

# Design of a Substation Grounding System for Fast Front Overvoltage

L. Kevin Yuan Jet, N., N. Mohamad Nor

**Abstract:** Grounding studies allow an optimized design of grounding system to provide protection for electrical components and personnel at substation. The design of grounding system needs to comply with IEEE Standard 80:2013. Field work is conducted with Fall-of-Potential method and Wenner's method to perform measurement soil test. Data from measurement test is used to develop two-layer soil model by using Sunde's graphical method. Calculation for tolerable step voltage and touch voltage are under 50kg body weight condition. Based on the findings, calculated values for tolerable step voltage and touch voltage are higher than calculated values for mesh voltage and touch voltage. The percentage of error is 7% when computed values and calculated values for tolerable voltages are compared. Higher tolerable voltages minimise the risk of getting electrical shock to any individual presents at substation during fault or lightning strike occurs. However, there is limitation in this paper related to software licensing where full simulation with grounding software required full access.

**Index Terms:** Grounding system, two-layer soil model, step voltage, touch voltage

## Nomenclature

$\rho$	soil resistivity in $\Omega$ -m
$A$	grid area in m
$x$	distance between electrode and potential probe in m
$R$	soil resistance in $\Omega$
$a$	spacing between two probes in m
$K$	reflection factor
$\rho_1$	top layer of soil resistivity in $\Omega$ -m
$\rho_2$	bottom layer of soil resistivity in $\Omega$ -m
$\rho_a$	apparent resistivity of soil in $\Omega$ -m
$h$	depth of top layer soil in m
$d$	diameter of ground conductor in m
$I_f$	fault current in kA
$E_{step,50}$	tolerable step voltage for 50kg body weight in V
$E_{touch,50}$	tolerable touch voltage for 50kg body weight in V
$I_B$	allowable body current in A
$I_s$	duration of shock in s
$R_B$	resistance of a human body in $\Omega$
$\rho_s$	surface material resistivity in $\Omega$ -m
$C_s$	surface layer derating factor
$h_s$	thickness of surface material in m

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L. Kevin Yuan Jet, Faculty of Engineering, Multimedia University, Cyberjaya, Malaysia.

N. Eng Eng, Faculty of Engineering, Multimedia University, Cyberjaya, Malaysia.

N. Mohamad Nor, Faculty of Engineering, Multimedia University, Cyberjaya, Malaysia.

$D$	spacing between parallel conductors in m
$n$	geometric factor of grid
$L_T$	total length of conductor in horizontal in m
$L_x$	total length of grid at x-axis in m
$L_y$	total length of grid at y-axis in m
$L_X$	max. length of grid conductor at x-axis in m
$L_c$	total length of grid conductor in m
$L_R$	total length of ground rods in m
$n_{side}$	number of grid wire pattern in one side
$L_r$	length of ground rod at grid mesh in m
$R_g$	grid resistance in $\Omega$
$I_G$	max. grid current in m
$S_f$	fault current division factor
$I_g$	root-mean-square symmetrical grid current in A
$D_f$	decrement factor for entire duration of fault in s
GPR	ground potential rise in kV
$E_m$	mesh voltage in V
$E_s$	step voltage in V
$K_i$	irregularity factor or correction factor for grid geometry for the simplified method
$K_{ii}$	corrective weighting factor that adjusts for the effects of inner conductors on the corner mesh for simplified method

## I. INTRODUCTION

Since high magnitude of voltage always involved in power transmission, all substations need to have grounding system for protection purpose. Grounding system is built beneath the soil where substation is located. The grid itself consists of a number of ground rods and conductors with the arrangement either in square, rectangular or irregular form depending on the layout of the substation. When lightning strikes or fault from any electrical components happen at the substation, the grounding system acts as protection system. It provides a pathway for these currents flow directly into earth instead to other electrical components or personnel at that time.

