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Grid Grounding Calculations for a 132-KV Substation Using Soil Backfilling

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ABSTRACT Safe and reliable grid design is complicated by the compact design of gas insulated substations (GIS). This paper discusses the complete grounding design procedure for a 132-KV substation in the city of Al Kharj based on the IEEE-80 specifications and local standard practices in the Kingdom of Saudi Arabia. To ensure a safely grounded grid design, local Saudi Electricity Company (SEC) standard design constraints were used. The current distribution electromagnetic interference, grounding, and soil structure (CDEGS) software was used to compare the test results for soils with and without backfilling. Due to the high resistivity of the plot, soil with a low resistivity should be used as backfill. The calculated results were compared to the standard values of ground potential rise, step voltage, touch voltage, and soil resistance. This paper contributes to an understanding of effective grounding techniques for soil with high resistivity and optimizes the increase in cost due to backfilling.

INDEX TERMS Grounding grids, CDEGS, step voltage, touch voltage, ground potential rise.

I. INTRODUCTION

Grid grounding is an established technique used to ensure the safety of grid equipment and individuals. Over time, air-insulated substations have been upgraded to GIS substations. The compact size of substations and the enhanced voltage levels due to increments in load consumption make the substations vulnerable to electric shocks. Grounding grids are necessary to achieve minimal impedance values and enable fault currents to flow easily toward the ground, thereby limiting potential surges to substation equipment and promptly clearing all types of transient surges. In general, ground grid impedance should be less than 1–5Ω [1]. Moreover, grounding a grid allows the installed equipment and protective devices to perform properly and safely. For electrical equipment, such as power transformers, capacitor banks, reactors, and auxiliary station transformers, safety and reliability are top priorities. To achieve stability for such equipment, neutral point grounding is essential. The integrity of the grounding grid under both normal and faulty conditions enables the continuity of service and ensures personal safety in a facility by limiting the danger of electric shock. To achieve reliable and cost-effective grid grounding, several factors should be considered. Based on IEEE-80 specifications, the CDEGS [2] software tool was used for analysis.

A new 132-KV substation called Al-Tawdihiyah tag# S/S 8725 has been designed for the city of Al Kharj, which is south of the capital city in the Kingdom of Saudi Arabia. The objective of this paper is to investigate and test the soil data provided by the Saudi Electricity Company for effective grounding. Soil backfilling was used due to high soil resistivity to achieve improved and reliable grid grounding resistance while minimizing the cost of backfilling. Multilayer soil was used to approximate a highly nonuniform soil, which requires complex calculations with a computer program or graphical methods. All the design constraints considered in this paper are based on local standard practice in the Kingdom of Saudi Arabia. For grid equipment safety, a pure conductive copper connection with the grounding grid is needed, as shown for a typical auxiliary transformer and ring main unit in Fig. 1. For this purpose, compression lugs, grounding rods, and a bare, soft drawn, annealed, stranded copper conductor with proper thermo welds or compression joints are necessary.

During design, the resistance between personnel and the ground should be high enough to prevent any type of current from flowing through the human body [3].

II. METHODOLOGY

Grid grounding mainly relies on proper grid conductor sizing that can achieve permissible touch and step voltages and grid potential rise relative to the grounding joints, which is

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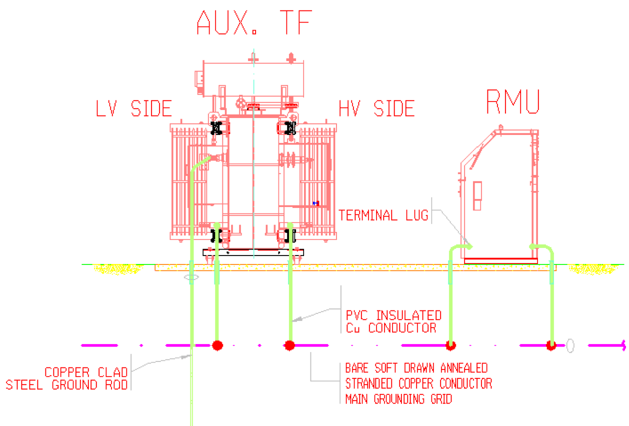

FIGURE 1. General arrangement for equipment grounding.

considered to be the potential of remote earth. During the construction phase of the substation, the criteria defined in the IEEE-80 publication "Guide for Safety in Substation Grounding" were followed to protect personnel and equipment from electric shocks. The local standards of the Saudi Electricity Company were followed as the design constraints to develop an effective grid ground framework in the Kingdom of Saudi Arabia [4]. Effective grid grounding helps to protect telecom and control equipment [4].

