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# OPTIMAL DESIGN OF GROUNDING SYSTEM FOR HV/EHV SUBSTATION

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## *ABSTRACT*

*Designing grounding systems for high voltage substations has been always considered a serious concern. High losses and costs of performing conventional designs have made researchers think of new substitute plans. The designed system should be able to provide safety for personnel and electrical devices under steady-state operation and transient disturbances. In this paper, a new strategy for designing high voltage substation grounding system is proposed, taking into account relevant IEEE standards. It will be shown that this approach, which is based on Autogrid Pro Grounding Software of SES & Technology Canada, will have more output parameters that makes the model more efficient, so it can be a sufficient replacement for other conventional methods. The simulation is carried out to grounding grid performance indices such as Grounding resistance, Mesh voltage, Step voltage & Grounding Potential Rise. A case study is done at 400/63 kV substation located in center of Iran is analyzed using Autogrid Pro Grounding Software and CymGrd software package.*

***KEYWORDS:*** *Safety, Touch and Step Voltages, Power Substation, Grounding system, Autogrid Pro Grounding Software.*

## I. INTRODUCTION

Passing high currents through the grounding system causes gradients of voltage over the surface of Earth, and as a result, various spots of the network will have differences in voltage level. If these voltages exceed a maximum level, there is possibility that safety of personnel and electrical devices will be endangered by high voltage differences between the steps of person (step voltage), or between a device and Earth.

Designing a grounding system should be such that the maximum voltage probable to happen becomes less than the tolerable voltage for human body.

In this paper, the authors propose the application of new software package, Autogrid Pro Grounding Software of SES & Technology Canada. Autogrid Pro Grounding Software provides a simple, integrated environment for carrying out detailed grounding studies. This package combines the computational powers of the engineering programs RESAP (soil measurements module), MALT (the MALT module is used to analyse power system grounding networks, and is often used to investigate potentials and currents diverted to nearby buried metallic structures) and FCDIST (fault current distribution module) with a simple, largely automated interface [1].

The main advantage of this software is offering a solution to the aforementioned problem, in which the allowable voltage level will vary depending on the devices installed in the network, and so the conductors will be determined based on a more complicated model. In section 2 of this paper, the analysis of soil and grounding resistance based on standard are presented. Consequently, a real case-study- a high voltage substation's grounding system in centre of Iran, has been designed using both

Autogrid Pro Grounding Software and CygmGrd. Results would show how accurate the final model would be in terms of controlling the fault voltages. In section 3 of this paper, modelling and simulation will be determined in four steps. Suggestions for future work and Conclusions are also presented.

## II. SOIL ANALYSIS AND GROUNDING RESISTANCE

Highly non-uniform soil characteristics may be encountered from Wenner Test results of the grounding design region. In such soil conditions, both two layer and multilayer soil models can be used. Multilayer soil models can be used if and only if there does not exist a feasible two-layer equivalent design according to [2]. The two-layer earth is widely used in modern power engineering grounding design (n=2).

RESAP program is designed to calculate the unknown function parameters $\rho_1$, $\rho_2$ and h, in order to obtain the best fit between the theoretical apparent resistivity values and the measured ones. The method used to achieve this goal is called "least Gradient Method". This method is now described:

The earth is characterized by [3]:

$\rho_1$ - Resistivity in upper layer

$\rho_2$ - Resistivity in lower layer

h - Thickness of upper layer.

$\rho(a)$, the theoretical apparent resistivity at spacing "a" as given by equation (1).

$$\rho_a = \rho_1 \left( 1 + \sum_{n=1}^{n=\infty} \frac{k^n}{\left(1 + \left(\frac{2nh}{a}\right)^2\right)^{1/2}} - \frac{k^n}{\left(4 + \left(\frac{2nh}{a}\right)^2\right)^{1/2}} \right) \tag{1}$$

Where:

$k = (\rho_2 - \rho_1)/(\rho_2 + \rho_1)$

$\rho_0(a)$, the apparent resistivity values as measured by the four-probe or Wenner method for a spacing "a".

$$\psi(\rho_1, k, h) = \sum_{1}^{N} \left( \frac{\rho_0(a) - \rho(a)}{\rho_0(a)} \right)^2 \tag{2}$$

Where N is the total number of measured resistivity values.