Reference mentions that Wenner's method or known as four-point method is required to perform soil measurement test [1]. Data from the tests are interpreted for soil resistivity based on type of soil model [2]. Uniform soil model and two-layer soil model are commonly used model in grid design. Reference states that two-layer soil model is a good approximation for analysis purpose [3]. Soil modelling is done by either inspection of resistivity measurement or computer algorithm. Sunde's graphical method is the first method in soil modelling and it still be applicable for two-layer soil model without



computer algorithm as mentioned in reference [4]. Simulation of grid design with computer software such as CDEGS (Current Distribution Electromagnetic Fields, Grounding and Soil Structure Analysis), ETAP (Electrical Transient Analysis Power) and Matlab are used to verify measured data in some papers [5][6][7]. Grounding system is relatively an interesting topic especially when comes to design part. This is because many considerations that need to be taken based on par IEEE Std 80;2013 requirement [8]. In this paper, there are three main objectives; to design grounding system for a medium-sized substation, to evaluate the safety criteria for step and touch voltages via grid design as well as to compare the computed values and calculated values for tolerable voltages.

II. METHODOLOGY

A. Grid design flow chart

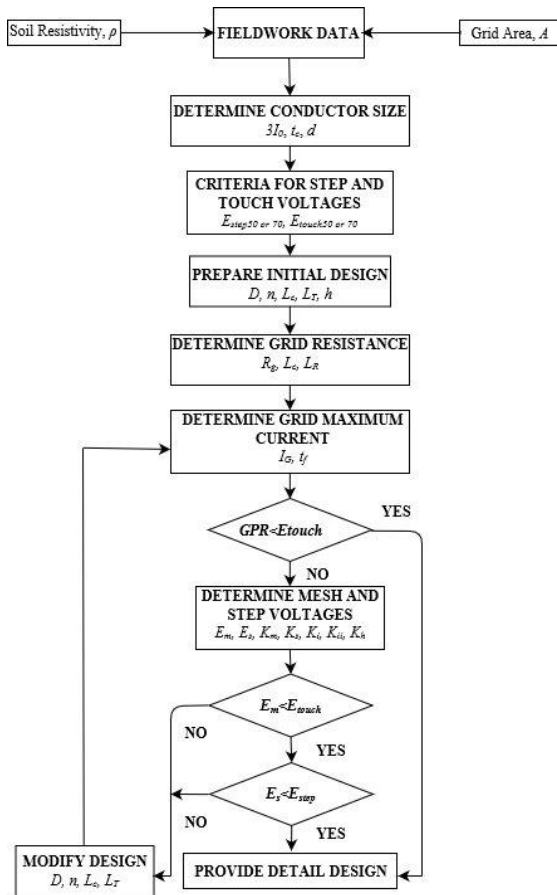


Fig. 1. The flow chart of grid design [8].

B. Safety Criteria of Step and Touch Voltages

Factors that could contribute to electric shock accidents are the presence of fault current with large magnitude, location of grounding system, soil resistivity, effect of current density on earth surface, insufficient contact resistance to limit current flow through the body of any individual who present during fault and improper duration of fault to recover. All the factors are linked with step voltage and touch voltage which determined the safety criteria of a grounding system. The safety criteria of the grounding system are achieved if tolerable step voltage is higher than the step

voltage and tolerable touch voltage is higher than the mesh voltage. To strengthen more in safety criteria of the grounding system, it was recommended that a thin layer of surface materials required. With the presence of surface material, these materials were usually high resistivity spread on the top layer of soil above the ground grid to increase the contact resistance between soil and feet of persons in substation.

C. Fieldwork Data

1) Four-point method

Four-point method was used to measure the soil resistivity of the particular area. Obtaining the soil resistivity was vital with this method as it gave accurate value. It was usually done with the set-up arrangement of four probes where there was specific spacing between them as shown in Fig. 2. The term of *a* represented the spacing between two probes whereas the term of *b* represented the burial depth of probe. Then all of the probes and electrode were connected to the earth tester, Megger. The set-up arrangement was conducted on 24 January 2018 at the vicinity area of incubator building. During the measurement day took place, the condition of soil was wet and mostly contained high moisture.

