TECHNICAL CALCULATION SHEET FOR SUBSTATION GROUNDING DESIGN

1 Objective

Design the substation grounding grid layout that meets the requirements listed in the National Electrical Code and follows the recommendations of the standard IEEE Std 80-2013 'Guide for Safety in AC Substation Grounding'

2 Scope

This analysis is performed for a rectangle 63.00 meters width by 84.00 meters length grounding grid calculating the total grid resistance, the ground potential rise, and final mesh and step potentials to finally compare them with the tolerable voltage for a human body of 70 kg weight.

3 Technical references

1. ANSI/IEEE STD 80-2013 'Guide for Safety in AC Substation Grounding' Published by the Institute of Electrical and Electronic Engineers.
2. ANSI/IEEE STD 81-2012 'Measuring Earth Resistivity , Ground Impedance, and Earth Surface Potentials of a Ground System' Published by the Institute of Electrical and Electronic Engineers. 2012 Edition.
3. National Electrical Safety Code. Published by the Institute of Electrical and Electronic Engineers. 2007 Edition.
4. ANSI/IEEE STD 142-2007 'Recommended Practice for grounding of Industrial and Commercial Power Systems'. Published by the Institute of Electrical and Electronic Engineers. 2007 Edition.
5. IEEE Transactions on Power Apparatus and Systems, Vol. PAS-100 No. 9 September 1981. 'Safe Substation Grounding' Part I.
6. IEEE Transactions on Power Apparatus and Systems, Vol. PAS-99, No. 4 July /August 1980. 'Bentonite Rods Assure Ground Rod Installation in Problems' Soils. Por Warren R. Jones.
7. NFPA 70 National Electrical Code
8. Electric Shock Hazard, IEEE Spectrum published by Dalziel C. F. February 1972. pp. 41-50.
9. 'Electrical Conductor Manual' published by Condumex
10. 'Project Short-Circuit and Protective Device Coordination Studies'.

4 Reference information and calculation of the grounding grid

For the design of the grounding grid is necessary to count with basic data such as: Soil resistivity, fault current, failure time duration, ground grid geometry and layout and the grid area. These data were obtained as follows:

4.1 Resistivity

In order to determine the resistivity of the different soil layers integrating stratigraphic sequence of the earth, a geophysical study in the modality of vertical electrical sounding (VES) was performed. The study followed the four points Wenner´s method. This method has proven in practice to be the most appropriate to determine the soil resistivity values. The study was performed following the recommendations of the ANSI/IEEE Std 81 'Recommended guide for measuring ground resistance and potential gradients in the earth 'and IEEE Std 80' Guide for alternating current substation grounding '.

The resistivity measurement program consisted of the execution of vertical electrical sounding (VES) located in the main substation area. Measurements were carried out with the aid of a resistivity measurement apparatus or resistivitymeter model , cable reels and copper metal electrodes.

As defined in the IEEE std. 81, the basic principle of the Wenner method consists in subjecting the ground to an electrical current which is injected through two electrodes connected to a transmitter system. The electrodes are usually steel or copper rods of 0.3 to 0.5 m. in length. These are driven into the ground. Once the current circuit is created through the ground, it creates an electric field composed of equipotential surfaces perpendicular to the current flow, which are distorted when crossing through the different layers of the stratigraphic sequence, producing a potential difference that is recorded from the surface, by two electrodes located on the line joining the two current electrodes, thereby obtaining apparent resistivity readings.

A measurement of the humidity per weight was made at each point on the ground where the soil resistivity measurements were taken, for those points where the degree of humidity exceded 80% the measurement was discarded
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Upon completion of the fieldwork, all the information was processed and interpreted. The final object of this procedure, like most geoelectrical methods, was to define the soil electrical resistivity.

Applying an analytical software based on the Dar Zarrouk curves, the apparent resistivity curves were traced for each point. From these curves the real resistivities were computed for each geoelectrical profile. ar The substation grounding grid will be located in the zone where the resistivity measurements were performed, at a burial depth of 0.50 m. where predominant values of resistivity are: 400.00 ohms-m.

4.2 Duration of failure

Determining the failure time is a direct function of operation time of the main disconnecting breaker, generally these times can be considered as follows:

The substation has a main power breaker. The opening time of the main contacts and arc extinction is considered to be 0.03 sec. However, it is necessary to consider the overtravel, detection and discrimination time of relays that will operate this device. This time can be considered negligible in the case of solid-state relays. Because in early stages of design the grounding is one of the first events in the construction, it is necessary to know the components and layout of the grid and generally in these stages the protection means is not known, so is conservative to also consider the operating time for relays. Applying a safety time factor the total time will be considered 0.50 seconds.