In order to obtain the best fit, **ñ** must be minimum. In order to do so we will use the least gradient method [2].

$$\frac{\delta\psi}{\delta\rho_1(\text{or h})} = -2\sum_{1}^{N} \left( \frac{\rho_0 - \rho}{\rho_0^2} \right) \frac{\delta\rho}{\delta\rho_1(\text{or h})} \tag{3}$$

We also have:

$$\Delta\psi = \frac{\delta\psi}{\delta\rho_1}\Delta\rho_1 + \frac{\delta\psi}{\delta\rho_2}\Delta\rho_2 + \frac{\delta\psi}{\delta h}\Delta h \tag{4}$$

In order to make sure that the calculations converge to the exact solution, the values of $\Delta\rho_1$, $\Delta\rho_2$ and $\Delta h$ should be such that:

$$\Delta\psi = -\tau\left(\frac{\delta\psi}{\delta\rho_1}\right)^2 - \sigma\left(\frac{\delta\psi}{\delta\rho_2}\right)^2 - \gamma\left(\frac{\delta\psi}{\delta h}\right)^2$$

$$\Delta\rho_2 = -\sigma\frac{\delta\psi}{\delta\rho_2} \tag{5}$$

$$\Delta h = -\gamma\frac{\delta\psi}{\delta h}$$

$\tau$, $\sigma$, $\gamma$ being positive values and small enough to guarantee a solution with the desired accuracy. Normally the following values are satisfactory:

$$\Delta\rho_1 = -\,0.005\left|\rho_1\right|\operatorname{sign}\left(\frac{\delta\psi}{\delta\rho_1}\right)$$

$$\Delta\rho_1 = -\,0.005\left|\rho_2\right|\operatorname{sign}\left(\frac{\delta\psi}{\delta\rho_2}\right) \tag{6}$$

$$\Delta h = -\,0.005\left|h\right|\operatorname{sign}\left(\frac{\delta\psi}{\delta h}\right)$$

Using equations (4), (5) and (6) the following equation is obtained:

$$\Delta\psi = -\tau\left(\frac{\delta\psi}{\delta\rho_1}\right)^2 - \sigma\left(\frac{\delta\psi}{\delta\rho_2}\right)^2 - \gamma\left(\frac{\delta\psi}{\delta h}\right)^2 \tag{7}$$

The calculations start by assuming initial values: $\rho_1^{(1)}$, $\rho_2^{(1)}$, and $h^{(1)}$

At iteration j the new values are given by:

$$\rho_1^{(j)} = \rho_1^{(j-1)} + \Delta\rho_1$$

$$\rho_2^{(j)} = \rho_2^{(j-1)} + \Delta\rho_2 \tag{8}$$

$$h^{(j)} = h^{(j-1)} + \Delta h$$

The calculations lead to two-layer earth:

$$\frac{\delta\rho}{\delta\rho_1} = 1 + 4\sum_{n=1}^{\infty}\left(\left(1 - \frac{n\left(1-k^2\right)}{[2k]^{1/2}}\right) - \left(\frac{k^n}{[A]^{1/2}} - \frac{k^n}{[B]^{1/2}}\right)\right)$$

$$\frac{\delta\rho}{\delta\rho_2} = \sum_{n=1}^{\infty}\left(\frac{2n}{k}\left(1-k^2\right)\left(\frac{k^n}{[A]^{1/2}} - \frac{k^n}{[B]^{1/2}}\right)\right) \tag{9}$$

$$\frac{\delta\rho}{\delta h} = \frac{16\rho_1 h}{2a}\sum_{n=1}^{\infty}\left(\frac{kn}{\left[B^3\right]^{1/2}} - \frac{k^n}{\left[A^3\right]^{1/2}}n^2\right)$$

Where:

$$A = 1 + \left(2nh/a\right)^2$$

$$B = 4 + \left(2nh/a\right)^2$$

$\rho_1$, $\rho_2$ and h are the calculated values at iterating j. see equation (8).

A good grounding system provides a low resistance to remote earth in order to minimize the GPR. For most transmission and other large substations, the ground resistance is usually about 1 Ω or less. In smaller distribution substations, the usually acceptable range is from 1 Ω to 5 Ω, depending on the local conditions [2].

Schwarz developed following set of equations in order to determine the grounding resistance in uniform soil conditions. Schwarz equations are composed of three equations and one equation for merging the three [2, 4]. Main equation merging the other three equations is given in Eq. (10).

$$R_g = \frac{R_1R_2 - R_m^2}{R_1 + R_2 - 2R_m} \tag{10}$$

Where, $R_1$, $R_2$, $R_m$ are determined by three different equations. $R_1$ is determining the ground resistance of a grid formed by straight horizontal wires and represented in Eq. (11).

$$R_1 = \frac{\rho}{\pi L_c}\left[\ln\left(\frac{2L_c}{a'}\right) + \frac{k_1.L_c}{\sqrt{A}} - k_2\right] \tag{11}$$

Where ρ is the soil resistivity in Ω-m, $L_c$ is the total length of all connected grid conductors in m, 2a is the diameter of conductor in m, $a'$ is $(a.2h)^{½}$ for conductors buried at depth h, or $a'$ is a on earth surface, A is the area covered by conductors in $m^2$, $k_1$ and $k_2$ are the coefficients found by the following equations according to the value of grid depth (h).

