Three Dimensional Grounding Grid Design

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Abstract

This study presents an advanced methodology and a computer model for analysis of grounding systems conforming to standards IEEE Std 80-2000, IEEE Std 81-1983 and IEEE Std 837-2002. The methodology and computer program is validated with actual system measurements. The accuracy of computer algorithm is dependent on how well the soil model and physical layout reflect actual field conditions. The tolerable voltage limits and the maximum predicted voltage values are calculated using empirical formula in given standard. The step, touch and mesh voltages and hot zones are calculated according to the recommendations in given standard and the differences between them are investigated and clarified. The simulations are carried out with the aim to verify the possibility of introducing some practical design criteria helpful for engineering applications. Substation grounding grid design and analysis module is specially designed to help engineers optimize the design of new grids and reinforce existing grids, of any shape, by virtue of easy to use, built-in danger point evaluation facilities.

1. Introduction

Substation grounding system design studies are increasing as available fault currents increase on today's electrical power grid. The economics is an important factor as well as human safety. Engineers want to design systems that protect human and equipment while providing an optimized economic solution without over designing grounding systems. That is why the use of more accurate computer algorithms in designing the grounding system is necessary for some of the cases stated as below:

- Parameters exceed the limitations of the equations,
- Due to significant variations in soil resistivity, multilayer or two-layer soil model is preferred,
- By using the approximate methods, uneven grid conductor or ground rod spacings are unable to be analyzed,
- To determine local danger points with a flexible method,
- For complex grids in which conductors and buried metallic structures are not connected to the grounding system.

2. Purpose

The main objectives of this study are to:

- Provide a suitable reference containing the necessary guidelines so that a grounding system designer can focus quickly on the most efficient design,
- Retain the step and touch voltages within the safety tolerance limits and to keep ground resistance small,
- Design a substation grounding system based on IEEE Std 80-2000 [1], IEEE Std 81-1983 [2], IEEE Std 837-2002 [3], standards in general,
- Assure that a person in the vicinity of grounded facilities is not exposed to the danger of critical electric shock.
- Determine the required grid conductor specifications,
- Compute the substation grounding resistance and study the effect of resistance formula, substation area, number of ground rods, soil homogeneity, grid conductor size and grid burial depth on the calculated value of substation resistance,
- Compute the ground potential rise, GPR,
- Compute the tolerable and maximum touch and step voltages,
- Display the surface potential profile as a percentage of GPR along any redetermined direction,
- Introduce a final report contains all design details.

3. Grounding Grid Design Software

Computer algorithms for modeling ground systems are based on:

- Individual component modeling like grid conductors and ground rods,
- Description of individual components with a set of equations,
- Ground-fault current calculation flowing into the earth,
- Surface potential calculation at any desired surface point.

Firstly, definition of a project and study should be done in performing a grounding study.

Secondly, the soil model that will be used for the subsequent analyses should be determined. In this step, the safety assessment calculations have also been performed including the maximum permissible step and touch voltages for particular surface and exposure conditions as defined in IEEE Std 80-2000 [1].

The third step is the electrode sizing determination (conductors and rods) which is taking into account the worst case fault parameters in the substation.

The next step is entering the geometrical configuration of the station layout such as coordinates, burial depth and physical dimensions.

Finally, it has to be assured whether the design for the station meets the necessary safety criteria or not. Potential profile plots should be generated to ascertain that touch and step potentials are not exceeded. The grid design may need to be modified and repeated if any of the safety criteria is not met. The procedure starts from the third step until acceptable results are obtained.

The software used in this study is composed of three main modules.

3.1. Soil Analysis Module

This module includes below parameters necessary for grounding design of site which is being simulated (Fig. 1).

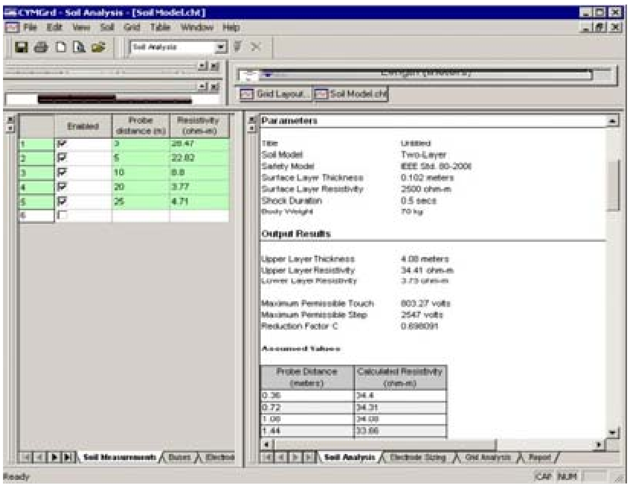

Fig. 1. Soil analysis module

1) Soil model (single or multi layered),
2) Upper layer thickness in meter,
3) Upper layer resistivity in ohm-meter,
4) Lower layer thickness in meter,
5) Lower layer resistivity in ohm-meter,
6) Fault duration in seconds,
7) Body weight in kilogram.

