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Research Article

Comprehensive Analysis of Grounding System in High Voltage Substation Using Soil Investigation Report

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***Abstract*— This study focuses on the design and analysis of grounding systems in high voltage substation. Thus, it aims to contribute to the development of safer and techno-economic design of grounding systems. In the study, the ground survey report data conducted at the transformer center site, which is a high voltage substation belonging to the Turkish Electricity Transmission Company (TEIAS), and the soil specific resistance data measured with the Wenner and Schlumberger methods at the same site were obtained. These data were used in the Current Distribution Electromagnetic Field Grounding Ground Structure Analysis Software (CDEGS) with analytical calculations described in the Guide for Safety in AC Substation Grounding (IEEE Std 80-2013). In addition, ground impedance, step and touch voltages were measured at the installed substation using the Fall of Potential Method (FPM) specified in IEEE Std 80-2013 standard. These measured values were compared with the analytical calculations and CDEGS software analysis results and a comprehensive evaluation was made. As a result, by examining geophysical data in the design of grounding systems, the soil structure can be determined close to the real situation by using programs that can analyze soil resistivity data measured by different methods. When the grounding impedances calculated, obtained with the CDEGS program and measured in the field were examined separately, it was found that the grounding impedance obtained with the CDEGS program was closer to the grounding impedance measured in the field.**

Index Terms— **CDEGS software, ground impedance, soil resistivity, ground potential rise, touch voltage and step voltage.**

I. INTRODUCTION

Grounding systems are of great importance for the safety of high voltage substations that play a critical role in power transmission and distribution. Grounding systems prevent over voltages from damaging people and equipment in fault conditions [1]. The main functions of grounding systems are to ensure safety, protect equipment, provide a reference point for electrical systems and safely route fault currents. There are various types of grounding in high voltage substation; these are direct, resistive, inductive and mixed grounding systems. Each type of grounding is determined by different protection needs [2]. The design of grounding systems is based on factors such as the soil resistivity, the arrangement of the electrodes, the sizing of the system and the choice of materials [3]. Low soil resistivity provides more effective protection, and the appropriate electrode arrangement distributes the current evenly. Material selection is based on corrosion resistance and conductivity. These are important design considerations that increase the safety and longevity of substation [4].

Soil resistivity is the resistance of soil to electric current and is a critical parameter for determining the effectiveness of grounding systems [5]. Soil resistivity varies depending on factors such as soil type, moisture, temperature and mineral content. Therefore, soil resistance plays an important role in the design of high voltage substation and its accurate measurement is vital for system safety [6]. Wenner and Schlumberger methods are generally used as soil resistivity measurement methods. Wenner method is a measurement technique using four electrodes. The electrodes are equally spaced and two electrodes are used for current measurement and the other two for voltage measurement [6, 7]. In this method, electrode placement and soil conditions affect the measurement accuracy [8]. The Schlumberger method is a widely used method for geophysical measurements. The electrode arrangement allows measurements at different depths. Current and voltage electrodes are placed at certain distances and soil resistivity is calculated. It gives precise results for groundwater and mineral exploration [9].The standards set by IEC and IEEE are widely used worldwide for the design of grounding systems in low and high voltage substation [10]. IEC standards cover a wide range from low voltage substation to electromagnetic compatibility, while IEEE standards provide detailed guidance specifically for high voltage systems [11, 12].Detailed analysis and optimization of grounding systems are necessary for safe and efficient operation of high voltage facilities [13, 14]. Computer aided grounding analysis software are modern engineering methods used to optimize the performance of grounding systems in high voltage substation [15].While design and analysis by traditional methods can be time-consuming in large-scale substation, computer-aided analysis speeds up these processes and provides more accurate results [16]. Therefore, computer-aided analysis software is nowadays used as effective tools in the design and evaluation processes of grounding systems.

The Fall of Potential Method (FPM) is a common and effective technique for measuring the ground impedance. It is used to determine the impedance of the electrical connection of the grounding system to ground. In this method, a current is applied to the grounding system under test and the voltage drop caused by this current is measured. Measured data is used to calculate the ground impedance [17].The use of geophysical data in the design of grounding systems in high voltage substations supports the determination of soil layers and layer thicknesses.

By using soil resistivity measured at different depths and with different methods and programs that can analyze these data together, soil structure can be determined close to the real

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situation.Using the soil resistivity values measured by Wenner and Schlumberger methods and based on the geophysical cross-sectional information obtained from the drilling, a five-layer soil profile was designed using CDEGS software to determine the most appropriate design reflecting the actual condition of the site.

When the grounding impedances calculated, obtained with the CDEGS program and measured in the field are examined separately, it is seen that the grounding impedance obtained with the CDEGS program is closer to the grounding impedance measured in the field.

II. MATERIALS AND METHODS

The following process steps were carried out in the high voltage substation where the study was carried out. Firstly, soil resistivity measurements are made from the natural ground surface in accordance with the grounding system specification regulated by TEIAS according to IEC, IEEE and TSE standards. These measurements include soil resistivity measurement at the natural ground elevation by Schlumberger method and determination of the soil layer thickness of the ground by drilling. Secondly, soil resistivity was measured with the Wenner method at the ground level where the Substation will be constructed. Finally, when the high voltage substation was completed, ground impedance, step and touch voltages were measured by FPM method.

A. Soil Resistivity Measurements

During the initial project design phase, drilling was carried out at four different points within the scope of ground investigation studies. Soil resistivity measurements were carried out with the Schlumberger method at a span of 120 meters along three lines, 22 in each line and 66 points in total. After the ground leveling operations were carried out, soil resistivity measurements were made at the ground elevation where the net would be placed, at a span of 60 meters on four lines, 14 in each and 56 points in total with the Wenner method.