It is very important that the ground grid meets the most critical conditions in the event of a failure, it is therefore necessary to consider the total opening time for the case where the main disconnecting mean fails and therefore the total failure time is the sum of the main disconnecting operation time, plus the operating time of the back up element upstream. A failure time duration of 0.50 sec. was finally considered fulfilling the maximum safety margin.

4.3 Grounding grid area and depth

The physical layout of the substation grounding grid is used to calculate a total grid area considering that the geometrical distribution is 84.00 meters length and 63.00 meters width.

The ground grid burial depth used for design is 0.50 meters. This depth is within the common range recommended by the standard IEEE Std.80-2013.

A uniform gravel layer is considered to be located over the entire substation are with a thickness of 0.102 meters. Because the resistivity of the gravel is difficult to measure or certificate a resistivity a value of 2500.00 Ω-m extracted from Table 3 of the standard IEEE std.80-2013 73 pp (Table 5.1) was used in the analysis.

4.4 Grounding electrodes (rods)

The grounding electrodes are Copperweld type rods of 10.00 meters long. These electrodes are distributed in such a way that they are not within the same 'relative ground cylinder'. This is achieved considering a free location radius equal to the length of a rod so that a rod of 10.00 meters long separated from another one by 20.00 meters for most cases. For some places where greater electrical potentials may appear, such as at the corners of the grid, there may be a greater density of rods.

As described in the standard IEEE Std. 80 is known that the diameter of the electrodes has a minimal effect on the resistance of the ground electrode connection, because the grounding cylinder is approximately the same between two electrodes of different diameters. For example, increasing the diameter of a rod of 3 m. from 0.159 m. to 0.254 m., the resistance decreases by only 9.5 %%. However doubling the diameter the weight and cost increases by 400 %%. It was also observed that increasing the diameter of the rod the relative ground cylinder size does not increase.

Considering these factors, 0.0191 m diameter ground rods were selected. These meet the mechanical requirements, have the electrical properties and comply with the economics of the project.

4.5 Summary of data considered for study

The general information used for the ground grid design is listed below:

Field	Value
Fault current	3180.00 A.
Fault current growth factor	1.00
Fault division factor	0.60
Design current	1908.00 A.
Fault clearing time	0.50 seconds
Ground grid length	84.00 meters
Ground grid width	63.00 meters
Soil resistivity layer 1	400.00 Ω - meter
Soil resistivity layer 2	600.00 Ω - meter
Gravel layer resistivity	2500.00 Ω - meter
Ground grid burial depth	0.50 meters
Gravel layer thickness	0.10 meters
Grounding rods length	10.00 meters
Grounding rods diameter	0.02 meters
Grounding conductor size	2/0 AWG/kCM
Grounding conductor total length	1659.00 meters
Connector type	Welded

4.6 Touch and step voltages tolerated by the human body

Both touch (contact) and step Tolerable voltages for the human body are calculated. For which the reducing factor for nominal value of soil resistivity Cs is required to be computed. This factor is a function of K factor. The K factor is calculated as follows:

$$K = \frac{\rho - \rho_s}{\rho + \rho_s}$$

Where:

K Reflection factor between different material resistivities.

ρ Resistivity of the earth beneath the surface material in [Ω-meter]

ρ_s Resistivity of the surface material in [Ω-meter]

$$K = \frac{400.00 - 2500.00}{400.00 + 2500.00}$$

$$K = -0.7241$$

The reflection factor between materials of different resistivities Cs is calculated from the equation given in the standard IEEE Std 80 using the K-factor and the thickness of the gravel layer. This is an empirical formula shown in section 7 of the standard IEEE Std. 80 that generates values within 5% of the values obtained using an analytical method that would require more time and resources.

Verifying that the comparison between the tolerable voltages and the voltages generated in the grid include this variation margin the method is simplified. Thus:

$$C_s = 1.0 - \frac{0.09 \cdot \left(1.0 - \frac{\rho}{\rho_s}\right)}{2.0 \cdot h + 0.09}$$

Where:

C_s	Surface layer derating factor
ρ	Resistivity of the earth beneath the surface material in [Ω-meter]
ρ_s	Resistivity of the surface material in [Ω-meter]
h	Thickness of the surface material[meter]

$$C_s = 1.0 - \frac{0.09 \cdot \left(1.0 - \frac{400.00}{2500.00}\right)}{2.0 \cdot 0.10 + 0.09}$$

$$C_s = 0.74$$

Therefore step and touch tolerable voltages by the human of 70 kg weight are:

