

Optimized Design of Earthing System for Substations with High Soil Resistivity and Limited Plot Area

Prudhvi Raj Bonda, *Student* and Mahesh K. Mishra, *Senior Member, IEEE*

Abstract—Over the past few years, the demand for electrical energy has been increasing rapidly. Consequently, to cater the load requirements, the number of substations being built has been continuously rising. For several technical and safety reasons, electrical power installations must be grounded and the uninterrupted flow of fault current to the earth can be achieved by maintaining the grounding system resistance as low as possible. For a substation with high grounding system resistance, a hazardous situation can be generated in the vicinity of the substation depending upon the level of the potential difference that exists between grounded structures and various points on earth during abnormal or fault conditions. Two of the most critical parameters that influence the design of the grounding system at an electrical substation are the soil resistivity and the area available for laying the grounding system. The main objective of this paper is to present an optimized design of earthing system for a substation located in high soil resistivity with limited plot area at Himachal Pradesh state of India using computer design program. A hybrid methodology for analyzing the performance of a grounding system with chemical ground electrolytic rods, ground enhancement materials and auxiliary wire mats has been developed. The design is based on the measured soil resistivity of the substation site and proposed methodology is found to be safe for operation.

Index Terms— Substation, Grounding, Grounding System Resistance, Soil Resistivity, Plot Area, Touch and Step Potentials.

I. INTRODUCTION

Substation is a key element of overall power system and effective functioning of any power system relies primarily on safe and consistent performance of substation.

Prudhvi Raj Bonda is the Post Graduate student from the Dept. of Civil Engineering, IIT Madras, Chennai 600036, India (e-mail: bprudhviraj99@yahoo.com).

Mahesh K. Mishra is the Prof. from the Dept. of Electrical Engineering, IIT Madras, Chennai 600036, India (e-mail: mahesh@ee.iitm.ac.in).

Continuous increase in the demand for electrical energy is the primary reason for the rise in the number of substations being constructed throughout the world. For several technical and safety reasons, electrical power installations must be grounded and the uninterrupted flow of fault current to the earth can be achieved by maintaining the grounding system resistance as low as possible.

A safe grounding design has two objectives: To carry electric currents into the earth under normal and fault conditions without exceeding any operating and equipment limits or adversely affecting continuity of service and reduce the risk of a person in the vicinity of grounded facilities being exposed to the danger of critical electric shock [1]. □

Grounding system design relies on various factors that vary from substation to substation. It is to be noted that two of the most critical parameters that influence the design of the grounding system at an electrical substation are the soil resistivity and the area available for laying the grounding system. In the recent past, there is a huge increase in the number of substations being built in hilly terrains and at these topographies, the resistivity of the soil is usually very high and also the area available for grounding is limited. In such locations, it is difficult to achieve safe operating conditions without an effective grounding system design.

In the last few years several authors have proposed the following methods for reduction of earth resistance. Vertical rods can be penetrated much deeper into soil by inserting them in an augured hole with backfill instead of directly driving [2]. Formation of a complex network of tree-like cracks, under the main grounding mat, filled with low resistivity materials [3]. Installation of a satellite electrode in an adjoining area of lower resistivity connected to the station grounding system [4]. Steel fibre conductive concrete with steel fibre and graphite as conductive fillers [5].

This paper presents few more effective techniques, which include use of chemical electrolytic ground rods, auxiliary wire mats and ground enhancing materials, for achieving the safe potential gradients along with the desired grounding system resistance in high resistivity soils for the substation located at Himachal Pradesh state of India using computer design program.

II. DESIGN OF GROUNDING SYSTEM FOR SUBSTATION WITH HIGH SOIL RESISTIVITY AND LIMITED PLOT AREA

Substation grounding is critical part of substation design. The design process adopted includes field data collection, determination of two-layer soil model using the measured soil resistivity data, determination of maximum grounding system resistance along with attainable step & touch voltages. The computer design program used for design process confirms to IEEE standard 80.