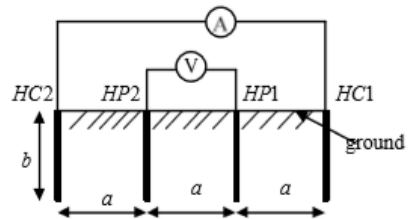


Fig. 2. The set-up arrangement for four-point method.

2) Sunde's graphical method

Sunde's graphical method is an alternate way to develop approximate two-layer soil model besides computer modelling. This method was also used to obtain the depth of layer of soil, *h*. As shown in Fig. 3, the method can determine the parameters  $\rho_1$  and  $\rho_2$  together with the plotted graph.

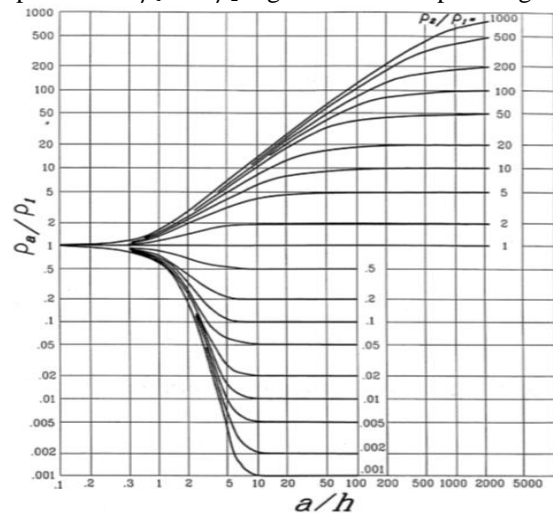


Fig. 3. The curves of Sunde's graphical method.

The following were the procedures of using Sunde's graphical method;

- a) A graph of apparent resistivity,  $\rho_a$  versus spacing between the electrodes was plotted.
- b)  $\rho_1$  and  $\rho_2$  were estimated from the plotted graph.  $\rho_1$  was obtained in which  $\rho_a$  corresponding to a smaller spacing whereas  $\rho_2$  was obtained from a larger spacing. In case the field data were not enough, the plotted graph was extended allowing these values can be obtained.
- c)  $\rho_2/\rho_1$  was determined and a curve on the Sunde graph in Fig. 3 was selected. The selected curve was either matched closely or interpolated where a new curve would be drawn on the graph.
- d) Within the region of the  $\rho_2/\rho_1$  curve of Sunde graph, the value on the y-axis was selected.
- e) One the x-axis, the corresponding value of  $a/h$  was obtained.
- f) Then the selected value of  $\rho_a/\rho_1$  was multiplied with  $\rho_1$  to obtain  $\rho_a$ .
- g) Next, in the plotted graph, the corresponding probe spacing was obtained.
- h) Lastly, the depth of the top layer of soil,  $h$  was calculated by using the appropriate probe separation,  $a$ .

### 3) Two-layer soil model

A two-layer soil model was presented by top layer of soil with definite depth whereas the bottom layer of soil with indefinite depth. In this work, two-layer soil model was selected as the soil model used for the grid design. One of the reasons was the measured soil resistivity varied significantly and it was also stated that the development of uniform soil model required almost constant or only slightly changed of soil resistivity according to IEEE Std 80;2013.

#### D. Determine Conductor Size

Conductors were parts of grounding system that played important role in ensuring the safety of electrical components and any individual at the substation. As important as its role, conductors with proper selection would able to maintain the integrity of a grounding system for long term.

In this work, copper with commercial hard drawn was selected as the grounding conductors for the grid design. Since there were no actual impedances and resistances used, the fault current,  $I$  or  $3I_o$  was assumed for 20kA. At the same time, the diameter of grounding conductor,  $d$  used during the fieldwork was 20mm.