A. GRID CONDUCTOR SIZING

Soft drawn, stranded copper should be used for the ground grid conductors. The conductor should be round to maximize cross-sectional contact with the ground. In coastal zones with low soil resistivity, a tinned copper conductor should be used. Copper-clad steel should be used for ground rods to resist fusing and prevent the electric joints under the severe conditions due to the increase in fault-current and fault period to which it might be exposed. The grounding conductor should be composed of soft-drawn, annealed copper. The required cross-sectional area is calculated based on IEEE std. 80 Eq. 30. The formula for calculating the Cu conductor area is given by

$$\mathrm{A_{mm^2}} = \frac{I_f}{\sqrt{\left(\frac{TACP\times 10^{-4}}{t_c \alpha_r \rho_r}\right)\ln\left(\frac{K_0+T_m}{K_0+T_a}\right)}} \tag{1}$$

where

tc = Maximum possible clearing, taken as 1.0 sec.

αr = Thermal coefficient of resistivity of the conductor material at the reference temperature

Tr = 0.00393

ρr = Resistivity of the ground conductor at the reference temperature Tr in $\mu\Omega$-cm = 1.72

TACP = Thermal capacity [4] J/cm^3.°C = 3.42

Tm = Fusing temperature in °C = 1083

Ta = Ambient temperature in °C = 50

k0 = 1/ α0 or k0 = (1/αr) - Tr = 234 [5].

B. TOLERABLE TOUCH VOLTAGE

Touch voltage is the voltage difference created between any electrically conductive equipment and a standing person who contacts that equipment. A person may contact equipment by touching it with both hands or with one hand while their feet are resting on the ground. Ideally, the ground voltage would be zero volts, creating a potential gradient during current leakage or fault current (i.e., the amount of current that flow through electrical equipment during electrical fault condition) [5].

$$\mathrm{Vt} = \frac{(1000 + 1.5 \times Cs \times \rho s) \times 0.116}{\sqrt{ts}} \tag{2}$$

where

Cs = Reduction factor for derating the nominal value of surface layer resistivity; it is 1 when there is no protective surface layer (protective layer resistivity equal to soil resistivity). For a protective surface layer with a resistivity higher than soil resistivity, Cs is < 1.

ts = Duration of the shock current in sec, which usually ranges from 0.5 to 1.0 sec. For SEC applications, this value will be taken as 0.5 sec or the back-up clearing time, whichever is greater.

Ps = Resistivity of the surfacing material in ohm-meters, which ranges from 1000 to 5000 in value [5].

The fault hazard analysis for achieving a permissible touch voltage limit is also defined by EN 50522 [6].

C. TOLERABLE STEP VOLTAGE

Step voltage Vs is the difference in surface potential that could be experienced by a person bridging a distance of 1 m with their feet without contacting any grounded object.

$$\mathrm{Vs} = \frac{(1000 + 6 \times Cs \times \rho s) \times 0.116}{\sqrt{ts}} \tag{3}$$

Here,

Cs = Reduction factor for derating the nominal value of surface layer resistivity; it is 1 when there is no protective surface layer (protective layer resistivity equal to soil resistivity). For a protective surface layer with a resistivity higher than soil resistivity, Cs is < 1.

ts = Duration of the shock current in sec, which usually ranges from 0.5 to 1.0 sec. For SEC applications, this value will be taken as 0.5 sec or the back-up clearing time, whichever is greater.

Ps = Resistivity of the surfacing material in ohm-m, which ranges from 1000 to 5000 in value [5]

The influences of step and touch voltages vary with body impedance and shoes, as considered in [7].

D. GROUND POTENTIAL RISE

The maximum electrical potential that a ground electrode may attain relative to a distant grounding point is assumed to be the potential of remote earth. This voltage, GPR, is equal to the maximum grid current multiplied by the grid resistance [5]

$$GPR = IG \times Rg \tag{4}$$

where

IG = Maximum grid current in amperes

Rg = Grid resistance in ohms [5]

The value of substation grounding resistance is calculated using the following formula:

$$Rg = \rho[\frac{1}{Lt} + \frac{1}{\sqrt{20A}} \times (1 + \frac{1}{1 + h\sqrt{20A}})] \tag{5}$$

where

Rg = Substation ground resistance in ohms

ρ = Average ground resistivity in ohm-m

A = Area occupied by the ground grid in m^2

Lt = Total buried length of conductors in m (this value is a combination of the grid rod length and the combined length of the earthing conductor and ground rods).

h = Depth of the grid in meters, excluding any asphalt covering [5]

Once the grounding mat has been laid along with the desired grounding electrodes, all ancillary grid equipment is bonded. The grid grounding conductor is determined through an iterative process using CDEGS software. (5) plays a vital role in the cost estimation of the total grid conductor length. Effective secondary protections will enhance substation reliability and grid life.