A. Soil Resistivity Measurements at the Substation Site

The substation considered for analysis is located in regions where the moisture content in the soil is very low and because of the presence of rocky beds, the soil resistivity is very high. If there is a significant variation in the resistivity of soil, a multi-layer soil model is preferred for accurate estimation of features. Design of substation earthing grid can be very challenging in the two-layer soils especially when the bottom layer soil resistivity is higher than that of the top layer.

Substation considered for this project is located near Lahal, Himachal Pradesh and soil resistivity measurements were conducted at the proposed site based on Wenner method using a four pole Megger Earth Tester. A total of 9 Earth Resistivity Test points, across the altitudes of 1579m, 1591m, 1600m, &1608m, have been used to determine the resistivity of the soil. Table I depict the measured soil resistivity field data where the apparent resistivity values are average of nine measurements traverses conducted for each probes spacing. The initial spacing between probes was 1m and has been increased up to 16m.

Table I. Soil resistivity data collected from the field

SI No.	Probe Spacing (meters)	Apparent Resistivity ($\Omega - m$)
1	1	63.84
2	2	96.47
3	2.5	112.41
4	3	48.98
5	4	86.62
6	5	97.86
7	6	115.83
8	8	139.42
9	9	271.3
10	12	180.96
11	16	161.35

B. Details of Input Required

The following depict the input data that has been considered for grounding system design,

1) *Fault current and duration*: Maximum earth fault current entering into the earthing grid. The fault duration is the time for which the fault current flows through the grounding system before protective devices operate and

interrupt the fault. Here, a fault current of 63kA is considered and fault-clearing time of 0.5 seconds is considered for conductor sizing and for estimation of the permissible step and touch potentials.

2) *Area of the substation site*: From site layout, we can find the area that the buried earth mat will cover. It will have a considerable impact on grid resistance. In our analysis, we have considered an area of 275m x 175m.

3) *Surface layer*: It is suggested that the use of a high resistivity surface layer is capable of improving the safety while designing substation-earthing grid in high resistivity soil [1]. The current through the body will be lowered considerably with the addition of the surface material because of the greater contact resistance between the earth and the feet. In this design surface layer with the resistivity of 3000ohm-m and depth of 0.1m is considered.

4) *Material for conductors and rods*: Material constant such as fusing temperature, thermal capacity, and conductivity will have an impact on size of the conductor chosen. Steel has been considered as the main conductor.

5) *Depth of grid*: It will have impact on grid resistance as per equation (52) of IEEE 80. IEEE 80 suggests that depth of burial shall be in between 0.5m to 1.5m below the surface. In our design depth of grid is 0.6m or 2ft.

C. Substation Soil Structure Analysis

Based on the measured soil resistivity field data, computer design program is used to determine two-layer soil model. It contains a top layer of finite depth and bottom layer of infinite depth. Fig. 1 comprising the resistance curve shows the relationship between resistance and probe spacing. Multi-layer soil model generated through numerical model is certainly helpful for deciding the methodology to be adopted for achieving the desired results.