#### E. Mathematical Calculation

##### 1) Two-layer soil model

The change of resistivity between these two layers was described with reflection factor,  $K$ . The reflection factor,  $K$  can be defined as (1) in the following;

$$K = \frac{\rho_2 - \rho_1}{\rho_1 + \rho_2} \quad (1)$$

##### 2) Tolerable step and touch voltages

The criteria amount of shock from the faults would important to be limit as much as possible before the safety of an individual could be endangered. The limit of these shocks which lead to maximum dangerous voltage was defined as following below;

$$E_{step,50} = (1000 + 6 \times C_s \times \rho_s) \times \frac{0.116}{\sqrt{t_s}} \quad (2)$$

$$E_{touch,50} = (1000 + 1.5 \times C_s \times \rho_s) \times \frac{0.116}{\sqrt{t_s}} \quad (3)$$

##### 3) Total effective length of ground conductors

Since grounding rods were used in this grid design, the total effective length of ground conductors,  $L_T$  was defined as (4);

$$L_T = L_c + L_R \quad (4)$$

(4) was then furthered expand into (5);

$$L_T = (2 \times n_{side} \times L_x) + (n_R \times L_r) \quad (5)$$

##### 4) Grid resistance

Substation with a proper and good grounding system would provide a low grid resistance,  $R_g$  to minimize the ground potential rise voltage. The grounding system with such features should have grid resistance of  $10\Omega$  or lower. To calculate the grounding resistance, the formula was defined as (6) in the following;

$$R_g = \rho \left[ \frac{1}{L_T} + \frac{1}{\sqrt{20A}} \left( 1 + \frac{1}{1 + \frac{h\sqrt{20}}{A}} \right) \right] \quad (6)$$

##### 5) Grid maximum current

Fault current division factor is the ratio of grid current flowed between the grounding grids to symmetrical fault current that represented by a factor was defined as (7);

$$S_f = \frac{i_g}{i_f} \quad (7)$$

The maximum grid current was defined as (8) as shown in the following;



$$I_G = D_f \times I_g \quad (8)$$

6) Ground Potential Rise

The GPR was the product of grid current and grid resistance that defined as (9);

$$GPR = I_G \times R_g \quad (9)$$

7) Mesh and step voltages

The mesh voltage was defined as (10) in the following;

$$E_m = \frac{\rho \times K_m \times K_i \times I_G}{L_m} \quad (10)$$

The step voltage was defined as (11) in the following;

$$E_s = \frac{\rho \times K_s \times K_i \times I_G}{L_s} \quad (11)$$

8) Geometrical factors of step and mesh voltages

For geometrical factor,  $K_m$ , the calculation for each  $K_{ii}$  and  $K_h$  are shown in the following;

$$K_{ii} = 1 \quad (12)$$

$$K_h = \sqrt{1 + \frac{h}{h_0}} \quad \text{where } h_0 = 1 \quad (13)$$

$$K_m = \frac{1}{2\pi} \times \left[ \ln \left[ \frac{D^2}{16 \times h \times d} + \frac{(D+2 \times h)^2}{8 \times D \times d} - \frac{h}{4 \times d} \right] + \frac{K_{ii}}{K_h} \times \ln \left[ \frac{8}{\pi \times (2 \times n - 1)} \right] \right] \quad (14)$$

The geometrical factor,  $K_s$  was defined in (15) as followed;

$$K_s = \frac{1}{\pi} \left[ \frac{1}{2 \times h} + \frac{1}{D+h} + \frac{1}{D} (1 - 0.5^{n-2}) \right] \quad (15)$$