The values of $k_1$ and $k_2$ in Eq. (11) are given in Table 1 for different values of the grid depth. In the formulations x is given as the length to width ratio of grid.

**Table 1.** Schwarz Method Parameters

| h | $K_1$ | $K_2$ |
|---|---|---|
| 0 | -0.04x+1.41 | 0.15x+5.50 |
| $1/(10A^{1/2})$ | -0.05x+1.20 | 0.10x+4.6 |
| $1/(6A^{1/2})$ | -0.05x+1.13 | -0.05x+4.40 |

In Eq. (12), $R_2$ determines the ground resistance of a rod bed.

$$R_2 = \frac{\rho}{2\pi n_R L_r}\left[\ln\left(\frac{4L_r}{b}\right) + \frac{2k_1.L_r}{\sqrt{A}}\left(\sqrt{n_R} - 1\right)^2\right] \tag{12}$$

Where $L_r$ is the length of each rod in m, 2b is the diameter of rod in m, $n_R$ number of rods placed in area A.

The third variable in Schwarz Equation is given in Eq. (13). $R_m$ is the combined ground resistance of the grid and the rod bed.

$$R_m = \frac{\rho}{\pi L_c}\left[\ln\left(\frac{2L_c}{L_r}\right) + \frac{k_1.L_c}{\sqrt{A}} - k_2 + 1\right] \tag{13}$$

One can obtain the grounding grid resistance by computing $k_1$, $k_2$, $R_1$, $R_2$ and $R_m$ in the given order and putting the calculated values in Eq. (10). References [2, 4] have the necessary derivations to obtain Schwarz equations.

## III. MODELLING AND SIMULATION

There are four steps in this study that should be considered:

### 3.1 Soil Analysis

Detailed soil resistivity measurements have been carried out at the substation site, using the Wenner 4-pin technique (i.e., the distances between adjacent electrodes are equal). The Wenner four-electrode arrangement is shown in figure 1 [2, 3].

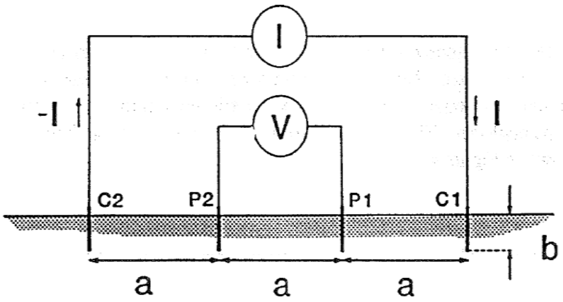


**Figure 1.** The Wenner four-electrode arrangement

Table 2 gives the apparent resistance values measured at the substation site (Ignore probe depth).
Usually, when the electrode penetration into the earth is shallow, the relationship between measured apparent resistances and resistivities can be approximated as follows:

$$\rho = 2\pi aR \quad (a \text{ in m})$$

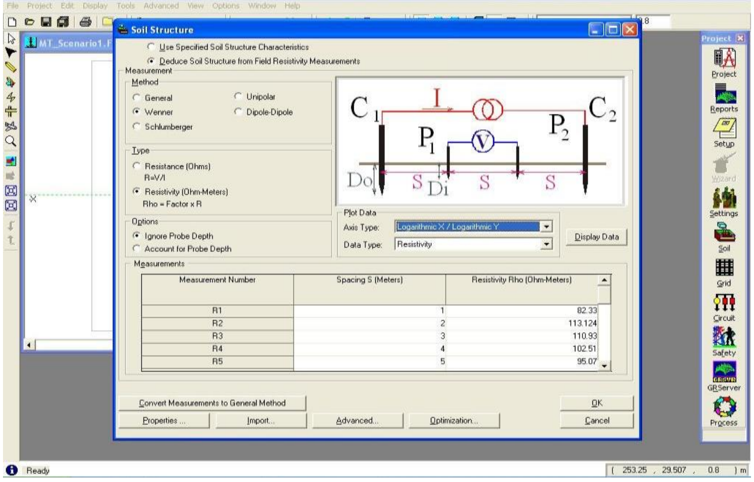
Where $\rho$ the apparent soil resistivity in Ω-m is, $a$ is the electrode spacing and R is the measured apparent resistance in Ω.

**Table 2.** Apparent Resistivity Measured at Substation Site Using the Wenner Method

| Probe Distance (meters) | Measured Resistivity (ohm-meters) | Probe Distance (meters) | Measured Resistivity (ohm-meters) |
|---|---|---|---|
| 1 | 82.330 | 7 | 84.256 |
| 2 | 113.124 | 9 | 73.070 |
| 3 | 110.930 | 11 | 62.90 |
| 4 | 102.510 | 13 | 51.40 |
| 5 | 95.070 | 15 | 28.180 |

In Autogrid Pro Grounding Software, the soil resistivity interpretation module RESAP is used to determine equivalent horizontally layered soils based on the site measurements. Although RESAP is capable of producing multilayered soil models, it is preferable to try to fit the measured results to the simplest soil structure (i.e., a two-layer model), at least initially. This minimizes the time required for the computations [1, 5].