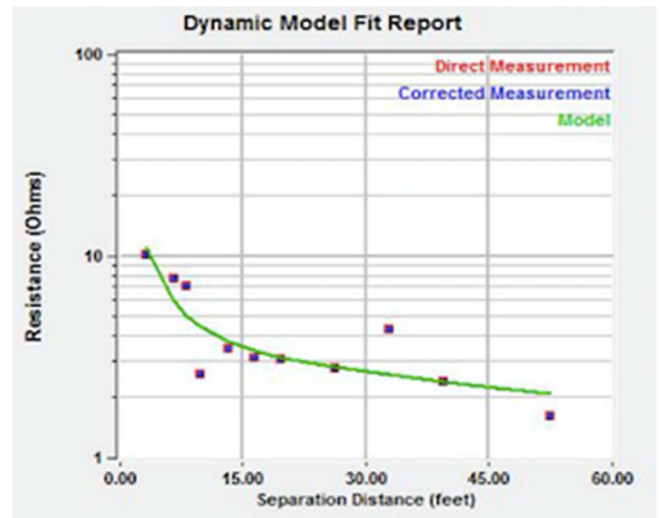


Fig. 1. Variation of resistance with respect to probe spacing

From Fig. 2, it can be seen that the first layer of soil consists a resistivity of 72.6Ωm with the thickness of approximately 12.9ft and the second layer of soil consists a resistivity of 366.2Ωm with infinite thickness. Hence at this topography, bottom layer soil resistivity is higher than that of the top layer or it can also be stated that the value of the soil resistivity increases as we go deeper into the earth.

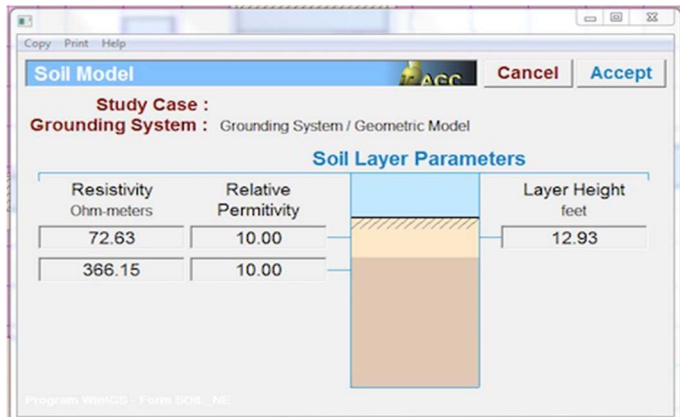


Fig. 2. Computed soil structure parameters

Estimation of permissible touch and step voltages has been done using the computer design program based on IEEE standard 80 as shown in Fig. 3. A body weight of 50kg is considered for the calculation and the fault current division is assumed to be 1 as no ground fault current is being diverted through overhead or shield conductors. The consolidated results have been detailed in Table II.

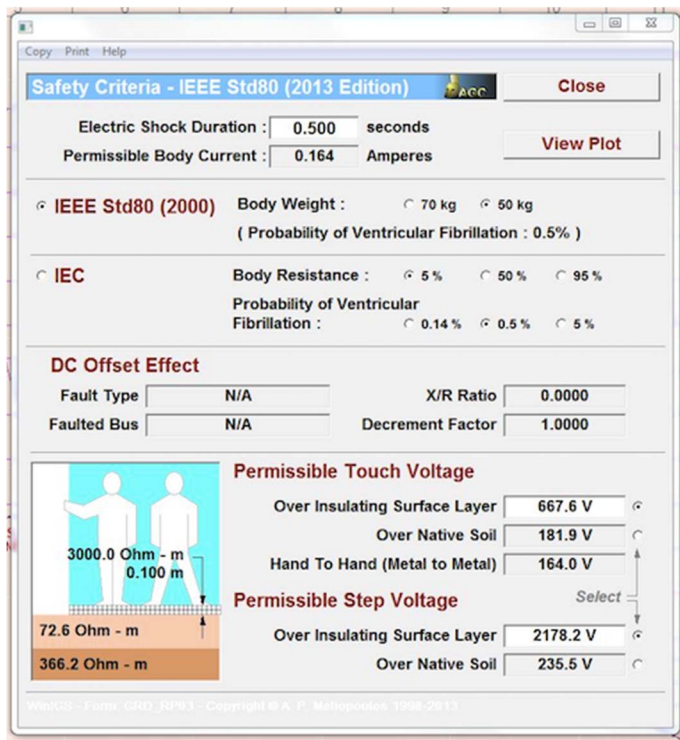


Fig. 3. Computed permissible voltages

Table II. Estimated results

Sl No.	Parameter	Result
1	Upper Layer Resistivity	72.6 Ωm
2	Lower Layer Resistivity	366.2 Ωm
3	Upper Layer Thickness	12.9 ft.
4	Permissible Touch Voltage	667.6 V
5	Permissible Step Voltage	2178.2 V