3.2. Grounding Grid Analysis Module

Electrical characteristic of site and properties of grid conductor used exist in this module (Fig. 2). Data below are entered from this module.

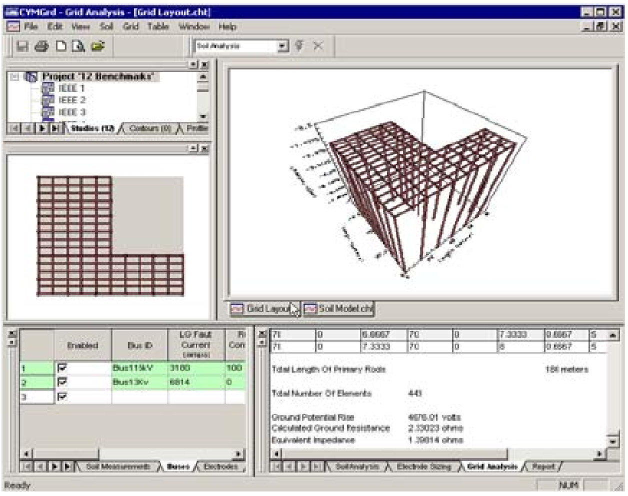

Fig. 2. Grounding grid analysis module

1) Network voltage in volt,
2) Earth fault current in ampere,
3) Length in meter and quantity of grounding rod and conductor,
4) Ground potential rise (GPR) in volt,
5) Calculated ground resistance in ohm,
6) Equivalent impedance in ohm.

3.3. Three Dimensional Potential Distribution Module

In this module, three dimensional potential distribution simulated by finite element method can be observed (Fig. 3).

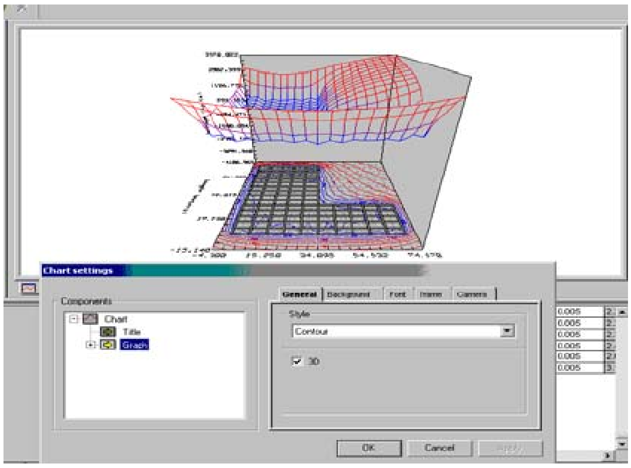

Fig. 3. Three-dimensional potential distribution module

4. Grounding Grid Design Methodology

Many graphical and analytical approaches have been suggested over the years in order to arrive at practical soil models [4-8, 10]. Since it is more common to find stratified soils which are composed of layers having different resistivities, techniques to interpret a set of soil resistivity measurements as a multi-layer soil model are currently used.

For many years in substation grounding practice, the two-layer model has been followed as a practical approach which has an upper layer of a definite depth and a lower layer of an infinite depth with a different resistivity. The software [9] supports Wenner four-pin soil measurement technique in which the distance (a) between each pair of probes is equal as given in Fig. 4 below:

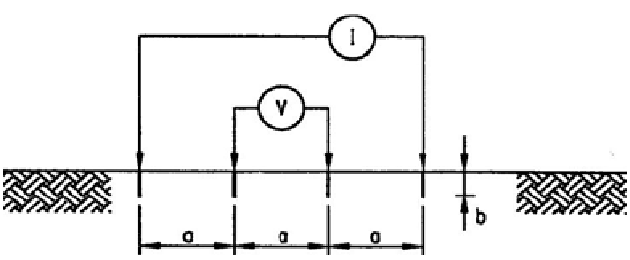

Fig. 4. Wenner four-pin method.