Figure 1 shows the general layout of the high voltage substation. The lines shown in red A, B and C are soil resistivity points measured by Schlumberger method, the lines shown in blue A, B, C and D are soil resistivity points measured by Wenner method and the points shown in green A, B and C are drilling locations.

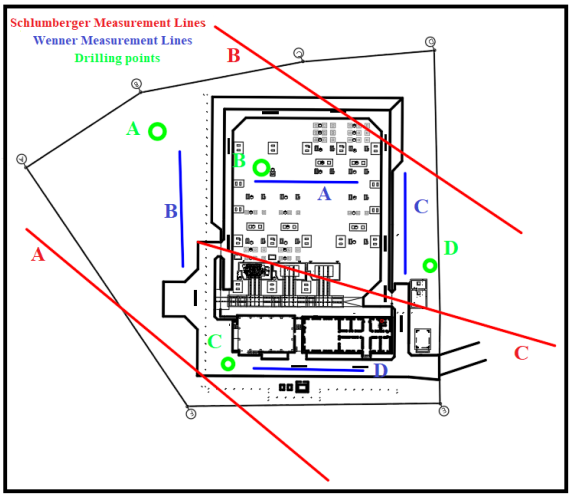


Fig.1. Soil resistivity test lines and drilling points on the general layout plan

The data obtained as a result of soil resistivity measurements are given in Table I and Table II.

Table I. Soil resistivity values measured by schlumberger method

Measured No	Distance Between Electrodes (m)	1st Measured Line (Ω·m)	2nd Measured Line (Ω·m)	3rd Measured Line (Ω·m)
1	3	47.41	51.5	68.55
2	4	54.28	50.74	68.83
3	5	68.62	48.88	70.50
4	6	77.00	49.50	73.33
5	8	96.52	56.10	69.30
6	10	120.59	64.83	72.91
7	12	134.40	70.93	72.80
8	14	155.55	82.62	68.85
9	16	173.33	88.00	76.66
10	18	190.50	94.34	79.37
11	20	192.50	102.60	83.68
12	24	210.83	119.16	89.83
13	30	235.00	139.20	101.50
14	36	238.45	155.62	115.45
15	42	234.38	171.50	117.19
16	50	219.60	184.74	128.00
17	60	176.00	206.17	137.28
18	70	159.83	211.00	136.65
19	80	150.76	206.74	137.83
20	90	156.62	206.31	132.25
21	100	148.96	192.73	127.40
22	120	135.55	165.00	110.31

Table II. Soil resistivity values measured by wenner method

Measured No	Distance Between Electrodes (m)	1st Measured Line (Ωm)	2nd Measured Line (Ωm)	3rd Measured Line (Ωm)	4th Measured Line (Ωm)
1	1	47.9	58	180.2	46.7
2	6	66	58.7	83.7	57.8
3	9	95.6	65.5	92.1	67.1
4	12	114.9	74.8	95.7	95.6
5	15	129.5	86.8	90.6	112.7
6	18	143.6	97.5	112.8	90.5
7	21	141.1	101.3	105.7	93.4
8	24	144.5	104.7	117.8	105.8
9	30	117.5	105.9	132.3	146.1
10	36	106.1	110.6	141.9	135.2
11	42	113.2	110.1	147.8	138.4
12	48	110	115	146.1	158.2
13	54	98.1	95.5	157.9	162
14	60	101.1	120.3	163.4	167.4

B. Design of Grounding System with Analytical Methods

While designing the grounding system, the parameters specified in Table III were used, taking into account the criteria of TEIAS grounding specification and electrical facilities grounding regulation. In analytical calculations, calculations were performed using the equations defined in IEEE Std 80-2013 standard. The soil resistivity value was taken as 115 Ω·m by taking the average of the values given in Table I measured by Wenner method.

The grounding system is designed as a ground grid system of horizontal grids and vertical rod electrodes as specified in IEEE Std 80-2013. The following analytical methods are used to calculate the ground impedance, step and touch voltage respectively.

Table III. Grounding design parameters

Symbol	Values		Description
I_G	20	kA	Short Circuit Current
$A_{MİN}$	120	mm²	Conductor cross-sectional
ρ	115.00	Ωm	Soil resistivity
h	0.65	m	Depth of grid conductors
ρ_s	2500	Ωm	Surface material resistivity
h_s	0.15	m	Thickness of the surface material
A	9078	m²	Area of the Grid
W_M	70	kg	Human weight
a	0.00618	m	Conductor radius
b	0.011	m	Rods radius
L_c	5677	m	Total length of grid conductor
L_x	102	m	length of conductor in X-Axis
L_y	89	m	length of conductor in Y-Axis
L_R	67.5	m	Total length of Ground Rods
h_o	1	m	Reference depth of the Grid
D	3	m	Spacing between parallel conductors
t_s	0,5	s	Duration of Earth Fault Current
K_1	1.364157		Coefficients of Schwarz equations
K_2	5.671910		Coefficients of Schwarz equations
C_s	0.779846		Dreading factor
K_m	0.372510		Spacing factor
K_i	5.048041		Correction factor
K_s	0.438165		Spacing factor for step voltage

1) Calculation of Grounding Impedance

To determine the impedance of the grounding system, the equations described in the IEEE Std 80-2013 standard and developed by Schwarz are used. The grounding impedance R_g is calculated using (1).

$$R_g = \frac{\rho}{\pi.L_C}\left[\mathrm{Ln}\left(\frac{2\cdot L_C}{a'}\right) + \frac{K_1\cdot L_C}{\sqrt{A}} - K_2\right] \quad (1)$$