There are predefined modules in both Autogrid Pro Grounding Software and CygmGrd that data sets can be entered through them.



○ Use Specified Soil Structure Characteristics
● Deduce Soil Structure from Field Resistivity Measurements

Measurement

Method: ○ General ● Wenner ○ Schlumberger ○ Unipolar ○ Dipole-Dipole

Type: ○ Resistance (Ohms) R=V/I ● Resistivity (Ohm-Meters) Rho = Factor x R

Options: ● Ignore Probe Depth ○ Account for Probe Depth

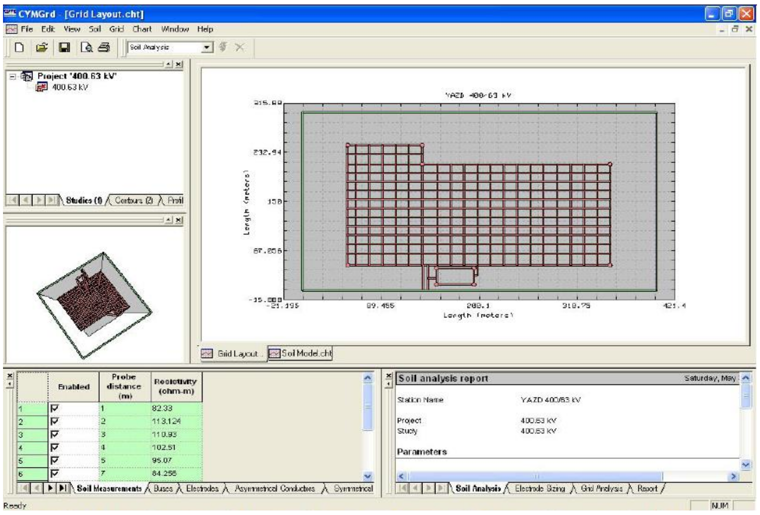
Plot Data
Axis Type: Logarithmic X / Logarithmic Y
Data Type: Resistivity

Measurements

| Measurement Number | Spacing S (Meters) | Resistivity Rho (Ohm-Meters) |
|---|---|---|
| R1 | 1 | 82.33 |
| R2 | 2 | 113.124 |
| R3 | 3 | 110.93 |
| R4 | 4 | 102.51 |
| R5 | 5 | 95.07 |

( 253.25 , 29.507 , 0.0 ) m

**Figure 2.** Input data window in Autogrid Pro



| | Enabled | Probe distance (m) | Resistivity (ohm-m) |
|---|---|---|---|
| 1 | ☑ | 1 | 82.33 |
| 2 | ☑ | 2 | 113.124 |
| 3 | ☑ | 3 | 110.93 |
| 4 | ☑ | 4 | 102.51 |
| 5 | ☑ | 5 | 95.07 |
| 6 | ☑ | 7 | 84.256 |

Soil analysis report Saturday, May

Station Name YAZD 400/63 kV

Project 400.63 kV
Study 400.63 kV

Parameters

**Figure 3.** Input data window in CymGrd

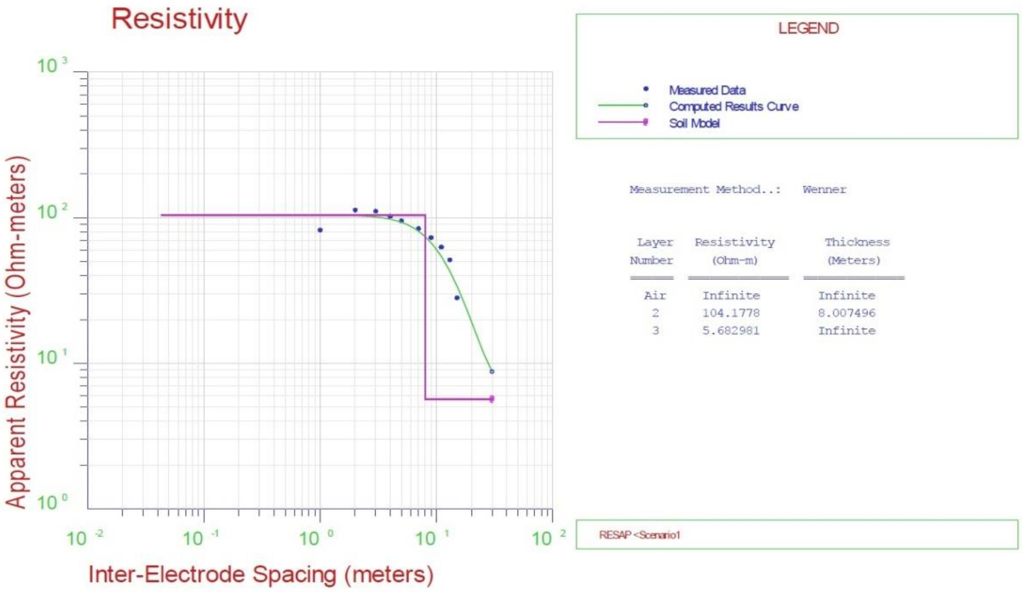
The computation results lead to an equivalent two-layer soil structure such as the one shown in Table 4.