III. GRID DESIGN CALCULATIONS

Resistivity governs the amount of current that passes through a material when a specific potential difference is applied. The following equation is used to determine the average soil resistivity to a depth equal to the distance between the electrodes:

$$\rho = 2\pi aR \tag{6}$$

where

p = Average soil resistivity

π = 3.1416

a = Distance between electrodes

R = Test instrument resistance reading in ohms [5].

Table 1 shows the earth resistivity test (ERT) measurements of electrode resistance and soil resistivity. The electrical resistivity test was conducted at the site for sixteen test points according to IEEE-81 in eight directions. The test was performed using a Terrameter SAS 1000 device with the 4-electrode Wenner array method.

Initially, the soil structure of the allocated substation plot was studied using the Wenner four point method [8] to gather earth resistivity (ohm-meter) data. The electrical resistivity test procedure uses a controlled current produced artificially between two electrodes implanted in the ground as the energy source. Another pair of electrodes measures the potential difference produced as a result of this current flow.

From the data obtained by varying the spacing and distribution of the electrodes, it is possible to compute the apparent resistivity of the ground. This parameter has been normalized over a uniform subsurface; it is independent of current input, electrode arrangement and spacing. The Wenner array was used at this site. The field procedure consists of taking a succession of apparent resistivity readings with increasing electrode spacing. The method relies on the fact that the larger the spacing between the current and potential electrodes, the greater the depth of investigation. Similarly, an integrated methodology ensures the protection of personnel and grid equipment against HV short circuits by providing an optimized and economical grounding system, as discussed in [9].

For the purpose of investigation, the method of varying electrode spacing was used. The array must always retain symmetry about a certain point, which is also an effective point of observation. The instrument used was a Geppulse Megger Digital Multi Earth Tester Serial No. 156 manufactured in Finland. This instrument, which is battery powered and has a maximum of 12 volts available, measures a minimum resistance of 0.001 ohms. The current electrodes were 85-cm-long steel stakes that can be easily driven into the ground. Table 2 shows the tabulated soil resistivity values, which are to be used for soil modeling. The probe direction was considered in four possible directions. The abbreviations used in Table 2 are defined below.

TABLE 1. Earth resistivity test values using Wenner method.

SOIL RESISTIVITY (ohm-m)	1.5	3	4.5	6	9	15
ERT-1	113	142	169	230	281	302
ERT-2	102	127	176	218	251	273
ERT-3	108	129	170	221	267	280
ERT-4	83	108	168	214	261	281
ERT-5	150	219	287	332	357	356
ERT-6	187	254	328	341	374	360
ERT-7	130	190	256	320	316	322
ERT-8	144	208	274	317	357	340
ERT-9	121	189	252	289	335	362
ERT-10	169	226	292	327	384	373
ERT-11	144	193	256	308	335	347
ERT-12	116	157	221	272	327	336
ERT-13	86	133	186	231	265	287
ERT-14	133	174	245	307	340	341
ERT-15	121	167	218	283	336	341
ERT-16	127	182	223	274	318	350
AVERAGE (ohm-m)	127	175	233	280	319	328

TABLE 2. Earth resistivity test values using the Wenner method.

Probe Direction & Distance		Resistivity (ohm-meter) 1.5	3	5	8	12	15
SR 1	NS	96	144	160	213	175	154
	EW	139	226	210	260		
	NW/SE	132	226	262	306	326	
	NE/SW	155	196	246	281	286	262
SR 2	NS	120	158	253	270	283	332
	EW	113	157	216	265	291	362
	NW/SE	112	174	230	221	297	360
	NE/SW	111	157	223	285	358	351
SR 3	NS	130	190	271	264	340	
	EW	125	222	202	283	323	338
	NW/SE	126	193	202	295	352	328
	NE/SW	124	214	234	285	341	336
SR 4	NS	167	275	303	323	381	412
	EW	204	270	275	313	401	407
	NW/SE	164	263	253	309	392	406
	NE/SW	172	263	272	320	409	439
Average value =		140.0975	140.0975	140	210	245	286

