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# Comparison of the safety criteria used for ground grid design at 161/23.9-kV indoor-type substation

Chien-Hsing Lee [a,*], Cheng-Nan Chang [b]

[a] Department of Systems and Naval Mechatronic Engineering, National Cheng Kung University, Tainan 701, Taiwan, ROC
[b] Central Region Construction Office, Taiwan Power Company, Fengyuan, Taichung 420, Taiwan, ROC

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ABSTRACT

This paper compares seven different standards, i.e., IEEE Std. 80, 2000 edition, IEC 60479-1, BS 7354, EA-TS 41-24, CENELEC HD 637 S1, DL/T 621 and ITU-T K.33 used for ground grid design at 161/23.9-kV indoor-type substation in the system of Taiwan Power Company. The calculated results from equations proposed by Sullivan and the Current Distribution Electromagnetic Grounding and Soil structure analysis (CDEGS) software package are also included. The results show IEC 60479-1 gives the lowest limits of tolerable touch and step voltages whereas BS 7354 gives the highest when no chippings on the ground surface are considered. The designed maximum predicted touch voltage obtained from Sullivan's equation is higher than those obtained from the formulas of BS 7354, EA-TS 41-24, DL/T 621 and CDEGS, the mesh voltage is higher than those from IEEE Std. 80, 2000 edition and CDEGS.


## 1. Introduction

Generally, it is important to have an effective design of ground grid so that fault currents can be dissipated effectively to the earth [1]. A safe ground grid design at a substation not only can provide means to dissipate electric currents into earth without exceeding any operating and equipment limits, but also can assure humans in the vicinity of grounded facilities which will not expose to the danger of critical electric shock under normal or fault conditions [2]. Recently, engineers in Taiwan Power Company (TPC) have followed the guidance of IEEE Std. 80, 2000 edition to design an indoor-type substation ground grid. However, it has seen on five editions (1961 [3], 1976 [4], 1986 [5], 1996 [6] and 2000 [2]). Sverak [7] had assessed its evolution from 1961 to 1996 editions and the development of basic equations for evaluation of the step and touch voltages in ac substations. Ma et al. [8] further discussed the changes between 1986 and 2000 editions. Sullivan [9] developed an expression to calculate the maximum predicted mesh and touch voltages and compared the results with IEEE Std. 80, 1986 edition [5], EA-TS 41-24 [10] and experimental data from EPRI. He [11] provided the formula to compute ground resistances and compared the results with IEEE Std. 80, 1986 edition, EA-TS 41-24 and BS 7354 [12]. Lee and Meliopoulos [13] compared the touch and step voltages obtained with IEEE Std. 80, 1986 edition and IEC 60479-1 [14]. Thapar et al. [15] modified the formula described in IEEE Std. 80, 1986 edition to evaluate the mesh and step voltages at a substation of any practical shape. Zhao et al. [16] provided a quantitative comparison of tolerable and maximum predicted voltages obtained with IEEE Std. 80, 2000 edition, EA-TS 41-24, BS 7354, ITU-T K.33 [17] and CENELEC HD 637 S1 [18]. Mohamad et al. [19] calculated the ground resistances based on IEEE Std. 80, 2000 edition and compared with experimental results obtained from two different papers [20,21]. Additionally, other recent studies [22–24] have shown the importance of grounding systems and provided the guidelines on the safety design of grounding systems using mathematical modeling or by experimental methods. In this paper, the tolerable voltage limits and the maximum predicted voltages obtained from seven standards, namely IEEE Std. 80, 2000 edition, IEC 60479-1 [25], BS 7354, EA-TS 41-24, CENELEC HD 637 S1, DL/T 621 [26] and ITU-T K.33 have been examined and compared. The calculated results from equations proposed by Sullivan and the CDEGS software package are also included.

## 2. Electric shock model

Electric shock may occur when an individual touches a grounded structure during a fault (touch voltage), walks in the vicinity of a grounding system during a fault (step voltage), or touches two separately grounded structures during a fault (metal to metal touch voltage), etc. The electric shock model as shown in Fig. 1a illustrates a human standing at an indoor-type substation and may be subjected to either touch or step voltages. The electric shock model is the circuit which determines the flow of electric current in the human body. The human body may come into contact with a ground or soil at three points (hand and two feet). The grounding system

* Corresponding author.
E-mail address: chienlee@mail.ncku.edu.tw (C.-H. Lee).