2) Calculation of Allowable Step and Touch Voltage

The dreading factor refers to the transition resistance caused by the foot contact of the personnel in the field with the ground and is calculated using (2). The surface layer dreading factor depends on the resistivity of the soil, the type and thickness of the surface material. Calculations were made based on the critical current value for a human weighing 70 kg as defined in IEEE Std 80- 2013. The allowable step voltage limit value E_{Smax} and the allowable touch voltage limit value E_{Mmax} are calculated using (3) and (4) respectively.

$$C_s = 1 - \frac{0{,}09\left(1-\frac{\rho}{\rho_s}\right)}{2.h_s+0{,}09} \quad (2)$$

$$E_{Smax} = (1000 + 1{,}5C_s.\rho_s)\frac{0.157}{\sqrt{t_s}} \quad (3)$$

$$E_{Mmax} = (1000 + 6C_s.\rho_s)\frac{0.157}{\sqrt{t_s}} \quad (4)$$

3) Calculation of Maximum Touch Voltage

As stated in IEEE Std 83-2013, the maximum touch voltage to be encountered in the grounding grid will occur at the center of the corner mesh. For the mesh voltage calculation, the Spacing factor K_m and the correction factor for grid geometry K_i depending on the geometrical configuration of the grid are used. The touch voltage E_m is calculated using (5).

$$E_m = \frac{\rho.I_G.K_m.K_i}{L_C + \left[1{,}55+1{,}22\left(\frac{L_r}{\sqrt{L_x^2+L_y^2}}\right)\right]\cdot L_R} \quad (5)$$

For the mesh voltage, the spacing factor K_m, which depends on the geometric configuration of the grid, is calculated using (6).

$$K_m = \frac{1}{2\pi}\left(\ln\left(\frac{D^2}{16.h.d} + \frac{(D+2.h)^2}{8.D.d} - \frac{h}{4.d}\right) + \frac{K_{ii}}{K_h}\ln\left(\frac{8}{\pi(2.n-1)}\right)\right) \quad (6)$$

For the mesh voltage, the correction factor K_i, which depends on the geometric configuration of the grid, is calculated using (7).

$$K_i = 0{,}644 + 0{,}148n \quad (7)$$

4) Maximum Step Voltage Calculation

The maximum level of step voltage to be encountered in the grounding grid will occur at the corner points of the grid and at steps of one meter outward from the inner fenestration. The maximum step voltage is calculated using (8).

$$E_s = \frac{\rho.I_G.K_s.K_i}{0{,}75.L_c+0{,}85.L_R} \quad (8)$$

For the maxsimum step voltage, the spacing factor K_s, is calculated using (9).

$$K_s = \frac{1}{\pi}\left[\frac{1}{2.h} + \frac{1}{D+h} + \frac{1}{D}(1-0.5^{n-2})\right] \quad (9)$$

C. Computer Aided Grounding System Design

In this section, the grounding system of the high voltage substations is designed in accordance with the limit values defined by the IEEE Std 80-2013 standard and the criteria of the Turkish Electricity Transmission Inc. Grounding System Specification and Grounding Regulation for Electrical Substation. The CDEGS (Current Distribution, Electromagnetic Fields, Grounding and Oil Structure Analysis) software used in this study is a software tool that identifies, supports and enhances grounding, electromagnetic interference, electromagnetic fields and transients. RESAP and MALZ modules of CDEGS were used.The RESAP (Soil Resistivity Analysis) computation module is used to determine equivalent earth structure models based on measured soil resistivity data.The MALZ (Frequency Domain Grounding Analysis) computation module is used to performance of buried conductor grid. In the following, soil resistivity, ground impedance, step and touch voltage analyses are given respectively using CDEGS software.Figure 2 shows the grounding gird image of the high voltage substation in the CDEGS software environment.

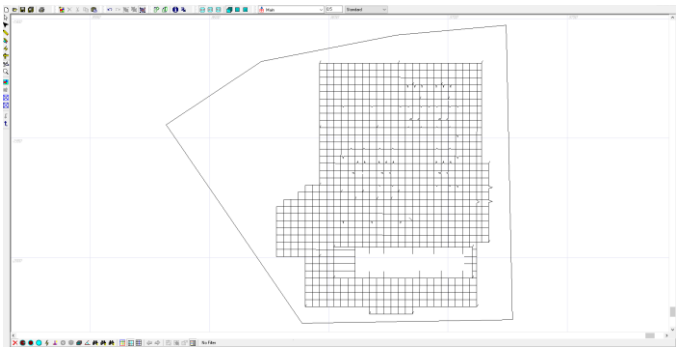


Fig.2. The grounding grid in CDEGS software environment

1) Analysis of Soil Resistivity

Instead of considering the soil resistivity only as an average value, it should be taken into consideration that the soil structure consists of layers and the layers have different resistivity values.

Figure 3 shows the soil resistivity data measured by Wenner and Schlumberger methods in CDEGS software and Figure 3 includes the soil resistivity listed in Table 1 and Table 2 on the x-axis and the soil model depth on the y-axis.