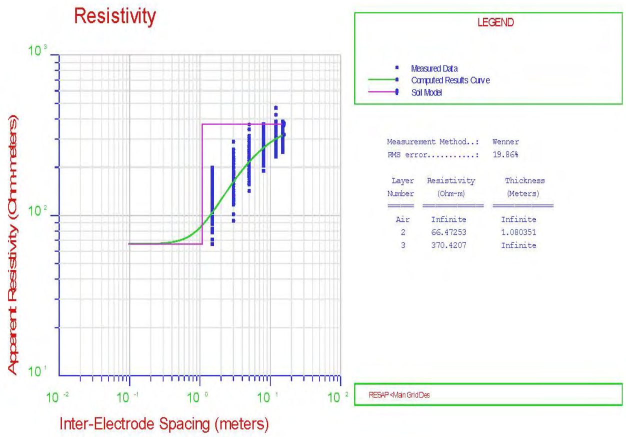

FIGURE 2. Soil resistivity model without backfilling.

NS = North-South
EW = East-West
NW/SE = Northwest-Southeast
NE/SW = Northeast-Southwest

The earth resistivity test values are used to compute the soil model in CDEGS. The resistivity of the upper layer is 66.47 ohm-m, and the resistivity of the lower layer is 370.62 ohm-m. Different locations showed that the presence of high-resistivity patches made safe grounding difficult, as shown below in Fig. 2.

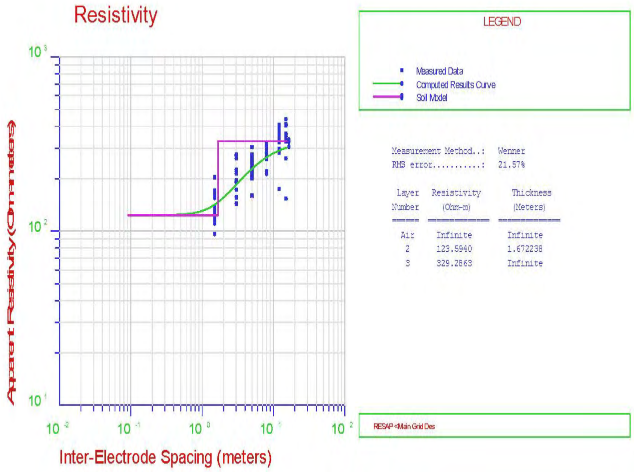

FIGURE 3. Soil resistivity model with backfilling.

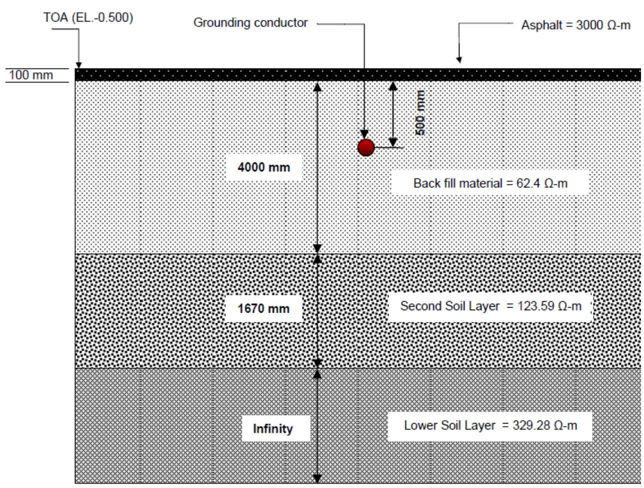

FIGURE 4. Sectional view for soil resistivity with backfilling material.

Due to high resistivity soil, low resistivity soil was used for backfilling to control soil grid resistance. As shown in Fig. 2, the resistivity of the upper layer is reduced to 123.59 ohm-m, and the resistivity of the lower layer is reduced to 329.28 ohm-m by using 8 probes installed at different locations. As per actual site conditions, the complete substation yard area was backfilled with soil at an average thickness of 1.8 m. In actual conditions, the grounding grid should be laid within the backfill soil.

Calculations were then performed with the soil model considering the top layer as backfill material with a low resistivity of 62.4 ohm-m and a thickness of 4 m, the second layer with a resistivity of 123.59 ohm-m and a thickness of 1.67 m and the final layer with a resistivity of 329.28 ohm-m and an infinite depth from the soil model, as shown in Fig. 4.