The voltage (V) is measured by the voltmeter when a current (I) is injected and measured by the ammeter. The measured or apparent resistivity (ρ) is given by:

$$\rho = \frac{4\pi a(V/I)}{\left[1 + \frac{2a}{\sqrt{a^2+4b^2}} - \frac{a}{\sqrt{a^2+b^2}}\right]} \quad (1)$$

or $\rho = 2\pi a\ (V/I)$ if $a >> b$ where b is the length of the probe.

The maximum permissible touch and step voltages under specific surface and exposure conditions are estimated. The safety assessment calculations comply with standard 'IEEE Guide for Safety in AC Substation Grounding', 2000 edition [1]. The purpose of the calculation is to arrive at a derating factor that will permit to take advantage of the high resistivity surface layer, thus permitting a higher touch voltage to be tolerated. The derating factor C_s can either be calculated as:

$$C_s = 1 - \frac{0.09\cdot(1-\rho/\rho_s)}{2h_s + 0.09} \quad (2)$$

For a 50 kg body weight:

$$E_{touch50} = (1000 + 1.5C_s\cdot\rho_s)\cdot 0.116/\sqrt{t_s} \quad (3)$$

$$E_{step50} = (1000 + 6.0C_s\cdot\rho_s)\cdot 0.116/\sqrt{t_s} \quad (4)$$

For a 70 kg body weight:

$$E_{touch70} = (1000 + 1.5C_s\cdot\rho_s)\cdot 0.157/\sqrt{t_s} \quad (5)$$

$$E_{step70} = (1000 + 6.0C_s\cdot\rho_s)\cdot 0.157/\sqrt{t_s} \quad (6)$$

where:

- t_s is shock duration in seconds.
- ρ_s is the resistivity of the surface material in ohm-meter.
- C_s is the derating factor when high resistivity surface material is present. The reduction factor C_s is a function of the reflection factor K and the thickness of the upper layer h.
- h_s is the thickness of the high resistivity surface layer material in meter.
- ρ_s is the resistivity of the surface material in ohm-meter.
- ρ is the resistivity of the earth below the high resistivity surface material in ohm-meter.

5. Simulations

The cases exposed in the Annex B and Annex E of the IEEE Std 80-2000 are used as a reference point [1], for which there are following comparative tables and the corresponding graphs in order to validate the results in this document. Design data is given in Table 1.

5.1. Square Grid with Ground Rods

Square grid 70 m × 70 m, 100 meshes with ground rods placed along the perimeter is seen below in Fig. 5. IEEE Std 80-2000 method also gives results for maximum allowable touch and step voltages, as well as the maximum real voltages in the system, for comparison of the calculations done by software. The obtained results using both techniques are shown in Table 2.

Table 1. Data used in grid design

Properties	Input Data
Body weight	70 kg
Crushed rock surface layer resistivity	2500 Ω.m
Crushed rock surface layer thickness	0.102 m
Clearing time	0.50 sec
Uniform soil resistivity	400 Ω.m
Max I_G fault current, X/R	6814 A, 16.2
I_G fault current	3180 A
Split factor S_f	0.6
Conductor material	Copper, hard-drawn
Ambient temperature	40 °C
Grid conductor diameter	0.01 m
Burial depth	0.5 m

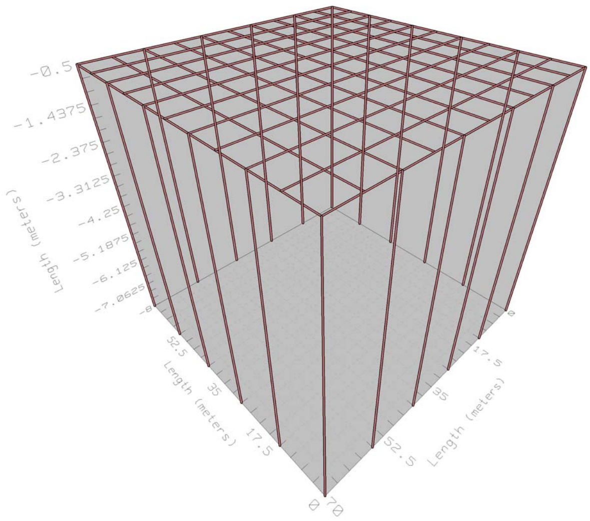

Fig. 5. 3-D grid layout for square grid with ground rods

Table 2. Comparative results for square grid with ground rods

	IEEE Std 80-2000	Software
Max. Allowable Touch Voltage (V)	838.20	840.55
Max. Allowable Step Voltage (V)	2686.00	2696.10
Reduction Factor, C_s	0.740	0.740
Rg (Ω)	2.780	2.675
GPR (V)	5304.00	5105.61

The maximum limit for touch voltages is violated on the corners of the grounding system which can be easily observed as Fig. 6.