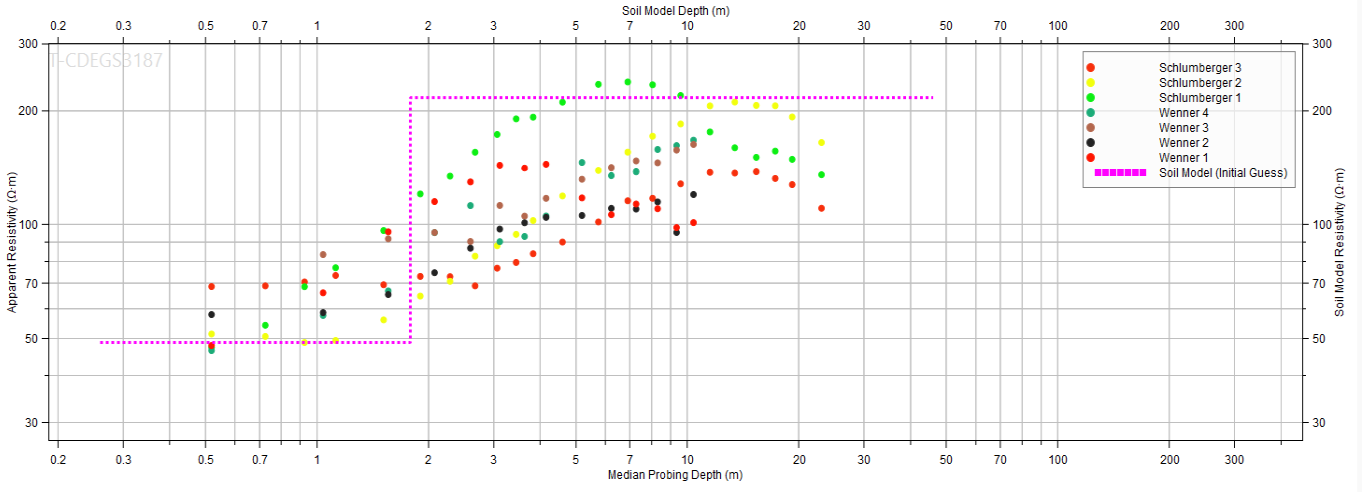


Fig.3. CDEGS software image of soil specific resistivity data measured by Wenner and Schlumberger method

In order to model the soil structure in CDEGS software in the most realistic way, soil specific resistivity values measured by Wenner and Schlumberger methods were analyzed with different number of layers. The data of these results are given in Table 4.

With CDEGS software, soil specific resistivity measurements are used to design a curve passing through these measurement points. In this curve design, the margin of error is expected to be low. A low margin of error in the designed curve is a value indicating the accuracy of the design.

Various soil profiles were created in CDEGS software by assuming different layer numbers. The grounding impedances calculated using these profiles are given in the Table 4.

Table IV.Soil profiles calculated with different number of layers and specific resistivity results

	Designed curve error (%)	1. Soil resistivity of layer	1. Soil thickness of layer	2. Soil resistivity of layer	2. Soil thickness of layer	3. Soil resistivity of layer	3. Soil thickness of layer	4. Soil resistivity of layer	4. Soil thickness of layer	5. Soil resistivity of layer	Calculated grounding impedance
CDEGS analysis using Wenner measurements	15.86	46.014	1.552	162.681	4.623	117.023					0.586
CDEGS analysis using Wenner and Schulumberg measurements	21.55	51.634	2.1873	156.68	21.202	134.8					0.606
CDEGS analysis using Wenner and Schulumberg measurements	21.52	47.51	1.26	92.59	2.74	171.79	11.76	137.38			0.6
CDEGS analysis using Wenner and Schulumberg measurements considering geophysical section and drilling data	16.91	44.42	1.45	177.01	3.31	72.35	5.77	362.88	16.33	32.45	0.457

The layer thicknesses, number of layers and specific resistances of the layers were determined more clearly with the approach that the soil specific resistivity data measured by the Wenner method covers the sections close to the surface and the soil resistivity data measured by the Schlumberger method covers the deeper sections. In order to determine the soil structure and layers, Figure 4 in the soil investigation report commissioned by TEIAS for the substation project was used.

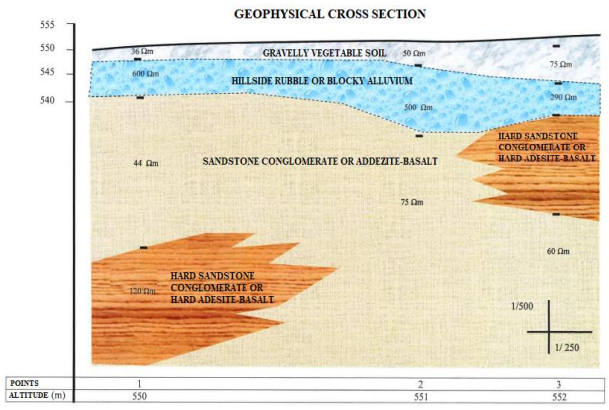


Fig.4. Geophysical cross section

Figure 5 shows the five-layer soil structure designed using soil resistivity in the RESAP module of the CDEGS software. The RESAP module designs a curve using the soil resistivity. This curve passes over the soil resistivity values with the closest accuracy according to the number of layers. The RESAP module calculates the layer thicknesses and the soil resistivity of each layer according to the number of layers selected.

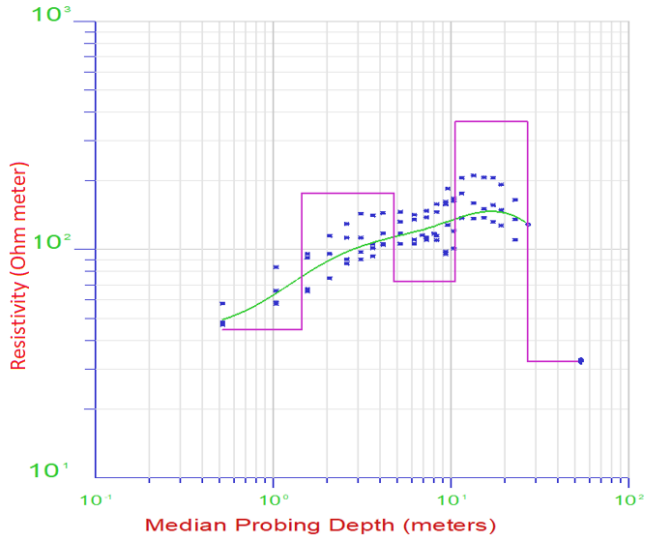


Fig.5. Five-layer soil structure designed in CDEGS software

Figure 6 shows the soil resistivity values and soil layer thicknesses calculated for the five-layer soil structure in the RESAP module of the CDEGS software. The designed curve passes over the measured soil resistivity values with an accuracy of 16.91%.