9) Irregularity factor

The irregularity factor,  $K_i$  was defined in (16) as followed;

$$K_i = 0.644 + 0.148 \times n \quad (16)$$

10) Geometrical factor of grid

$$n = n_a \times n_b \times n_c \times n_d \quad (17)$$

where

$$n_a = \frac{2 \times L_c}{L_p}$$

$n_b = 1$  for square grids

$n_c = 1$  for square and rectangular grids

$n_d = 1$  for square, rectangular and L-shaped grids

III. RESULTS AND DISCUSSION

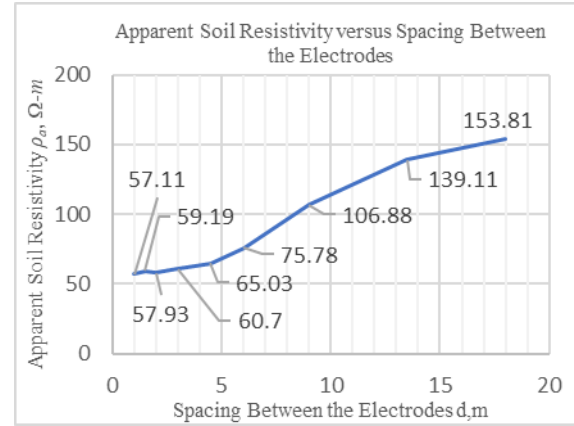


Fig. 4. The graph of apparent soil resistivity versus spacing between electrodes.

In Fig. 4, the soil data obtained from fieldwork is displayed in the form of graph where the y-axis represents the soil resistivity,  $\Omega\text{-m}$  and x-axis represents the probe spacing,  $a$ . It is an upward trend as soil resistivity increases when the probe spacing increases showing that the top layer of soil resistivity is lower than the bottom layer of soil resistivity.

From this work, the surface material of washed granite is used as thin layer on the designed grid. It is to minimise the danger faced by the personnel or power equipment within the vicinity when there is fault. The reflection factor,  $K$  is -0.9763 and it indicates that the current density is uniformly spread across the grounding grid due to tendency of grid current flows downward into lower resistivity of soil layer instead of higher resistivity one.

I. THE COMPARISON BETWEEN TOLERABLE VOLTAGES WITH STEP AND MESH VOLTAGES.

Parameter	Value
Tolerable step voltage ( $E_{step,50}$ )	3298.52 V
Step voltage ( $E_s$ )	695.29V
Tolerable touch voltage ( $E_{touch,50}$ )	947.67V
Mesh voltage ( $E_m$ )	814.11V

In Table I, the mesh voltage is 814.11V which is lower than 947.67V for the tolerable touch voltage,  $E_{touch,50}$ . The step voltage is 695.29V which is also lower than 3298.52V for the tolerable step voltage,  $E_{step,50}$ . High step voltage means the difference in voltage between two points from grounding point is large and a person could be at risk of injury easily. From the result, the tolerable step voltage is able to provide protection against risk of injury from the magnitude of step voltage. Next, mesh voltage is the difference in voltage between the metallic object connected to the grid and the soil potential within the grid. From the



result, the grid is considered as safe.

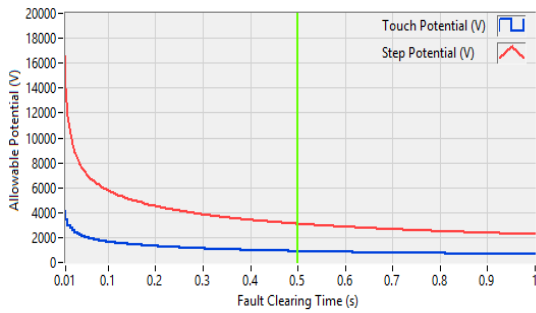


Fig. 5. The simulation result for tolerable step and touch voltages.

Fig. 5 shows the simulation of tolerable voltages obtained in SafeGrid Earthing software. The computed values are then compared with the calculated values to verify data for grid design. Table II shows the comparison between calculated values and computed values as well the percentage of error. For tolerable step voltage, calculated value is 3298.52V and its computed value is 3080.10V with percentage of error by 7.09%. For tolerable touch voltage, calculated value is 947.67V and its computed value is 885.90V with percentage of error by 6.97%. Table III shows the overview for all parameters and materials used in this grid design.