D. Hybrid Design of Grounding System

Optimization of the design can be easily achieved by numerical models through computer design programs. Also, simplified equations or analytical models cannot evaluate the required parameters either if the shape of the grid is uneven or if the soil comprises multi-layers. A grounding system at a substation often requires the form of a horizontal grid supplemented by a number of vertical conductors. The reduction in earth resistance can be achieved by horizontal grid, as it increases the area in contact with soil and creates a number of parallel paths. In addition to earthmat with horizontal ground conductors, the alternate methods for enhancing the substation grounding system comprise the use of the following,

1. Driven chemical electrolytic ground rod.
2. Horizontal conductor in ground enhancing material.
3. Auxiliary rectangular wire mats.

In this design, these additional rods or mats are made to bond with the existing main ground mat and thereby assist in achieving the desired results.

D.1. Driven chemical electrolytic ground rod.

Chemical electrolytic ground electrodes provide a low grounding resistance in areas of high soil resistivity and low moisture conditions. These electrolytic rods are installed in an augured hole and typically back-filled with low resistivity materials. These rods can be placed to whichever required depth irrespective of the sub-soil conditions. The chemical electrode can be connected to the main grounding system through pigtail/wire.

These electrolytic rods usually consist a number of holes throughout their length. These holes are meant for allowing the moisture to enter the electrode and get mixed with the inherent salts for developing an electrolytic solution that flows into the soil around the conductor, which thereby enhances the conductivity. The salts present in the electrolytic rods can be replaced whenever required and this method of achieving low impedance is reliable for a lot of years. For the considered case study, two numbers of 10 feet and seven numbers of 80 feet chemical electrolytic ground rods have been taken into consideration for achieving the safe operating conditions.

D.2. Horizontal conductor in ground enhancing material

As per [1], high potentials occur along the plot boundary. The solution to mitigate this problem is to effectively increase the diameter of the conductor running throughout the periphery of the grounding system, which can be achieved by encasing the conductor in a ground enhancement material.

A trench of specific dimensions has to be excavated before laying the horizontal conductor. The conductor running throughout the periphery of the substation must be enclosed with this low resistivity or ground enhancing material like bentonite. A total volume of 2546 cubic feet of low resistive material was required to bring the attainable voltages to safer values in this case study.

D.3. Auxiliary rectangular wire mats

Usually, in high voltage substations, auxiliary earthing mat comprising of closely spaced conductors shall be provided, at depth of one feet from ground level, below the operating handles of the manual operated mechanism boxes of the isolators and these boxes are directly connected to the auxiliary earthing mat for safety of the personnel from electric shocks.

The similar principle has been used in this earth grid design. Closely spaced wire mats were installed at various locations where the voltage levels exceeded permissible values. These closely spaced conductors placed at a level higher (above one feet from grid) than the main grounding grid can contribute significantly in the reduction of surface potentials as well as in lowering the overall grounding impedance. In this design, few number of auxiliary earth mats have been installed at multiple locations throughout the periphery of the substation and a total of 6620 feet of 3/8” mild steel has been utilized for this purpose.

The grounding grid setup shown in Fig. 4 provides a visual representation of the designed grid along with the location of all the enhancement materials considered above.



Fig. 4. Top view of hybrid earthing grid

Fig. 5 depicts the total quantity of conductor used to achieve the desired grounding system resistance along with the safe potentials. Main grounding mat made up of 5/8” mild steel, chemical electrolytic ground rods, ground enhancing material (Bentonite) and auxiliary rectangular ground mats made up of 3/8” mild steel were used to achieve the desired results.