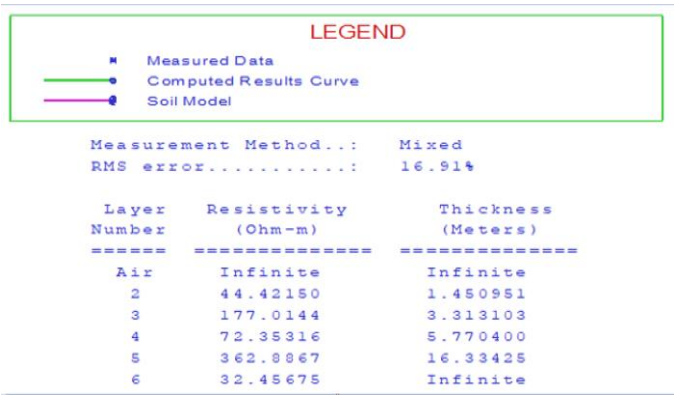


Fig.6. Soil resistivity values and soil layer thicknesses calculated in CDEGS software

2) Analysis of Step and Touch Voltage with CDEGS Software

For the analysis of the touch voltage, sampling points were placed at 0.5 m intervals around the perimeter of each point of inner and outer the fence and sections of the grid including the grounding conductors and stakes shown in Figure 2. As a result of the analysis, the highest value of the touch voltage was found to be 1312.56 V. In the analysis, the highest acceptable value of the touch voltage was found to be 872.708 V according to IEEE Std 80-2013 standard.

The sections where the touch voltage exceeds the limit values are the corner points of the grid, the sections where the fence is close to the grounding grid and the far corner points of the fence. Figure 7 shows a screenshot of the touch voltage analysis results with CDEGS software. In the color scale in Figure 7, there is a voltage upper limit for each color. The touch voltage in each part of the substation is shown with the color scale.

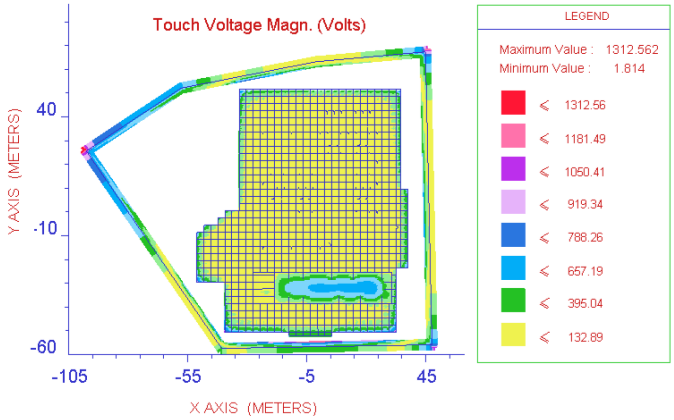


Fig.7. CDEGS software touch voltage analysis result

Figure 8 shows a screenshot of the touch voltage 3D analysis results with CDEGS software. The touch voltage at each point in the substation is shown on a rising scale from blue to red. 3D image was created with the points determined on the z-axis in proportion to the touch voltage.

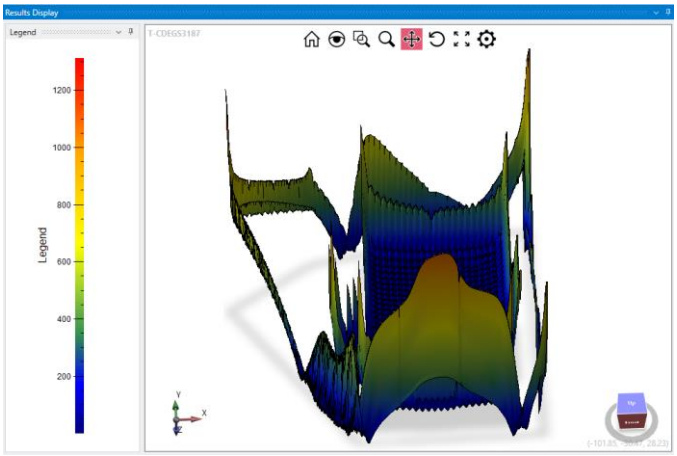


Fig.8. CDEGS software touch voltage 3D analysis

Sampling points were established around the perimeter of the grid and one meter out from the fence and step voltages were obtained in detail. As a result of the computer analysis, the highest value of the step voltage was found to be 722.82 V. The highest acceptable value of the step voltage is calculated as 2844.979 V according to IEEE Std 80-2013 standard. Figure 9 shows a screenshot of the step voltage analysis results with CDEGS software. In the color scale in Figure 9, there is a voltage upper limit for each color. The step voltage in each part of the substation is shown with the color scale. As can be seen from the figure, the highest step voltage is at the corner points of the grounding grid. There is no section where the step voltage exceeds the threshold value.

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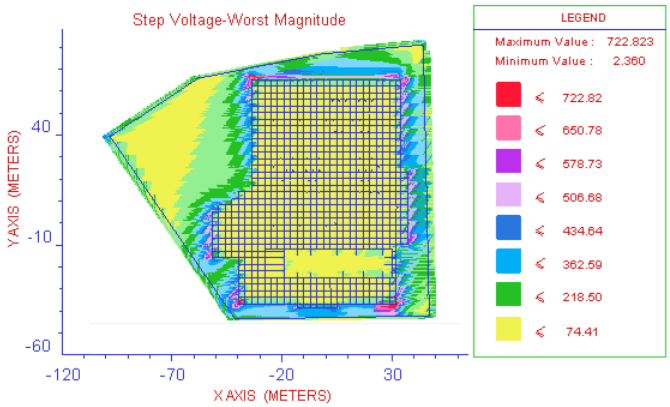


Fig.9. CDEGS software step voltage analysis result

Figure 10 shows a screenshot of the step voltage 3D analysis results with CDEGS software. The step voltage at each point in the substation is shown on a rising scale from blue to red. 3D image was created with the points determined on the z-axis in proportion to the step voltage.