## II. THE COMPARISON BETWEEN CALCULATED AND COMPUTE VALUES.

Parameter	Calculated Voltage, V	Computed Voltage, V	Percentage of Error, %
Tolerable Step Voltage	3298.52	3080.10	7.09
Tolerable Touch Voltage	947.67	885.90	6.97

## III. THE OVERALL SUMMARY OF GRID DESIGN.

No.	Parameter Description	Value	Unit
1	Surface material	Washed granite	
2	Surface material resistivity ( $\rho_s$ )	5000	$\Omega$ -m
3	Surface layer thickness ( $h_s$ )	0.08	m
4	Soil resistivity ( $\rho$ )	60	$\Omega$ -m
5	Symmetrical fault current ( $3I_a$ )	$20 \times 10^3$	A
6	Type of grounding conductor	Copper	
7	Diameter of grounding conductor ( $d$ )	0.020	m
8	Duration of fault current ( $t_c$ )	0.50	s
9	Reflection factor, $K$	-0.9763	
10	Surface layer derating factor ( $C_s$ )	0.6369	
11	Tolerable step voltage ( $E_{step,50}$ )	3298.52	V
12	Tolerable touch voltage ( $E_{touch,50}$ )	947.67	V
13	Spacing between equally conductor ( $D$ )	4	m
14	Total effective length of ground conductor ( $L_T$ )	940	m
15	Geometry factor composed of $n_a, n_b, n_c, n_d$ ( $n$ )	11	
16	Grid resistance ( $R_g$ )	0.70	$\Omega$
17	Fault current division factor ( $S_f$ )	0.60	
18	Symmetrical grid current ( $I_g$ )	$12 \times 10^3$	A
19	Decrement factor for the entire duration of fault ( $D_f$ )	0.60	
20	Maximum grid current ( $I_G$ )	$12 \times 10^3$	A
21	Ground potential rise (GPR)	$8.4 \times 10^3$	V
22	Geometrical factor for mesh voltage ( $K_m$ )	0.4852	
23	Irregularity factor for grid geometry ( $K_i$ )	2.272	
24	Effective buried length for mesh voltage ( $L_m$ )	974.94	m
25	Mesh voltage ( $E_m$ )	814.11	V
26	Geometrical factor for step voltage ( $K_s$ )	0.3022	
22	Effective buried length for step voltage ( $L_s$ )	711	
23	Step voltage ( $E_s$ )	695.29	V

## IV. ACKNOWLEDGMENT

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## AUTHORS PROFILE



2018 and currently working as Mill Engineer in IJM Plantation.

**Kevin Lee Yuan Jet** is previously a Bachelor of Degree in Electrical holder in Multimedia University, Cyberjaya Campus. During his final year project, he engaged with Dr Ngu and Dr Normiza in consultation and conducting experimental tests related to the properties of soil at Multimedia University. He completed his Degree studies in



In Multimedia University, she is an Assistant Programme Coordinator for Electrical Program, member of Industrial Linkage Committee and Internal Maintenance Audit for Faculty.

**Ng Eng Eng** is currently a Senior Lecturer at Faculty of Engineering, Multimedia University, Cyberjaya Campus. She obtained her Doctor of Philosophy (PhD) in Electrical Engineering (Power System) in 2012. During these years, Dr. Ngu has published many journals and proceedings related with transmission lines and fault location studies.



She completed her Doctor of Philosophy (PhD) in Electrical Engineering, University of Wales, College of Cardiff, United Kingdom in 2002. Dr. Normiza has published many journals and proceedings for the past 20 years. She also involved with consultancy works and delivered seminars in her area of expertise such as high voltage engineering, grounding system and lightning protection system.

**Normiza Binti Mohamad Nor** is currently an Associate Professor of Electrical Engineering at Faculty of Engineering, Multimedia University, Cyberjaya Campus.