**Table 3.** Substation Soil Characteristics

| Soil Model | Two-Layer Model |
|---|---|
| Body Weight | 70 kg |
| Surface Layer Thickness | 0.15 m |
| Surface Layer Resistance | 3000 Ω-m |
| Shock Time Period | 0.5 sec |

**Table 4.** Resulted Values from Two-Layer Soil Model

| Subject | Autogrid Pro | CygmGrd |
|---|---|---|
| Upper Layer Thickness (m) | 8.007496 | 8.69 |
| Upper Layer Resistance (Ω-m) | 104.1778 | 103.66 |
| Lower Layer Resistance (Ω-m) | 5.682981 | 0.01 |
| Allowed Touch Voltage (volts) | 990 | 998.57 |
| Allowed Step Voltage (volts) | 3326.5 | 3328.18 |
| Error Between Measured and Outputs (%) | 11.25 | 12.65 |



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Measurement Method..:   Wenner

 Layer   Resistivity      Thickness
Number     (Ohm-m)         (Meters)
======  =============   =============
  Air     Infinite         Infinite
   2      104.1778         8.007496
   3      5.682981         Infinite
```

**Figure 4.** Two-layer soil structure in Autogrid Pro Grounding Software

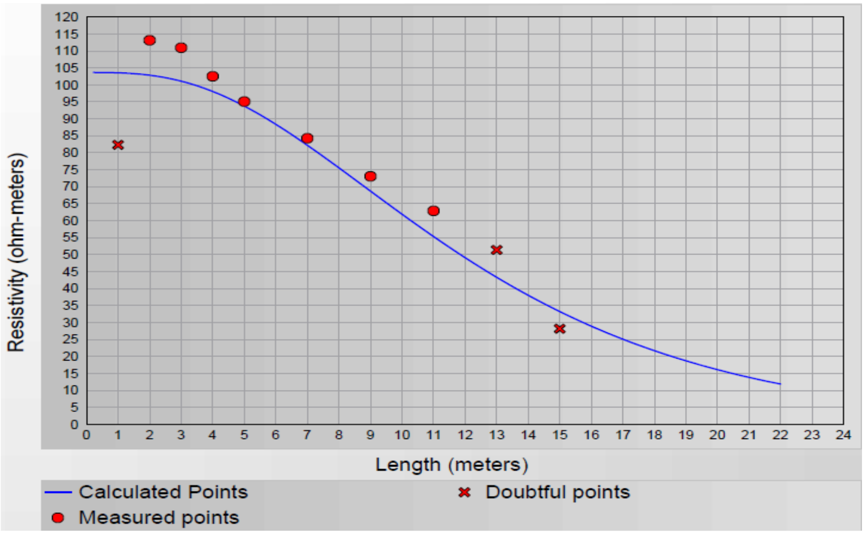

**Figure 5.** Two-layer soil structure in CygmGrd

In Table 4, in the last column, the error between the computed and measured resistivities by Autogrid Pro Grounding Software is less than CygmGrd; Therefore Autogrid Pro gives Two-Layer Soil Model with more accurate.

## 3.2 Input Parameters for Network Analysis

The same design has been performed for both Autogrid Pro Grounding Software and CygmGrd. The main inputs are entered as follow:

**Table 5.** Main Input Data Sets

| | |
|---|---|
| Nominal Frequency | 50 Hz |
| Rated Symmetrical Three Phase Short Circuit Current | 50000 A |
| The Distance Factor from Power Plant | 1 |
| fault Current Division Factor | 0.6978 |
| Original Electrical Current Flowing In Electrode | 32000 A |
| Depth of Burial Conductor | 0.8 m |
| Diameter of Grid Conductors | 0.01178 m (3/0 AWG) |