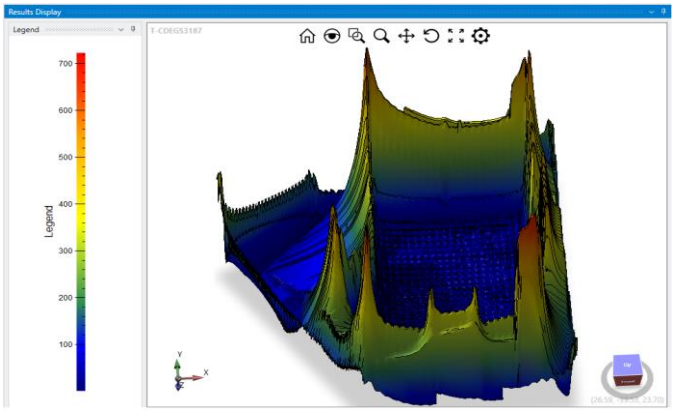


Fig.10. CDEGS software step voltage 3D analysis

The voltage values at 134316 points within 500 meters of the high voltage substation were analyzed and a ground potential rise map was created accordingly. Figure 11 shows a screenshot of the ground potential rise map analyzed with CDEGS software. The color scale in Figure 11 has a voltage upper limit for each color. The ground potential rise in the area within 500 meters of the substation is shown with the color scale. With the help of this map, the possible electrical effects of the high voltage substation on the surrounding structures have been checked and it is seen that safe working conditions are provided.

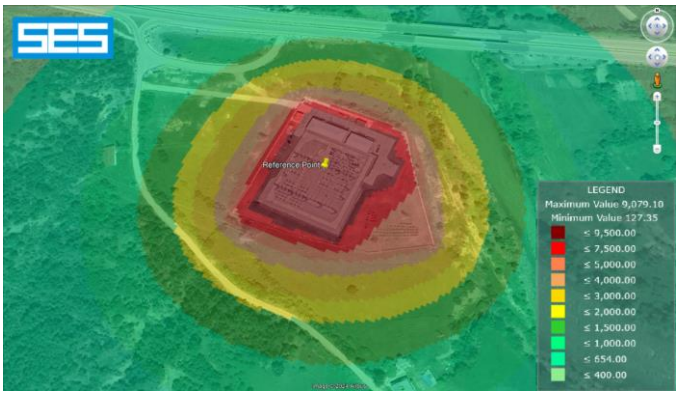


Fig.11. Ground potential rise map with CDEGS software

Comparison of analytical calculations and CDEGS analysis results are given in Table V.

Table V. Comparison of analytical calculations and CDEGS analysis results

	CDEGS Analysis	Analytical Calculations
Grounding Resistance (Ω)	0.457	0.5633
Allowable Step Voltage (V)	2844.979	2819.29
Maximum Step Voltage (V)	772.82	1178.95
Allowable Touch Voltage (V)	872.208	871.35
Maximum Touch Voltage (V)	1312.56	747.84

D. Impedance Measurement of the Grounding System

Within the scope of the designed grounding grid, all calculations and design works for the grounding system of the high voltage substation were completed and the construction of the substation was realized in accordance with the project criteria. The grounding grid has been carefully laid and the installation of all components has been completed to ensure safe and effective operation of the substation. After this stage, the FPM method specified in the IEEE Std 80-2013 standard was used to verify the functionality of the grounding system and its compliance with safety standards. Figure 12 shows a schematic representation of the ground impedance measurement with the FPM method.

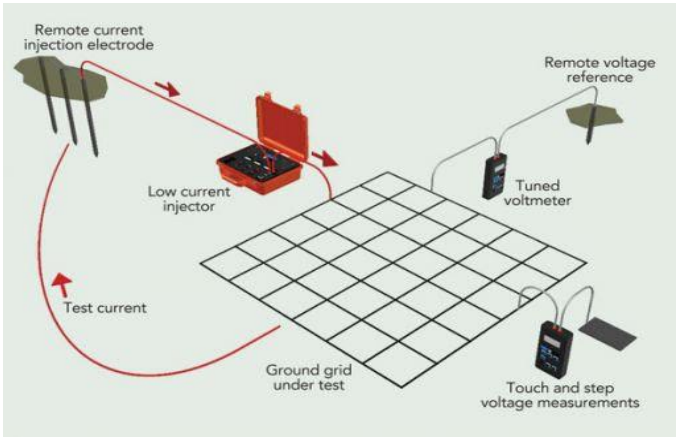


Fig.12. Grounding impedance measurement scheme

To measure the grounding impedance of this system, a current of 12 A was circulated between a remote current electrode and the grounding grid as shown in Figure 12. Current electrodes were placed at a distance of 800 m, which is more than five times the 136 m diagonal length of the grounding grid. The measured voltage values were used in equations 10 and 11 to calculate the impedance values corresponding to the distance d.

$$V_g = \sqrt{\frac{(V_1^2+V_2^2)}{2} - V_b^2} \quad (10)$$

$$Z = \frac{V_g}{I} \quad (11)$$

Explanations of the abbreviations used in the equations are given below,

V_g Calculated voltage
V_1 Voltage measured at polarity 1
V_2 Voltage measured at polarity 2
V_b Voltage measured at unenergized
d Distance between grounding grid and current electrodes
Z d distance dependent measured impedance
U Test voltage
I Test current circulating between the grounding grid and current electrodes

III. FINDINGS AND DISCUSSION

The impedance values calculated from the voltage values obtained using the FPM method specified in the IEEE Std 80-2013 standard are given in Table VI.