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

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

Where:

C_s	Surface layer derating factor as a function of (hs , K)
ρ_s	Surface material resistivity [Ω-meter]
t_s	Failure time [seconds]

$$E_{step}70 = \frac{(1000 + 6 \cdot 0.7429 \cdot 2500.00) \cdot 0.157}{\sqrt{0.50}}$$

$$E_{step}70 = 2696.10\ Volts$$

$$E_{touch}70 = \frac{(1000 + 1.5 \cdot 0.7429 \cdot 2500.00) \cdot 0.157}{\sqrt{0.50}}$$

$$E_{touch}70 = 840.55\ Volts$$

4.7 Grounding grid resistance

Using the general project data and applying the expanded Sverak formula (52) obtained from section 14 of IEEE Std 80, the resistance of the grounding grid will be:

$$R_m = \rho \cdot \left(\frac{1}{L} + \frac{1}{\sqrt{20 \cdot A}} \cdot (1 + \frac{1}{1 + h \cdot \sqrt{\frac{20}{A}}}) \right)$$

Where:

R_m	Grounding grid resistance [Ohms]
ρ	Resistivity of the earth beneath the surface material in [Ω-meter]
ρ	$\frac{\rho \cdot lyr_1 + \rho \cdot lyr_2}{2}$ for 2-layer soil
h	Ground grid burial depth [meters]
A	Grounding grid area [m^2]
L	Total length of conductors in grid plus total length of rods if included. [meters]

$$R_m = 500.00 \cdot \left(\frac{1}{2039.00} + \frac{1}{\sqrt{20 \cdot 5292.00}} \cdot (1 + \frac{1}{1 + 0.50 \cdot \sqrt{\frac{20}{5292.00}}}) \right)$$

$$Rm = 3.27\ \Omega$$

As the grid design includes the installation of rods the Schwarz's equation is applied to compute the total resistance of a grounding system consisting of horizontal (grid) and vertical (rods) electrodes:

The resistance of the grid conductors is calculated applying the following equation:

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

Where:

ρ	Is the soil resistivity [Ω - meter]
L_c	Is the total length of all connected grid conductors in [meters]
a'	Is $\sqrt{a \cdot 2 \cdot h}$ for conductors buried at Depth h in [meters] or
a'	Is a for conductor on earth surface in [meters]
A	Is the area covered by conductors in [m^2]
k_1, k_2	Are the coefficients determined according to graphs 25(a) and (b) of IEEE Std.80.

$$R_1 = 3.0533\ \Omega$$

Subsequently, the value of the resistance of the rod bed R_2 is determined:

$$R_2 = \frac{\rho}{2 \cdot \pi \cdot n_r \cdot L_r} \cdot \left(\ln\left(\frac{4 \cdot L_r}{b}\right) - 1 + \frac{2 \cdot k_1 \cdot L_r}{\sqrt{A}} \cdot (\sqrt{n_r} - 1)^2 \right)$$

Where:

L_r	Is the length of each rod in [meters]
$2b$	Is the diameter of rod in [meters]
n_r	Number of rods placed in Area A

$$R_2 = 3.2774\ \Omega$$

Additionally, the value of the mutual resistance between the mesh and the rod bed is calculated:

$$R_M = \frac{\rho}{\pi \cdot L_c} \cdot \left(\ln\left(\frac{2 \cdot L_c}{L_r}\right) + \frac{k_1 \cdot L_c}{\sqrt{A}} - k_2 + 1 \right)$$

$$R_M = 2.67\Omega$$

The combined resistance of the grid with the rod bed will then be (Schwarz´s equation):

$$R_g = \frac{(R_1 \cdot R_2) - R_M^2}{R_1 - R_2 - 2 \cdot R_M}$$

$$R_g Schwarz = 2.9053\ \Omega$$

It is verified that the grounding grid meets the resistance specified in the Mexican Official Standard NOM-001-SEE-2012 within section 921-25 (b) which states:

The total electrical resistance of the grounding system should have a value less than 25 ohms (including all the elements of the system) for substations up to 250 kVA and 34.5 kV, 10 ohms for substations greater than 250 kVA and up to 34.5 kV, and 5 Ω for substations operating with higher voltages at 34.5 kV.