A design of parallel and crisscross conductors is chosen for grounding system. In this design, conductors are implemented in the direction of structures, so that the total length of grounding system connections would be shortened. The distances between conductors are normally chosen 15 m [6, 7]. It is possible to draw the system in two ways:
i) Entering the geometric data of conductors from input window in the software.
ii) Drawing the grounding system in AutoCAD and then exporting it to software.
In this paper, the second method has been used.

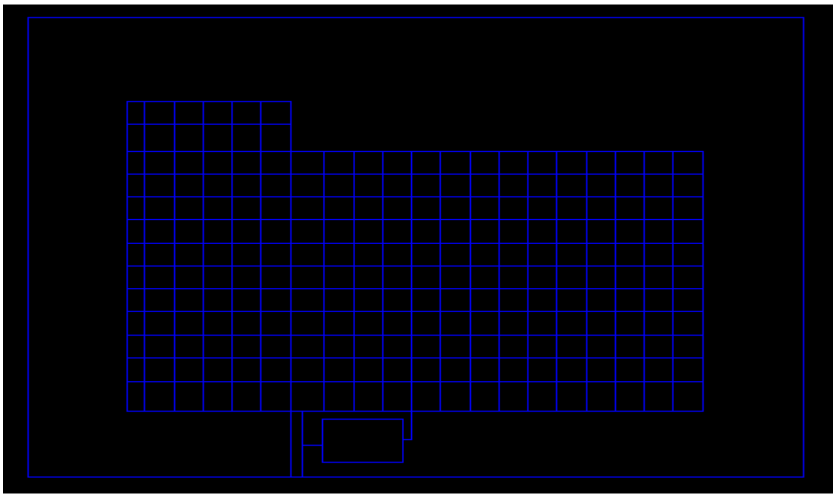

**Figure 6.** Drawn grounding system in AutoCAD

The main results are given in the following table:

**Table 6.** Main Outputs

| Subject | Autogrid Pro | CygmGrd |
|---|---|---|
| Max. Touch Voltage (volts) | 953.56 | 960.48 |
| Allowed Touch Voltage (volts) | 990 | 998.57 |
| Max. Step Voltage (volts) | 162.3 | 100.15 |
| Allowed Step Voltage (volts) | 3326.5 | 3328.18 |
| Main Electrode Potential Rise (GPR) | 1110.4 | 950.94 |
| Number of Conductors in Electrode | 54 | 54 |
| Ground Resistance (Ω) | 0.0347 | 0.0272 |
| Total Buried Length of Metallic Structures (m) | 1400.418 | 1400.42 |

With analysing and comparing values of table 6, it could be concluded that:

i) In the last column, it is mentioned that total conductor length is 1400.418 m.

ii) In the above tables, calculated touch voltages is lower than maximum acceptable value; and so there is not any problem for grounding system maximum touch voltage.

iii) As Autogrid Pro gives two-layer soil model with more accurate and the grounding system resistance computed by the grounding module MALT, therefore ground resistance value is correct comparing with CygmGrd.

iv) In IEEE Std. 80-2000, the touch voltage limit is:

$$E_{Touch\,70} = \left(1000 + 1.5\ C_s\rho_s\right)\left(\frac{0.157}{\sqrt{t_s}}\right)$$