The grounding grid should cover the protected area within the substation boundary and should extend at least 1.5 m outside the substation boundary on all sides. The grounding grid should be buried at a depth ranging from 0.5 to 1.5 m [4] below the final grade (excluding asphalt covering).

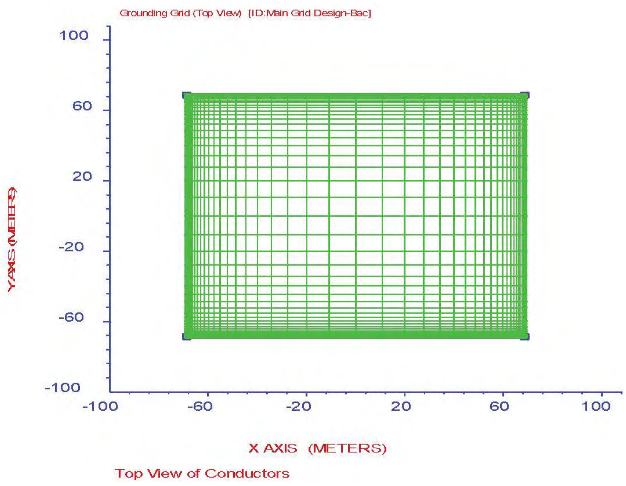

FIGURE 5. Auto grid pro: Main grid design (top view).

The spacing of the main conductors generally ranges from 3 to 15 m [4]. In congested areas, reduced intervals may be desirable. Grid spacing should be halved around the perimeter of the grid to reduce periphery voltage gradients. Reinforcement bars in concrete slabs, foundations and duct banks should be connected to the grounding grid using the appropriate thermo weld joints. The main conductors and secondary conductors should be bonded at points of crossover by thermo welds. This connection is normally achieved with a grid of horizontally buried conductors and is supplemented by a number of vertical rods connected to the grid.

Ground rods should have minimum dimensions of 19 mm $\varphi\times$ 3.6 m [4], and the size should be selected for the breaker short circuit rating. For two-layer and multilayer soil models in which the upper layer has high soil resistivity, deep driven rods should be considered so that the rod is in contact with the low-resistivity lower soil layer. Prior to backfilling, the ground rods should be installed. As per recommended engineering practice, solid ground rods are used in this study [10].

A soft-drawn, annealed copper conductor with a cross-sectional area of 150 mm^2 is selected (2). A 100$\times$100 m mesh, as shown in Fig. 5, is laid 0.5 m below the asphalt level. For grounding grid design in the KSA, the soil resistivity of asphalt should be considered to be 3000 ohm-m at a depth of 0.1 m.

Design parameters are considered based on the Saudi Electricity Company [4]. The symmetrical ground fault current (If) is considered to be 40 kA for the system, and the X/R ratio equals 20. The current division factor (Sf) is 0.7. The time of current flow (tc) during the duration of shock (ts) is 1 sec. It is assumed that the fault current includes any conceivable system additions over the next 25 years. Thus, no additional safety factor for system growth is added; that is, Cp = 1. The safety factor for a body to bear the shock of a current for the majority of people (weighing approximately 50 kg) is calculated by the following formula:

$$I_B = \frac{0.116}{\sqrt{ts}} \tag{7}$$

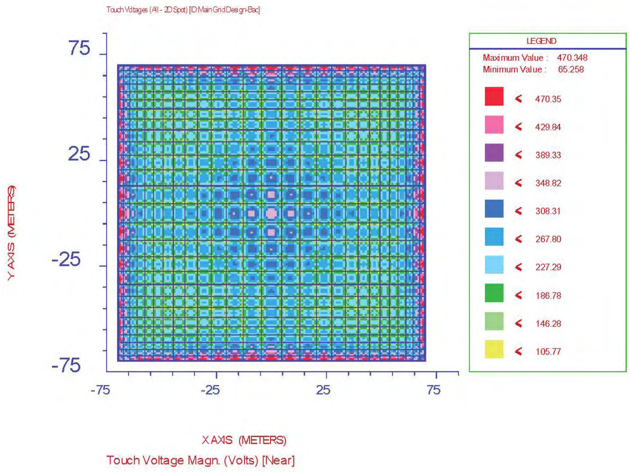

FIGURE 6. Touch voltage (all-2D spots) without backfilling.