Table VI. Grounding impedance measured results

Distance (m)	Test Current	Unenergized Measured Voltage	Measured Voltages			Calculated
	Current (A)	V_b (V)	V_1 (V)	V_2 (V)	V_g (V)	Z (Impedance)
25	12.40	0.050	5.010	5.010	5.01	0.400
50	12.50	0.061	5.035	5.035	5.03	0.403
75	12.10	0.085	5.035	5.035	5.03	0.416
100	12.30	0.090	5.008	5.048	5.05	0.410
150	12.30	0.092	5.068	5.068	5.07	0.412
200	12.30	0.094	5.064	5.064	5.06	0.412
250	12.30	0.088	5.067	5.067	5.07	0.412
300	12.30	0.075	5.065	5.065	5.06	0.412
350	12.20	0.075	5.068	5.068	5.07	0.415
400	12.40	0.076	5.073	5.073	5.07	0.409
450	12.40	0.081	5.075	5.075	5.07	0.409
496	**12.30**	**0.081**	**5.081**	**5.085**	**5.08**	**0.413**
550	12.20	0.084	6.035	6.035	6.03	0.495
600	12.50	0.089	7.082	7.086	7.08	0.567
650	12.50	0.094	7.490	7.510	7.50	0.600
700	12.30	0.096	7.510	7.510	7.51	0.611
750	12.30	0.098	7.511	7.512	7.51	0.611
800	12.80	0.116	8.760	8.770	8.76	0,684

The graph created with the calculated impedances is given in Figure 13.When the curve is examined, as the voltage electrode is removed from the grounding grid, a rapid increase is observed in the impedances measured after a certain distance. The value measured at the point where this increase starts is considered as the grounding impedance of the substation. With the assumption of a spherical electrode system, the value taken at 62% of the distance where the current electrodes are located is very close to the point where the rise begins in the graph and is approximately the same as the value determined. This shows that an accurate impedance measurement was made. As a result of the field measurements, the grounding impedance of the substation was measured as 0.413 ohm.

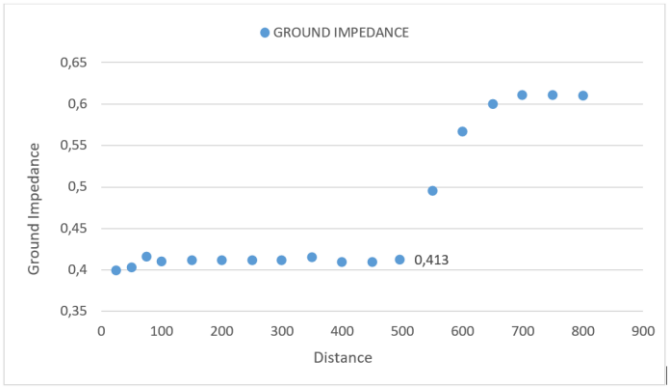


Fig.13. Impedance values corresponding to distance d

A 25 cm thick gravel model with a resistivity of 2500 Ωm was added to the top layer of the soil and field measurement points were matched with the step and touch voltage analysis performed in the CDEGS software.

A 25 cm thick gravel model with a resistivity of 2500 Ωm was added to the top layer of the soil. Analyses were performed in CDEGS software with the designed grounding structure. Field measurement points were matched with the step and touch voltage analysis. The five-layer soil with gravel added with CDEGS software is given in Figure 14.

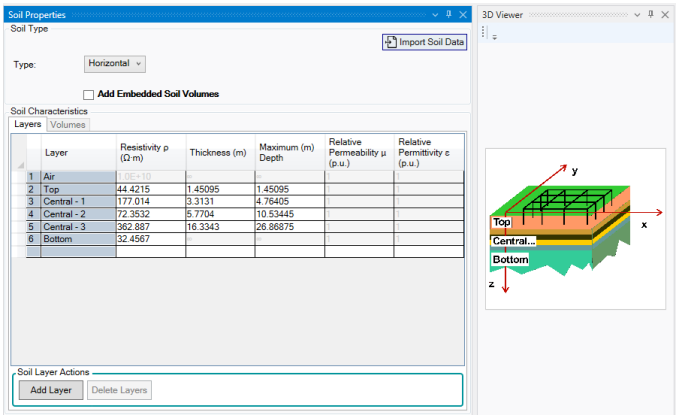


Fig.14. Layers and layer thicknesses of the five-layer soil structure to which gravel was added with CDEGS software

Touch voltages were measured on the equipment in the field with the test setup used for grounding impedance. The short circuit current value that will occur at the time of failure is taken as 20 kA and the values measured in the field are calculated to the voltage values that will occur at the time of failure. The values obtained are given in Table VII.