But in Autogrid Pro, a value of $1.3\ C_s\rho_s$ (instead of $1.5\ C_s\rho_s$) is used to the parallel resistance of the feet for uniform soil conditions. The main reason for this is due to the difference in shape, size and burial depth between the two electrodes used to model a foot [3]. Note that user can enter the desired values (safe allowable values for touch and step voltages) in the entry fields Step and Touch.

v) Entering data is very easy in Autogrid Pro and it can be modified easily different characteristics of ground grid.

The following plot shows the touch voltages throughout the grid in Autogrid Pro Grounding Software. The touch voltages can reach values as large as 953.566 Volts. All values are safe, the maximum value being 990 Volts, and the analysis is complete.

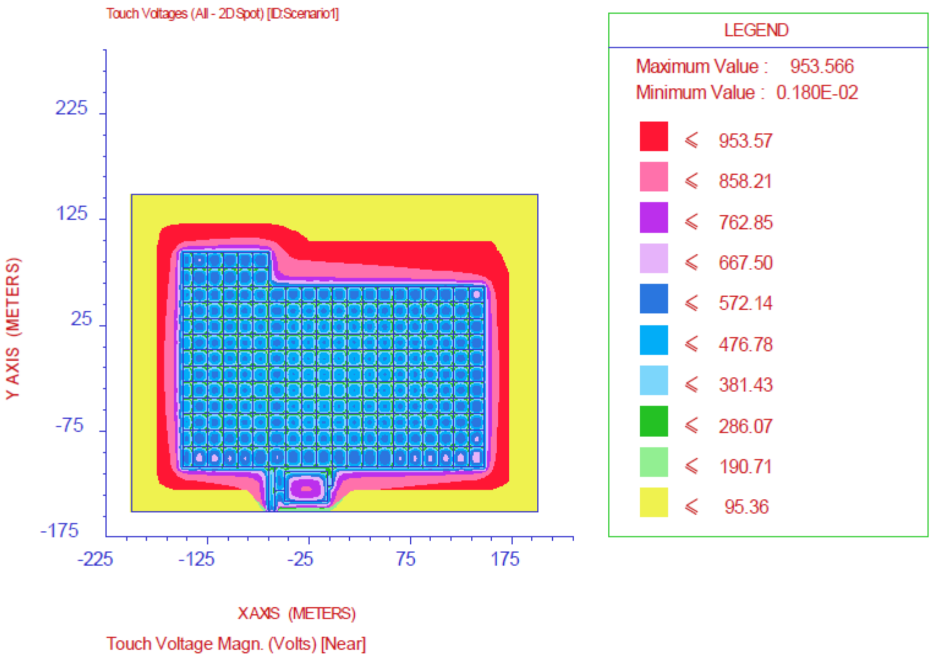

**Figure 7.** Touch voltage distribution in Autogrid Pro

Figure 8 shows the step voltages throughout the grid in Autogrid Pro Grounding Software. The maximum step voltage reached is 162.308 Volts. This is below the safe step voltage limit computed in the presence of crushed rock (3326.5 Volts).

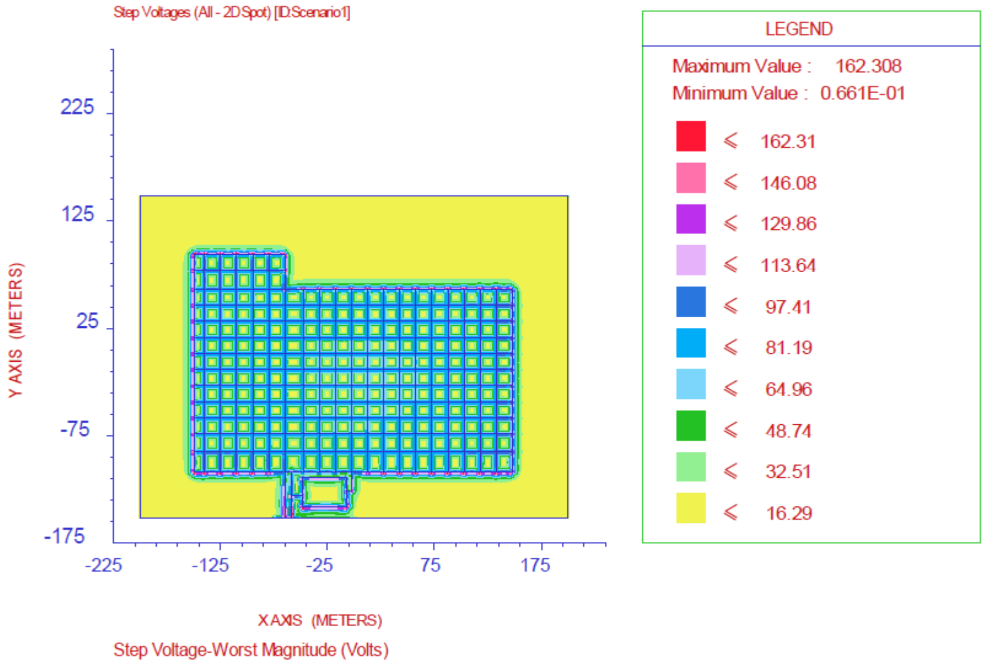

**Figure 8.** Step voltage distribution in Autogrid Pro

The figure 9 shows the touch voltages throughout the grid in CygmGrd. All areas are safe.

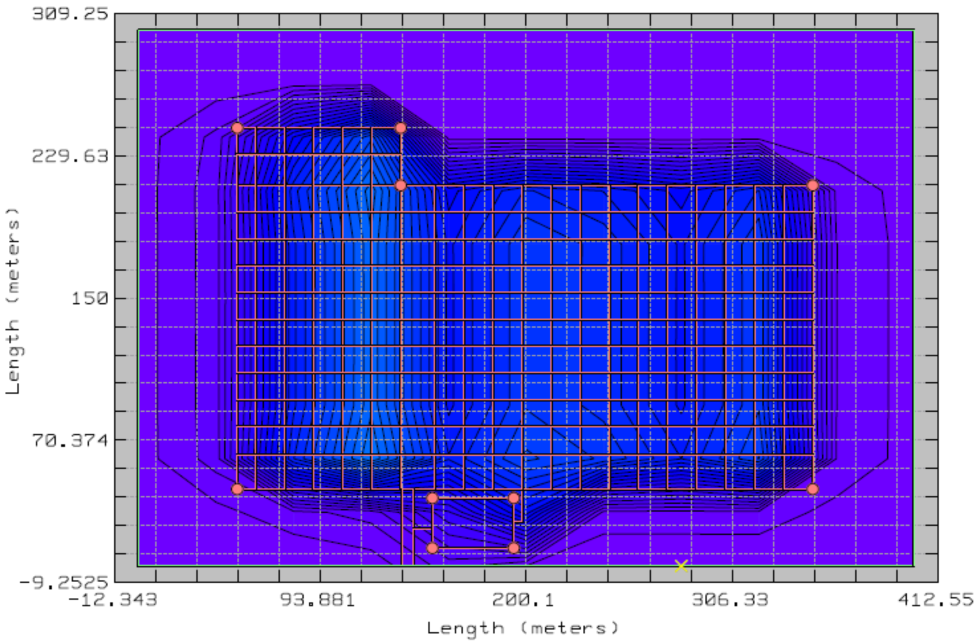

**Figure 9.** Touch voltage distribution in CymGrd

The diagram in Figure 10 contains 6 curves with 3 different colours. Three curves which drawn with bold lines will show touch, step, and ground voltages; and the other curves as dotted lines will show the maximum of these above-mentioned voltages.

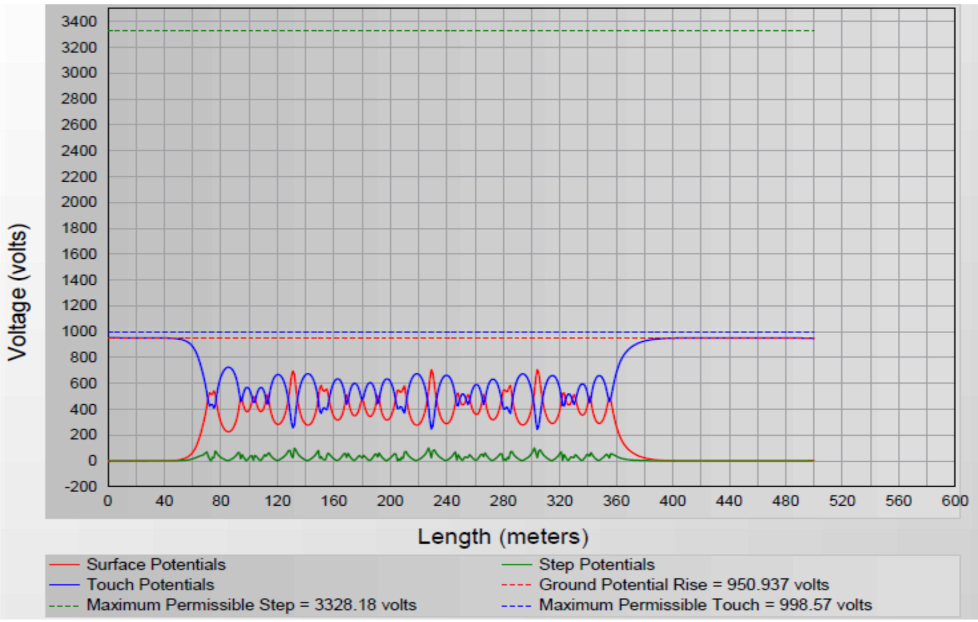

**Figure 10.** Step, Ground and Touch voltage profile in CymGrd

As a result, it can be seen from this profile, that the design for grounding system using CymGrd software is acceptable.

## IV. FUTURE WORK

- Mathematical calculations to determine limit of ground potential rise of substation