4.8 Ground potential rise

With the ground grid resistance value and the maximum failure current the ground potential rise is obtained and is verified whether it is greater than the tolerable voltages of the human body.

$$GPR = I_g \cdot R_m$$

Where:

GPR	Ground Potential Rise [Volts]
I_g	Design failure current [Amperes]
R_m	Ground grid resistance [Ω]

$$GPR = 1908.00 \cdot 2.9053$$

$$GPR = 5543.25 Volts$$

It is noted that Ground Potential Rise is not greater than the step and touch permissible voltages. Therefore, it is considered that the design of the grid meets the safety criteria for personnel. However, a more detailed analysis of the grid voltages will be performed to ensure that personnel safety is guaranteed.

4.9 Ground grid voltages calculation

To determine the ground grid voltages is necessary to calculate the number of conductors in parallel. The value of 'n' can be applied to rectangular or irregularly shaped grids that can be considered as a number of parallel conductors in an equivalent rectangular grid. For which the following formula is applied:

$$n = n_A \cdot n_B \cdot n_C \cdot n_D$$

Where:

n_A	$\frac{2 \cdot L_c}{L_p}$
n_B	1 for square grids
n_C	1 for square or rectangular grids
n_D	1 for square, rectangular and L-shaped grids
L_c	Total length of horizontal grid conductors in meters
L_p	Perimeter grid length in meters

The value obtained for the n_A factor is: 11.29.

The value obtained for the n_B factor is 1.01. Therefore, the number of effective parallel conductors n is: 11.34.

in order to determine the geometric factor K_h to calculate the potential generated in the grid it is necessary to calculate first the additional K_h, K_i and K_{ii} factors factors.

Following, the K_h factor is calculated using the following equation:

$$K_h = \sqrt{1 + \frac{h}{h_o}}$$

Where:

h	Ground grid burial depth
h_o	1 m (Grid depth reference)

Because the grid layout includes rods installed on the perimeter, the K_i factor is calculated from the following equation:

$$K_{ii} = \frac{1}{2 \cdot n^{\left(\frac{2}{n}\right)}}$$

Where:

n	Number of equivalent parallel conductors

Using the $K\ h$ and K_i factors the grid geometrical factor is calculated applying the following equation:

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

Where:

K_{ii}	1 For grids with ground rods along the perimeter, or for grids with ground rods in the grid corners, as well as both along the perimeter and throughout the grid area.
K_{ii}	$\frac{1.0}{(2\cdot n)^{\left(\frac{2}{n}\right)}}$ For grids with no ground rods or grids with only a few ground rods, none located in the corners or on the perimeter.
K_h	$1+\frac{h}{h_o}$
h	Ground grid burial depth
h_o	1 m (Grid depth reference)
D	Spacing between parallel conductors in meters
n	Number of parallel conductors in the same direction
d	Grid conductor diameter [m]

Therefore, the geometric factor is:

$$k_m = \frac{1}{2\cdot 3.14159265}\cdot \ln\left(\frac{7.0000^2}{16\cdot 0.5000\cdot 0.0093}+\frac{(7.0000+2\cdot 0.5000)^2}{8\cdot 7.0000\cdot 0.0093}-\frac{0.5000}{4\cdot 0.0093}\right) + \frac{0.5767}{1.2247}\cdot \ln\left(\frac{8}{3.14159265\cdot(2\cdot 11.3440-1)}\right)$$

$$k_m = 0.8975$$

The K_i factor is determined by the following equation:

$$K_i = 0.644 + (0.148\cdot N)$$

Where:

N	Number of parallel conductors in the same direction [m]

$$K_i = 0.644 + (0.148\cdot 11.3440)$$

$$K_i = 2.3229$$

The grid contact voltage is calculated using the following equation:

$$E_m = \frac{\rho\cdot K_m\cdot K_i\cdot I_g}{L_m}$$

Where:

E_m	Grid contact voltage [Volts]
ρ	Soil resistivity [Ω-m]
K_m	Geometric factor
K_i	Rod distribution factor
I_g	Ground fault current [Amps]
L_m	Effective length of buried conductors [m]

Replacing values:

$$E_m = \frac{400.00 \cdot 0.90 \cdot 2.32 \cdot 1908.00}{2292.15}$$
$$E_m = 694.13\ Volts$$

Ground grid step voltage is determined using the following equation:

$$E_p = \frac{\rho \cdot K_s \cdot K_i \cdot I_g}{L_s}$$

Where:

E_p	Grid step voltage [Volts]
ρ	Soil resistivity [Ω-m]
K_s	Spacing Factor
K_i	Rod distribution factor
I_g	Ground fault current [Amps]
L_s	Effective length of buried conductors [m]
	igual a $(0.75 \cdot L_c + 0.85 \cdot L_R)$

Replacing values:

$$E_p = \frac{400.00 \cdot 0.41 \cdot 2.32 \cdot 1908.00}{0.75 \cdot 1659.00 + 0.85 \cdot 10.00 \cdot 38}$$
$$E_p = 459.44\ Volts$$

4.10 Conclusions

As seen from the potential calculation, the grounding grid voltage does not exceed the voltage tolerable by the human body. As can be appreciated:

Grounding grid step voltage (459.4358 V) is lower than the human body step tolerable voltage (2696.0971 V) and lower than the grid touch voltage (694.1298 V) is lower than the human body touch voltage (840.5479 V).