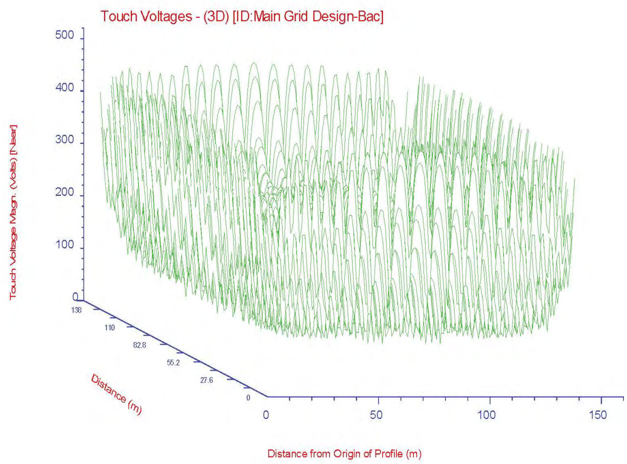

FIGURE 7. Touch voltage (all-3D spots) without backfilling.

where

I_B = rms magnitude of tolerable shock current through the body in amperes.

ts = Duration of the current exposure in sec (shock duration). [5]

Possible destruction due to transient and fault current could be encountered due to different possibilities, as discussed below.

The first, second and asphalt layers have resistivities of 66.47 ohms, 370 ohms and 3000 ohms, respectively. A total of 28 pure copper steel clad rods with diameters of 19 mm were buried at a vertical depth of 3.6 m. After placement of the rods, the touch voltage was calculated by using (2). The calculated touch voltage Vt1 of 470.34 V was greater than the permissible touch voltage Vt2 of 468.8 V. The touch voltage with the variant grid potential modeling is shown below for all 2D spots and 3D spots in Figs. 6 and 7, respectively.

The touch voltage results did not satisfy the grid safety requirements, and a large touch voltage value was found at the