- The new GIS substations are within built-up areas, and therefore, the supply to these substations is with cables rather than overhead lines. Therefore, the division of current [8-11] between the grid system and the cable must be settled by experimental results.

## V. CONCLUSIONS

A sufficient plan for a high voltage substation grounding system is the one that besides providing technical requirements and safety issues is reliable in terms of economic aspects. There are different ways to do the calculations and draw a plan for the grounding system; either hand calculations that takes time and less accurate results compared to standards, or using software packages like: Autogrid Pro Grounding Software or CymGrd. Autogrid Pro Grounding Software is powerful software with exceptional capabilities. Number of input/output parameters in Autogrid Pro Grounding Software is more than other software packages and the soil resistivity interpretation module RESAP is used to determine equivalent horizontally layered soils based on the site measurements. Although RESAP is capable of producing multilayered soil models, it is preferable to try to fit the measured results to the simplest soil structure (i.e., a two-layer model), at least initially. This minimizes the time required for the computations. In this paper, an optimized design for a 400/63 kV substation in Yazd, centre of Iran, is developed using Autogrid Pro Grounding Software and CymGrd software package. The network is divided into several smaller grounding systems that have uniformly distributed soil. Step, touch, and Earth potential are all under the maximum allowable values from IEEE Std. 80-2000. Predicting the most probable location for happening of a fault is a good candidate for future works. This gives us a method for predicting behaviour of a substation in fault happening situations.

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