Bill of Materials			
Study Case : Grounding System / Geometric Model			
Layers: <input type="radio"/> Single <input type="radio"/> Multiple <input checked="" type="radio"/> All Layers			
Type and Size		Quantity	
1	Chemical Ground Rod (10.00 feet)	2	
2	Chemical Ground Rod (80.00 feet)	7	
3	Horizontal Ground Conductor	2545.16	cubic feet
4	STEEL/3/8HS	6620.00	feet
5	STEEL/5/8	23985.93	feet

Fig. 5. Conductor quantity estimated through hybrid methodology

Fig. 6 provides the final value of grounding system resistance obtained by adopting the aforementioned design methodology.

Ground System Resistance Report				
Study Case Title: Grounding System / Geometric Model				
Frequency: 60.00 Hz				
Group Name	Node Name	Resistance (Ohms)	Voltage (Volts)	Current (Amperes)
MAIN-GND	NEWBUS_A	0.6600	41578.14	63000.00
		Rp = 0.6600	Earth Current:	63000.00
			Fault Current:	0.00
			Split Factor:	N/A

Fig. 6. Grounding system resistance report

Table III provides the consolidated results of the adopted design. It can be observed that by adopting the above-mentioned design methodology, the earth resistivity has remained lesser than 1 ohm and the attainable voltages were well below the permissible or allowable limits. Hence, it can be concluded that the proposed design is safe for operation.

Table III. Outcomes of the design

Sl No.	Parameter	Result
1	Ground Resistance	0.66 Ω
2	Attainable Touch Voltage	645 V
3	Attainable Step Voltage	921.2 V
4	Chemical Electrolytic Ground Rods	580 ft.
5	3/8" dia. Mild Steel	2018 m
6	5/8" dia. Mild Steel	7311 m
7	Ground Enhancement Material	2546 cubic ft.

Fig. 7 and Fig. 8 illustrate the contour plot of touch and step potential profiles along the designed substation grid. It can be seen that the attainable potentials at all the points are lesser than the tolerable step and touch voltage limits and hence the implemented design is termed to be safe for operation.

Multi – dimensional rendered views of the touch and step voltage plots along the grid area can be seen in Fig. 9 and Fig. 10. Also, the periphery of the substation comprised higher voltages (red in colour) compared to other regions, so more number of conductor material was required to bring these voltages within permissible limits.