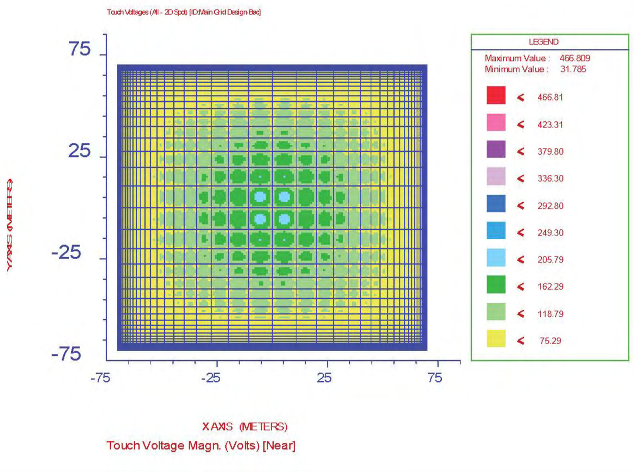

FIGURE 8. **Touch voltage (all-2D spots) with backfilling.**

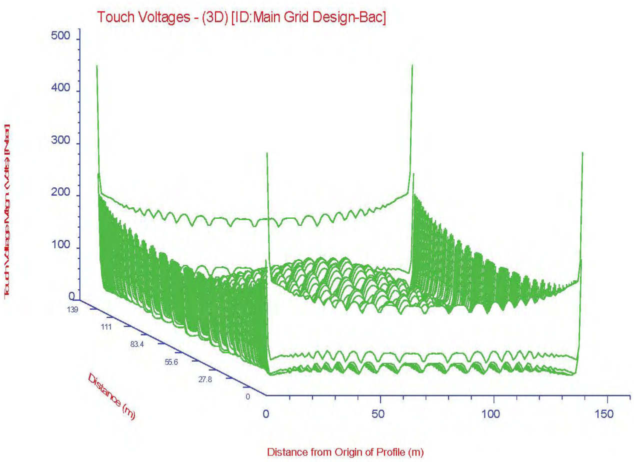

FIGURE 9. **Touch voltage (all-3D spots) with backfilling.**

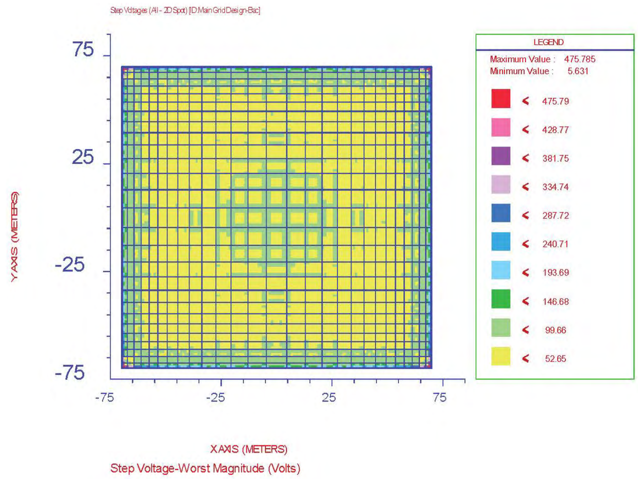

FIGURE 10. **Step voltage (all-2D spots) without backfilling.**

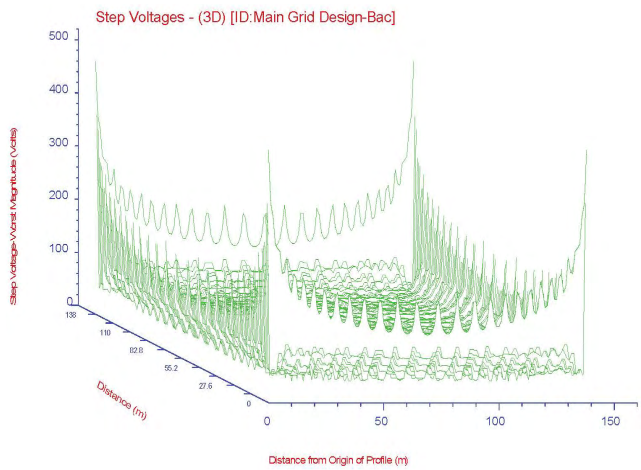

FIGURE 11. **Step voltage (all-3D spots) without backfilling.**

grid periphery, which was addressed by backfilling soil in the high-resistance plot areas. The first, second and asphalt layers have resistivities of 62.4 ohms, 123.59 ohms and 3000 ohms, respectively.

A total of 28 pure copper steel clad rods with diameters of 19 mm were buried at a vertical depth of 3.6 m. After placement of the rods, the touch voltage was calculated by using (2). The calculated touch voltage Vt1 of 466.8 V was less than the permissible touch voltage Vt2 of 468.8 V. The touch voltage obtained by variant grid potential modeling for backfilling with a low-resistivity soil is shown for all 2D spots and 3D spots in Figs. 8 and 9, respectively.

The first, second and asphalt layers have resistivities of 66.47 ohms, 370 ohms and 3000 ohms, respectively. A total of 28 pure copper steel clad rods with diameters of 19 mm were buried at a vertical burial depth of 3.6 m. After placement of the rods, the step voltage was calculated by using (3). The calculated step voltage Vs1 of 585.64 V was greater than the permissible touch voltage Vs2 of 500 V. The step voltage obtained by variant grid potential modeling is shown for all 2D spots and 3D spots in Figs. 10 and 11, respectively.

The step voltage results did not satisfy the grid safety requirements, and a large touch voltage value was found at the grid periphery, which was addressed by backfilling soil in the high-resistance plot areas. The first, second and asphalt layers have resistivities of 62.4, 123.59 and 3000 ohms, respectively.

A total of 28 pure copper steel clad rods with diameters of 19 mm were buried at a vertical burial depth of 3.6 m. After placement of rods, the step voltage was calculated by using (3). The calculated step voltage Vs1 of 475.78 V was less than the permissible touch voltage Vs2 of 500 V. The step voltage obtained by variant grid potential modeling for backfilling with a low-resistivity soil is shown for all 2D spots and 3D spots in Figs. 12 and 13, respectively.

GPR should be restricted as much as possible to safeguard microprocessor-based equipment and communication equipment [4].

The proposed grid has a grid spacing of 3 m, which gradually decreases at the mesh periphery. A total of 28 grounding

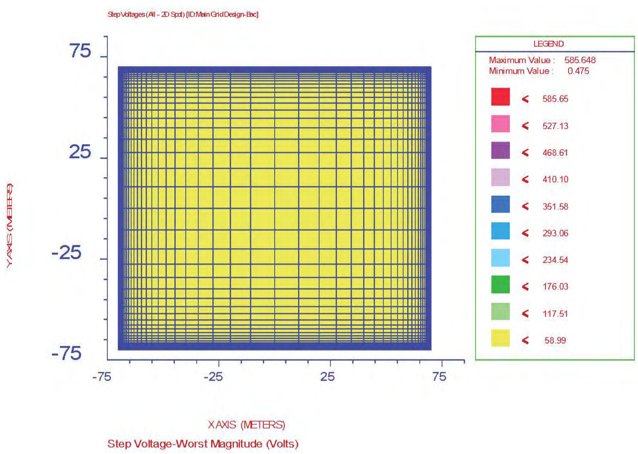

FIGURE 12. Step voltage (all-2D spots) with backfilling.