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**Nomenclature**

$V_{TH}$ Thevenin equivalent voltage (in V)
$R_{TH}$ Thevenin equivalent resistance (in Ω)
$R_{body}$ body resistance (in Ω)
$R_{shoe}$ shoe resistance (in Ω)
$I_{body}$ tolerable body current (in A)
$R_1$ resistance of ground grid conductors (in Ω)
$R_2$ resistance of ground rods (in Ω)
$R_m$ mutual resistance between ground grid conductors and ground rod (in Ω)
$R_g$ ground resistance of the substation (in Ω)
$\rho$ uniform soil resistivity (Ωm)
$L_C$ total length of ground grid conductors (in m)
$d$ diameter of each ground grid conductor (in m)
$h$ depth of ground grid conductors (in m)
$A$ total area of the ground grid (in $m^2$)
$n_r$ quantity of ground rods
$L_r$ length of each ground rod (in m)
$a$ radius of each ground rod (in m)
$L$ length of the ground grid (in m)
$W$ width of the ground grid (in m)
$r$ radius of circular plate of the ground grid (in m)
$L_T$ total length of ground grid conductors and ground rods (in m)
$V_{touch50}$ tolerable touch voltage for 50-kg person (in V)
$V_{touch70}$ tolerable touch voltage for 70-kg person (in V)
$V_{step50}$ tolerable step voltage for 50-kg person (in V)
$V_{step70}$ tolerable step voltage for 70-kg person (in V)
$V_{touch}$ tolerable touch voltage (in V)
$V_{step}$ tolerable step voltage (in V)
$R_{body}^{touch}$ body resistance for the path specified by the touch voltage (in Ω)
$R_{body}^{step}$ body resistance for the path specified by the step voltage (in Ω)
$h_s$ surface layer thickness (in m)
$k$ reflection factor
$E_{mesh}$ maximum predicted mesh voltage (in V)
$E_{step}$ maximum predicted step voltage (in V)
$E_{touch}$ maximum predicted touch voltage (in V)
$I_G$ maximum grid current that flows between a ground grid and surrounding earth (in A)
$D_f$ current decrement factor
$S_f$ current division factor
$I_f$ maximum ground fault current (in A)
$L_M$ effective buried length of the conductors for mesh voltage (in m)
$L_S$ effective buried length of the conductors for step voltage (in m)
$L_R$ total length of ground rods (in m)
$L_P$ peripheral length of the ground grid (in m)
$D$ spacing between ground grid conductors (in m)
$D_m$ maximum distance between any two points on the ground grid (in m)

**Table 1**
Standard specified values for the Thevenin equivalent circuit.

| Standards | $R_{TH}$ (Ω) | $R_{body}$ (Ω) | $R_{shoe}$ (Ω) | $R_s$ (Ω) | $I_{body}(t_s)$ (A) |
|---|---|---|---|---|---|
| IEEE Std. 80, 2000 edition | $1.5C_s\rho_s$ for touch voltage<br>$6.0C_s\rho_s$ for step voltage | 1000 | 0 | No guidance | $0.116/\sqrt{t_s}$ for 50-kg person<br>$0.157/\sqrt{t_s}$ for 70-kg person |
| BS 7354 | $1.5\rho_e$ for touch voltage<br>$6.0\rho_e$ for step voltage | 1000 | 4000 | No guidance | Curve $C_2$ (Fig. 4) |
| EA-TS 41-24 | 0 | 1000 | 4000 | No guidance | Curve $C_1$ (Fig. 4) |
| CENELEC HD 637 S1 | $1.5\rho_s$ for touch voltage | Voltage-dependent and path-dependent (Figs. 2 and 3) | 1000 | No guidance | Curve $C_2$ (Fig. 4) |
| DL/T 621 | $1.5\rho_s$ for touch voltage<br>$6.0\rho_s$ for step voltage | 1500 | No guidance | No guidance | $0.116/\sqrt{t_s}$ |
| ITU-T K.33 | 0 | 750 For typical case<br>562 For severe case | 3000 For leather sole<br>2000 For elastomer sole | 180 For typical case<br>0 For severe case | Curve $C_2$ (Fig. 4) for typical case<br>Curve $C_1$ (Fig. 4) for severe case |

*Note*: $C_s$ = surface layer derating factor, $\rho_s$ = surface layer resistivity, $\rho_e$ = effective resistivity, $t_s$ = duration of shock current, $R_s$ = source resistance.

and soil are represented with a Thevenin equivalent at the points of contact. When a fault occurs, voltages will appear between any pair of the points of contact. The Thevenin equivalent in this case is a three terminal circuit and can be computed with proper analysis methods [13]. Thus, the Thevenin equivalent circuits of touch and step voltages can be simplified to those of Fig. 1b and c. Values in the circuits specified by standards are summarized in Table 1. Since IEC 60479-1 has been used by various standards to establish their safety limit curves, it is excluded from this part.

## 3. Calculation of ground resistances and assessment of ground grid safety

### 3.1. Designed ground resistances

#### 3.1.1. IEEE Std. 80, 2000 edition

The Schwarz's equation is a simple formula described in IEEE Std. 80, 2000 edition for calculation of the ground resistances at a substation. Equations of the ground resistances for the horizontal