Table VII. Touch voltage measurement results

Touch Voltage Measurement Points	Measured Voltage (V)	Test Current (A)	Touch Voltage (V)	CDEGS Touch Voltage (V)
A Phase Surge Arrester	0.028	12.3	45.53	35.24
B Phase Surge Arrester	0.027	12.3	43.90	47.42
Circuit Breaker	0.006	12.3	9.76	38.89
Bus 1 Disconnector	0.045	12.3	73.17	61.13
A Current Transformer	0.020	12.3	32.52	41.22
B Current Transformer	0.020	12.3	32.52	46.29
Circuit Breaker	0.010	12.3	16.26	48.82
Field Distribution Box	0.008	12.3	13.01	33.62
C Current Transformer	0.011	12.3	17.89	46.32
Bus 2 Disconnector	0.010	12.3	16.26	38.23
C Phase surge Arrester	0.018	12.3	29.27	56.12
Bus 1	0.013	12.3	21.14	36.24
C Phase Circuit Breaker	0.008	12.3	13.01	47.42
Line Current Transformer	0.001	12.3	16.63	40.17
Transfer Disconnector	0.001	12.3	16.63	40.17
A Phase Line Breaker	0.010	12.3	16.26	43.82
Line Current Transformer	0.011	12.3	17.89	36.52
Line Voltage Transformer	0.011	12.3	17.89	57.42
Bus 2	0.038	12.3	61.79	62.07

Table VII shows that the touch voltages measured at various points of the site match the touch voltage analysis obtained with CDEGS. The step voltage values measured in the field between the transformer platform and the control building are given in Table VIII.

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Table VIII. Step voltage measured results

Distance between transformer and control building	Measured Voltage (V)	Test Current (A)	Step Voltage (V)	CDEGS Step Voltage (V)
1-2 m	0.005	12.3	7.882	48.81
2-3 m	0.002	12.3	2.816	48.81
3-4 m	0.002	12.3	3.636	57.79
4-5 m	0.004	12.3	6.504	57.79

The step voltages between the inner fence and the outer fence measured in the field are given in Table IX.

Table IX. Step voltage measured results

Distance between inner the fence and outer the fence	Measured Voltage (V)	Test Current (A)	Step Voltage (V)	CDEGS Step Voltage (V)
1-2 m	0.002	12.3	2.816	80.5
2-3 m	0.002	12.3	2.816	60.41
3-4 m	0.002	12.3	3.003	41.2
4-5 m	0.003	12.3	5.393	41.2

The step voltages measured between the transformer platform and the control building in Table VIII and between the inner fens and the outer fens in Table IX are compared on the step voltage analysis obtained with CDEGS. The small difference between the compared values is acceptable considering the highest value of the step voltage calculated as 2844.979 V according to IEEE Std 80-2013 standard. This measurement difference is due to the high transition resistance between the metallic disc with a radius of 0.08 m, representing the foot, and the gravel surface, as defined in IEEE Std 80-2013, used for step voltage measurement in the field.

Table X. Comparison of results

	CDEGS Analysis	Analytical Calculations	Field Measurements
Grounding Resistance (Ω)	0.457	0.5633	0.413
Maximum Touch Voltage (V)	1312.56	747.84	73.17
Maximum Step Voltage (V)	772.82	1178.95	7.88

Table X compares the grounding impedance, step and touch voltages calculated by analytical methods, obtained by CDEGS and measured in the field. The maximum touch voltage found in the CDEGS software touch voltage analysis is higher than the maximum touch voltage found by analytical calculation. The maximum step voltage found in the CDEGS software step voltage analysis is lower than the analytically calculated maximum step voltage. The highest step and touch voltages measured in the field are lower than the maximum step and touch voltages found by analytical calculation and the maximum step and touch voltages found by CDEGS analysis.

IV. CONCLUSION

In this study, the grounding system of a high voltage substation is comprehensively analyzed from the design phase to the final control tests after installation.In the geophysical cross section given in the soil investigation report, the soil layer structure, approximate layer thicknesses and resistivity values of the layers are given.

In order to determine the most appropriate design reflecting the soil structure, the number of layers was determined from the geophysical cross-section and used to create the soil profile. Knowing the number of layers facilitated the determination of layer thicknesses and specific resistances of the layers.In the analysis performed by using CDEGS software with the assumption of different layer thicknesses, utilizing the geophysical cross-section with the soil investigation report data enables more accurate soil profiles to be designed.

Using the soil resistivity values measured by Wenner and Schlumberger methods and based on the geophysical cross-sectional information obtained from the drilling, a five-layer soil profile was designed using CDEGS software to determine the most appropriate design reflecting the actual condition of the site. Real soil structure has different resistivity values and different layer thicknesses.

When the grounding impedances calculated, obtained with the CDEGS program and measured in the field are examined separately, it is seen that the grounding impedance obtained with the CDEGS program is closer to the grounding impedance measured in the field.

In the analysis performed with the CDEGS software, the points where the touch voltage is the highest are the corner points of the designed grid structure and the remote sections of the outer fence. The irregularity factor used in the analytical calculations was insufficient to account for the effect of these points. It makes it difficult to calculate the highest allowable touch voltage with analytical methods as it moves away from smooth geometries.

When the step and touch voltages are examined, it is seen that the maximum step and touch voltages calculated with the IEEE Std 80-2013 standard are different from the highest step and touch voltages found in the analysis performed on the CDEGS software. The difference in step and touch voltages are due to the fact that the grid geometry is approximately rectangular in the analytical calculation.

The step and touch voltages measured in the field study are considerably smaller than the highest step and touch voltages calculated analytically during the design phase. This is because the thickness of the ground covering material (gravel) used in the calculations is lower than that of the plant site. When the touch voltage results obtained from the CDEGS software are analyzed, it is seen that the tapping voltage decreases considerably towards the inner parts of the grounding grid and is similar to the field measurements.

In engineering applications, it is expected that the calculated and designed and realized applications are exactly compatible. Designing with high accuracy offers many advantages in grounding system design in terms of cost and safety.

Nowadays, detailed grounding analysis is important for the reliability and techno-economics of the power grid. By using computer-aided software, it is possible to reach the desired design parameters in grounding systems within limits. Thus, the number of nets, the depth of the buried grounding grid, the length of the conductor, the number of piles and the placement points can be obtained more accurately. As a result, designs that will provide optimum benefit with minimum cost can be made in grounding systems using computer-aided software.

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