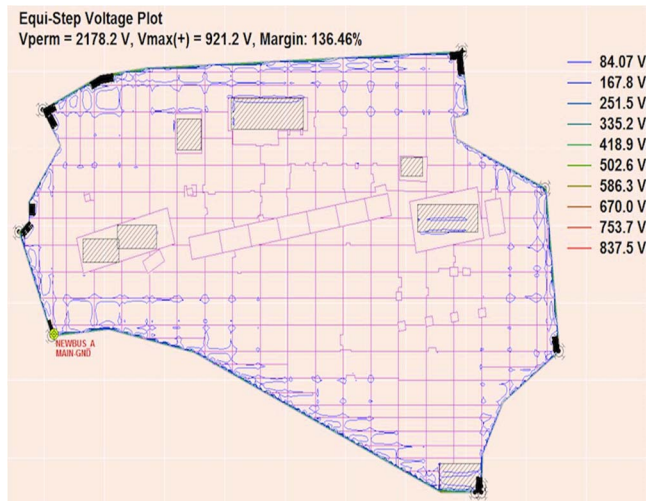


Fig. 8. Step voltage plot

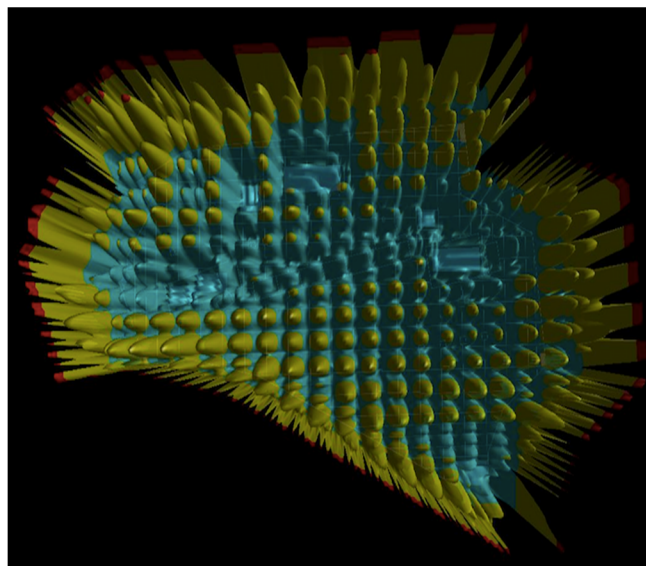


Fig. 9. 3-D Rendered view with touch voltage plot

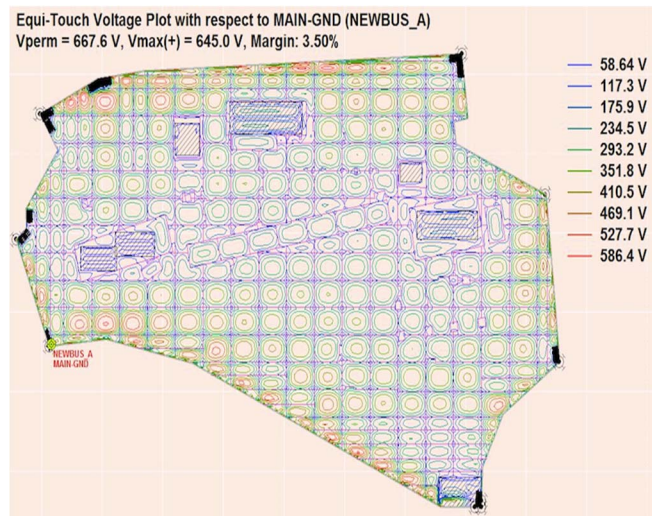


Fig. 7. Touch voltage plot

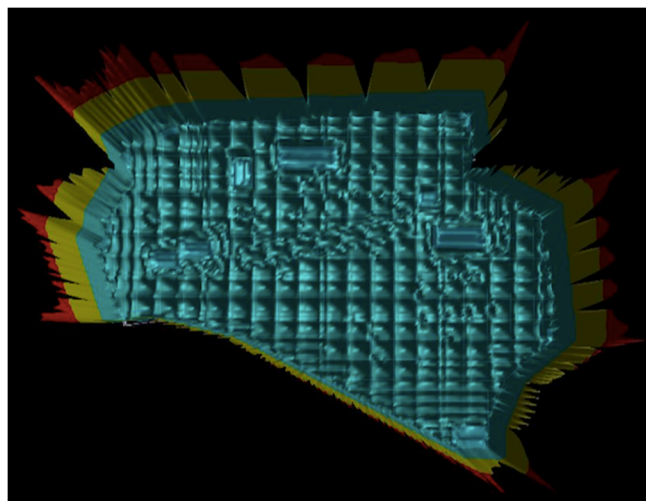


Fig. 10. 3-D Rendered view with step voltage plot

III. CONCLUSION

In the recent past, there is a huge increase in the number of substations being built in hilly terrains and at these topographies, the resistivity of the soil is usually very high and the area available for grounding is also limited. In such locations, it is difficult to achieve the safe operating conditions without an effective grounding system design.

This paper presented hybrid grounding system design methodology encompassing chemical electrolytic ground rods, auxiliary wire mats and ground enhancing materials along with the horizontal ground grid. Such materials and techniques were used for achieving safer potential gradients along with the desired grounding system resistance in highly resistive soil for a substation situated in the state of Himachal Pradesh, India using computer design program. The whole hybrid design scheme has been demonstrated in this paper and the effectiveness of the scheme could be validated from the aforementioned results that are compliant with IEEE standard 80, and hence the design is termed to be safe for operation.

IV. REFERENCES

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