 1$ *for square, rectangular and L-shaped grids*

and

$$n_I = \frac{2L_c}{L_p}; \qquad n_{II} = \sqrt{\frac{L_p}{4\sqrt{A}}};$$

$$n_{III} = \left[\frac{L_x L_y}{A}\right]^{\frac{0.7A}{L_x L_y}}; \qquad n_{IV} = \frac{D_m}{\sqrt{L_x^2 + L_y^2}}$$

A = area of grid, m²
L_C = total length of conductors forming the grid, m
L_p = peripheral length of the grid, m
L_x = maximum length of the grid in the x direction, m
L_y = maximum length of the grid in the y direction, m
D_m = maximum diagonal of the grid, m

5. *Equations 11 and 12:* Modify the definitions of effective buried conductor lengths, $L = L_m$ and $L = L_s$, using different co-factors for the mesh and step voltage formuli, as follows:

5a. For the calculation of mesh voltages by (11), the effective buried length, L_M, applicable to grids with ground rods in the corners, as well as along the perimeter and inside the grid, is:

$$L_m = L_c + \left[1.55 + 1.22\left(\frac{L_r}{\sqrt{L_x^2 + L_y^2}}\right)\right] L_R \tag{24}$$

where

L_C = total length of grid conductors, in m
L_R = total length of all ground rods, in m
L_r = length of each ground rod, in m

5b. For the calculation of step voltages by (12), the effective buried length L_s, applicable to grids with or without ground rods, is:

$$L_S = 0.75 L_c + 0.85 L_r \tag{25}$$

6. Implement a modification of the irregularity factor K_i, which has been derived by Thapar in conjunction with the extended formulation of parameter n. Compared to previous definitions, there is a slight adjustment both in the slope and in the starting point of the K_i curve:

$$K_i = 0.644 + 0.148\, n \tag{26}$$

4. Comparative Results

In order to illustrate the practical impact of the described developments within the 1961-96 period, calculations of the maximum step and mesh voltages are performed for two cases of an identical rectangular grid, one with and one without ground rods, using three sets of simplified equations:

For 1961-76 editions: (1-3) and (11-16),
For 1986 edition: (1), (5), (7), (8), (10-12) and (17-22)
For 1996 edition: (1), (5), (7), (9), (17-18) and (24-26)

Sample problem: A rectangular grid covering area of 63 m x 84 m, is either equipped with 38 peripheral ground rods, each 10 m long (Case 1, adapted from page 186, Appendix C of [3]), or has no ground rods (Case 2). The grid is buried in a 0.5 m depth and consists of square meshes spaced 7 m apart, in a 10 x 13 pattern. Soil resistivity is 400 ohm-m, the grid conductor diameter 1 cm and the grid current is 1908 A.

- *Results:* Cases 1 and 2 are shown in Table I and Table II.

- *Comparison with computer calculations:* Analysis of Case 1, done with the SGA algorithm [17], indicates E_m = 519.4 volts and E_s = 349.7 volts. Similarly, calculations performed by the algorithm TWOG [11] for Case 2, yield E_m = 803 volts and E_s = 543 volts. These comparisons are, however, only a half of the picture. It is the safety criteria, that make the whole picture interesting.

- *Safety Assessment:* Suppose, for instance, that either grid, Case 1 or Case 2, was installed in 1960 and covered with 10 cm (4 inch) layer of crushed stones, with an average resistivity 2500 ohm-m. The substation is continuously in operation since 1961.

TABLE I
CASE 1 - GRID WITH 38 GROUND RODS

Year of Std 80 Edition :		1961-76	1986	1996
Mesh Voltage	*Em*	714.07 volts	715.18 volts	590.50 volts
assuming:	*n*	13	11 .402 rounded to 11	11.344
	Lm	2039 m	2096 m	2292.2 m
	Ki	2.886	2.559	2.323
	Kii	-	1.0	1.0
	Km	0.661	0.768	0.763
Step Voltage	*Es*	491.07 volts	429.67 volts	459.14 volts
assuming:	*n*	13	13	11.344
	Ls	2039 m	2096 m	1567.3 m
	Ks	0.455	0.406	0.406

TABLE II
CASE 2 - GRID WITHOUT GROUND RODS

Year of Std 80 Edition:		1961-76	1986	1996
Mesh Voltage	*Em*	877.63 volts	1044.43 volts	943.59 volts
asumming:	*n*	13	11.402 rounded to 11	11.344
	L	1659 m	1659 m	1659 m
	Ki	2.886	2.559	2.323
	Kii	-	0.57	0.57
	Km	0.661	0.887	0.883
Step Voltage	*Es*	605.93 volts	542.85 volts	578.68 volts
assuming:	*n*	13	13	11.344
	L	1659 m	1659 m	1244.3 m
	Ks	0.456	0.406	0.406

A truly pertinent question then is: What value can be deducted as the maximum allowable time of accidental exposure, for which the grid design can be considered safe? Calculated,

TABLE III
SAFETY EVALUATION

Year of Std 80 Edition	1961-76	1986	1996
Allowable time for CASE 1, second:	1.205	0.533 [a] 0.645 [b]	1.022 [c] 1.004 [d]
Allowable time for CASE 2, second:	0.798	0.250 [a] 0.302 [b]	0.400 [c] 0.393 [d]
Surface layer resistivity, ohm-m:	2500	1550 [a] 1773 [b]	1868 [c] 1846 [d]

[a] Cs obtained from Fig. 1 ; [b] Cs by (10) ; [c] Cs by (9) ; [d] Cs by (10a)

As it can be deducted from Table III, the fact that the exposure time is a quadratic function of the worst accidental circuit voltage, that is, of the previously calculated mesh voltage, makes a lot of difference in each evaluation.

Conclusion

The development and refinements of simplified equations for the mesh and step voltage calculations, together with the evolution of safety criteria during the 1961-96 period, have been summarized. For brevity, no attempt has been made to describe the analytical underpinnings of the electrical gradient problem involved, or the research of shock currents.

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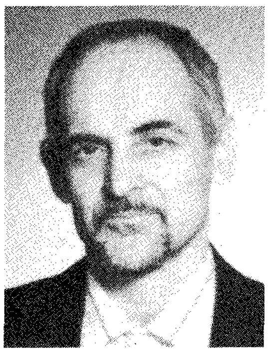

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