The conclusion is that the grounding grid layout proposed is safe, IEEE Std.80 compliant and will provide a proper personnel protection.

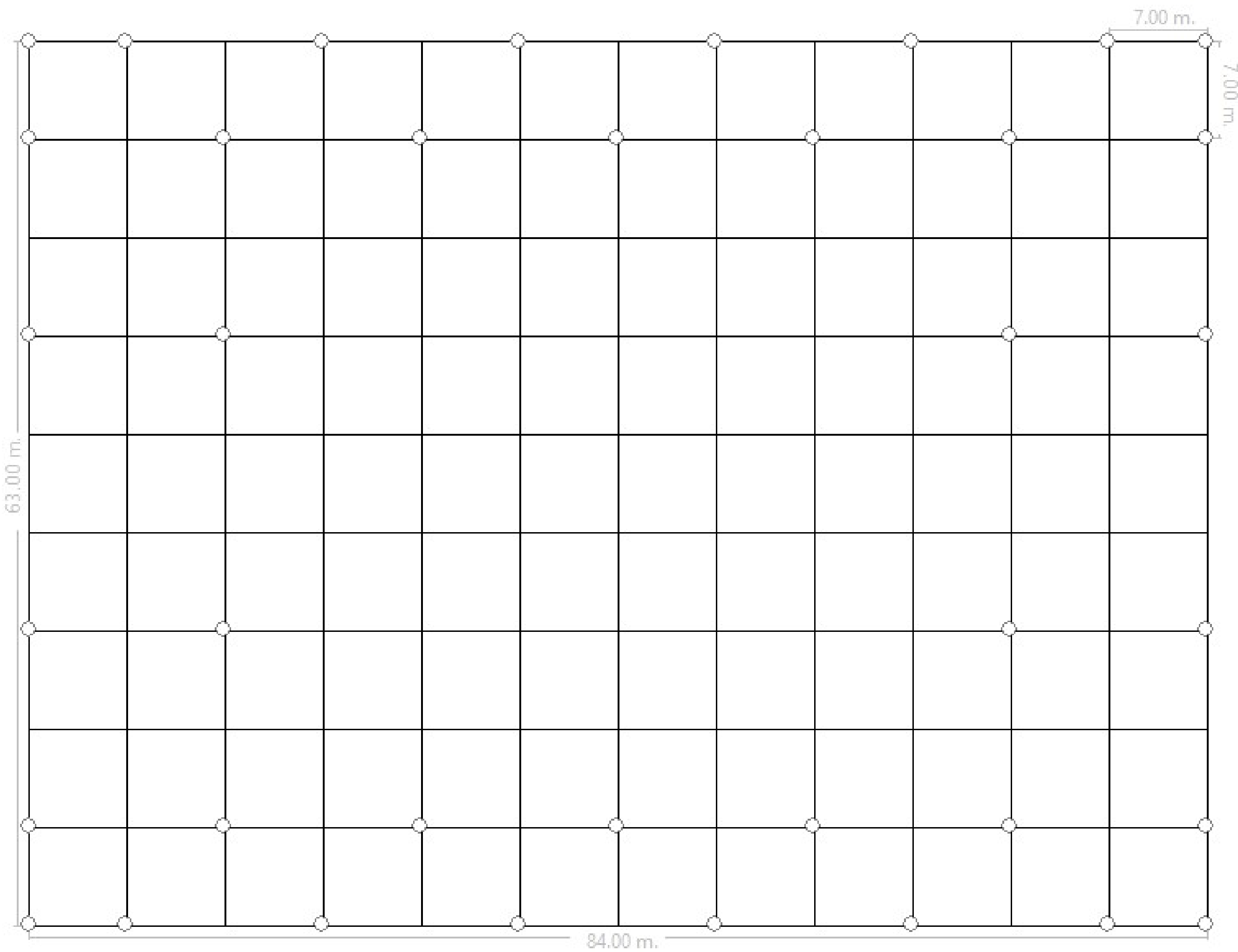

Figure 1: Grounding grid image