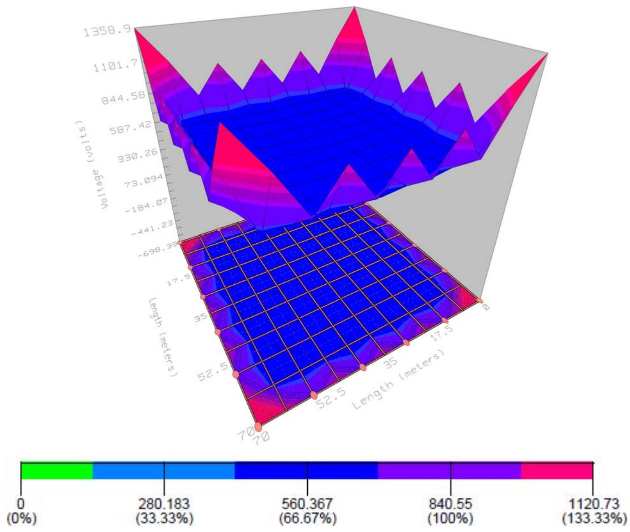

Fig. 6. 3-D grid layout for square grid with ground rods

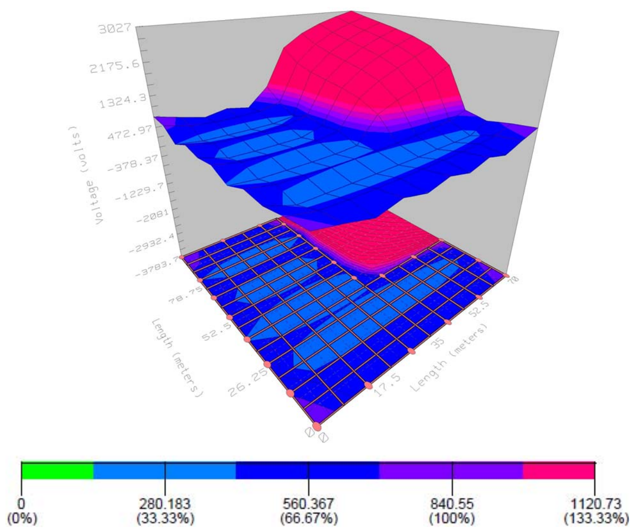

Fig. 8. 3-D grid layout for L-shaped grid with ground rods

5.2. L-Shaped Grid with Ground Rods

L-Shaped grid 70 m × 105 m, 100 meshes with ground rods placed along the perimeter is seen below in Fig. 7. For comparison of the calculations done by both techniques, the obtained results are shown in Table 3.

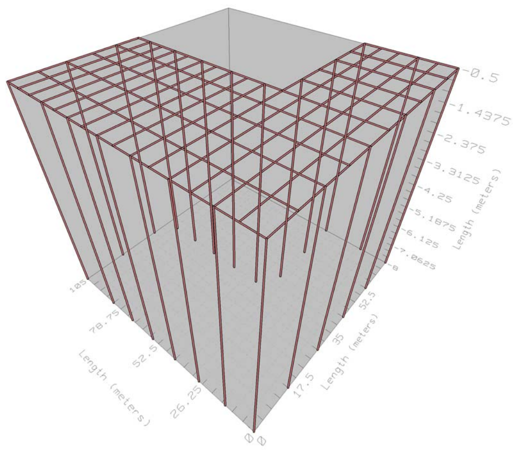

Fig. 7. 3-D grid layout for L-shaped grid with ground rods

Table 3. Comparative results for L-shaped grid with ground rods

	IEEE Std 80-2000	Software
Max. Allowable Touch Voltage (V)	838.20	840.55
Max. Allowable Step Voltage (V)	2686.00	2696.10
Reduction Factor, Cs	0.740	0.740
Rg (Ω)	2.740	2.330
GPR (V)	5227.92	4562.49

The maximum limit for touch voltages is violated on the outside of the L-shaped grounding system which can be easily observed as Fig. 8.

5.3. Unequally Spaced Grid with Ground Rods

Unequally spaced grid 91.44 m × 91.44 m, 64 meshes with ground rods placed along the perimeter is seen below in Fig. 9. For comparison of the calculations done by both techniques, the obtained results are shown in Table 4.