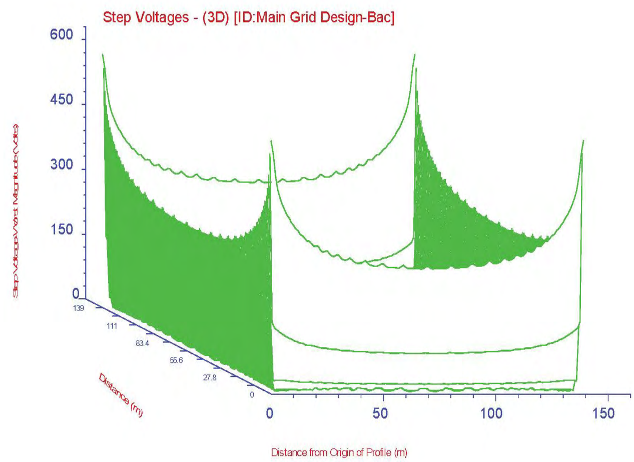

FIGURE 13. Step voltage (all-3D spots) with backfilling.

rods were used at different locations, with each rod having a length of 3.6 m and a diameter of 1.9 cm. Table 2 shows the grid grounding design comparisons for multilayer soil resistivity, touch voltage, step voltage, grid resistance, total buried length of conductor and ground potential rise before and after soil filling.

Safe and permissible design requirements have been obtained. All equipment with a metallic body should be connected with compressed thermo weld lugs, and ground rods for power transformers, auxiliary transformers, lightning masts, surge arresters, etc. should be added to complete the grid design details.

Comparative results for the final values from CDEGS are summarized in Table 3.

Grounding rods were fixed per the grid ancillary equipment. The grounding grid spacing was decreased at the grid periphery, and the length of the buried conductors was increased to lower grid resistance by 64%. As a result, the increase in buried length was constrained to achieve safe grid substation and restricted increase in cost. The desired effective grounding details of the rods used are listed in Table 4.

TABLE 3. Comparison of grounding grid design final parameters.

Sr#	Parameters	Values Without Backfilling	Values With Backfilling
1	Soil resistivity layer #01 (ohm-m)	Infinity	Infinity
2	Soil resistivity layer #02 (ohm-m)	66.47	62.4
3	Soil resistivity layer #03 (ohm-m)	370.42	123.59
4	Touch Voltage (V)	470.34	466.8
5	Step Voltage (V)	475.78	585.64
6	Grid Resistance (ohm)	0.97	0.75
7	Total Buried Electrode (m)	8500	13261
8	GPR (V)	27279	21132

TABLE 4. Details of rods for grid grounding.

Sr#	Parameters	Quantity Without Backfilling	Quantity With Backfilling
1	Rods for Main Grid	28	28
2	Rods for Power Transformer	18	18
3	Rods For Auxiliary Transformer	02	02
4	Rods For Surge Arrestor & Capacitor bank	12	12
5	Rods For Test Pits	12	12
6	Rods For Lightening Mast	3	3
7	Rods For Building	6	6

In Table 4, the rods for the grid grounding have been kept the same before and after backfilling from the simulation of the backfilling soil. The new soil results showed that rods had not increased from the old soil. Thus, the cost has been restricted to avoid the increase in the rods.

IV. CONCLUSION

In this paper, we investigated an effective grid grounding technique. Based on the available land for the allocated 132-KV substation, the soil resistivity was high enough to increase the ground potential. Due to an abnormal increase in the voltage gradient, the functionality of telecom and other control devices is expected to be compromised. Furthermore, the grid potential rise could be reduced by treating the high-resistivity soil patches.

Backfilling with low-resistivity material and appropriately positioning ground rods can minimize the possible risk of shock for grid equipment and personnel. Furthermore, burying conductors at an adequate depth and properly grounding electric equipment with neutral point grounding protects costly equipment and ensures the safety of personnel.

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