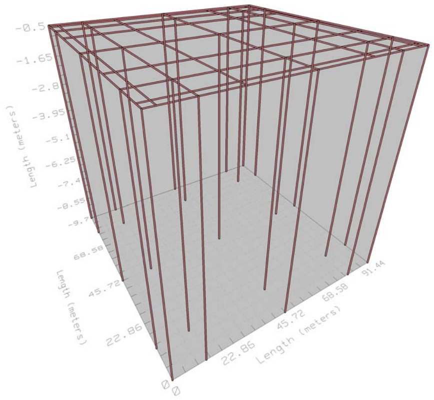

Fig. 9. 3-D grid layout for unequally spaced grid with ground rods

Table 4. Comparative results for unequally spaced grid with ground rods

	IEEE Std 80-2000	Software
Max. Allowable Touch Voltage (V)	838.20	840.55
Max. Allowable Step Voltage (V)	2686.00	2696.10
Reduction Factor, Cs	0.740	0.740
Rg (Ω)	2.740	2.330
GPR (V)	5227.92	4562.49

As easily seen also from this simulation, if we keep ground resistance low, the discrepancies between results are nearly negligible. The maximum limit for touch voltages of the unequally spaced grounding system can be observed as Fig. 10.

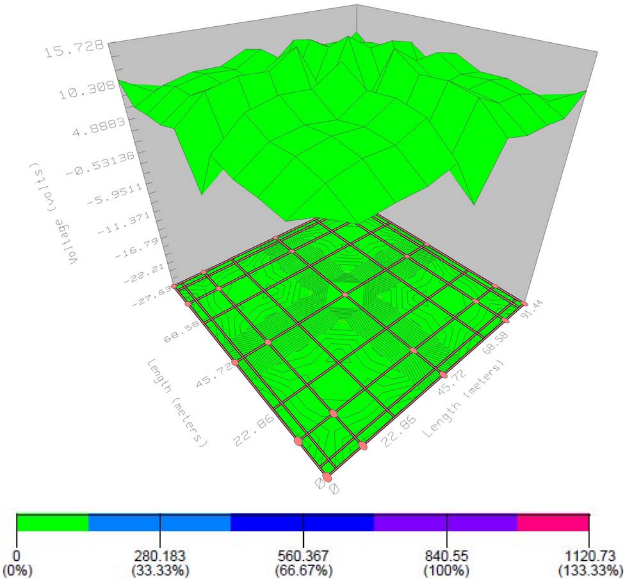

Fig. 10. 3-D grid layout for unequally spaced grid with ground rods

6. Conclusions

Although analysis techniques based on computer simulation are expensive yet, it is clear that the usage of them cause cheap and reliable earthing grid regulation. It is necessary to regenerate parametric analysis so that includes multi layer soil conditions. Earthing grid regulating standards need harmonization between them.

If the results of this study are summarized as below, it shows that:

1. The safety level for equipment and people can be enhanced using unequally spaced grounding grids by decreasing earth surface potential gradients and making conductor leakage current distribution more uniform,
2. A non-uniform conductor spacing, having more conductors at the edges of the grids, provides the most efficient design,
3. An unequally spaced grounding grid is an economical and reasonable technique as shown in simulation,
4. The design of rectangular grids buried in uniform soil without ground rods could be adjusted and applied to any practical substation grounding grid design.

Tracking the basic rules suggested by IEEE Std 80-2000, IEEE Std 142-2007 and many computational algorithms to obtain safe grounding system, an expert system methodology for analysis and design of the substation grounding systems is given. Step by step design technique with necessary explanations is used to represent the required information. The developed expert system can be very useful tool in analysis and design of the substation grounding systems.

When designing earthing grid systems for large electrical substations, calculations performed in this study shows that IEEE Std 80-2000 is the most conservative since it predicts the lowest level of tolerable voltage and also the body current formulas provide adequate margins of safety for modern transmission and distribution systems. The safety criterion is compared and their differences are shown to prove that IEEE Std 80-2000 provides the most useful procedures for grounding system safety assessment.

The most critical touch voltages are found in the corners of grounding grid cases as shown in simulations.

To achieve more accurate results, computer aided design programs are needed for complex algorithms of calculations requiring the use of computational tools. Since it offers the possibility of making a closest to the reality detailed analysis, the finite elements method is the best way to represent the grounding systems study nowadays.

More accurate computer results are compared with several equations for E_s and E_m from cases with various mesh sizes, grid shapes, lengths and numbers of ground rods and they are found to be better than the equations. The cases include square, rectangular, L-shaped, equally and unequally spaced grids. They are run without and with ground rods. The total ground rod length is varied with different numbers of ground rod lengths and locations. Most practical examples of grid design are considered. The comparisons show that it is possible to track the computer results with acceptable accuracy.

7. References

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