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The present work was submitted to the faculty of electrical and mechanical engineering

EVALUATING THE CONDITION OF THE SUBSTATION'S GROUNDING GRID WITH ITS RELATION TO CORROSION

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Ulaanbaatar/Nalaikh, 2024/05/10

Statutory Declaration

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Abstract

This thesis evaluates the condition of the grounding systems in the substations of the Erdenet Mining Corporation. The research involved assessing soil resistivity, measuring grounding grid corrosion, and determining grounding resistance across 13 substations operating at various voltage levels. The analysis revealed critical insights into the grounding equipment's state, the corrosion rates, and the environmental factors affecting the system.

Most substations exhibited grounding resistance values within the permissible limits defined by international and Mongolian standards. However, certain substations, like TSRP-2 and TSRP-3, exhibited significant mechanical damage due to corrosion, necessitating immediate intervention. Ampacity calculations demonstrated diverse requirements for conductor sizing, ranging from 3.5 kA to 14 kA, with the TSRP-1 substation showing the highest short-circuit current ampacity.

The findings from this study offer valuable recommendations for ensuring safety, enhancing grounding system reliability, and improving corrosion protection measures at the Erdenet Mining Corporation's substations. The results underscore the importance of periodic inspections and targeted interventions to maintain optimal grounding conditions.

1. Introduction

Erdenet Mining Corporation, one of Mongolia's largest mining enterprises, is 100% property of the Government of Mongolia. It was established in 1978 and is situated in Erdenet, within the Orkhon province, approximately 370 kilometers northwest of Ulaanbaatar, the nation's capital [6].

The mine is renowned for its large copper-molybdenum deposits. The mineral resources are mined primarily from the Erdenetiin Ovoo deposit, which spans approximately 10 kilometers. With an estimated reserve of over 1.5 billion tons of ore containing 0.54% copper and 0.036% molybdenum, the deposit has historically made significant contributions to the country's economy. Erdenet Mining Corporation is one of the top taxpayer companies in Mongolia. In 2021, 1.2 trillion MNT was accounted for in the government and local budgets [6].

The Erdenet mine processes around 32 million tons of ore annually, yielding about 530,000 tons of copper concentrate and roughly 4,500 tons of molybdenum concentrate. The extracted ore is hauled to the primary crusher using dump trucks before being conveyed to the milling facility. Advanced processing and refining technologies are used to extract copper and molybdenum concentrates, which are then exported to international markets [7].

The Erdenet Mining Corporation continues to expand its operations, investing in modern equipment and research to optimize extraction processes. These efforts aim to improve efficiency and ensure sustainable mining practices. Additionally, Erdenet Mining Corporation strictly follows environmental and safety standards, taking realistic actions to eliminate dust emissions and manage waste effectively. Its central role in Mongolia’s mining industry has a steady output and importance in the global supply chain [7].

1.1 Electrical Department of the mine

The Electrical department “Цахилгаан цех” of Erdenet Mining Corporation was founded and constructed in 1977. The electrical department supplies power to all facilities of the factory, as well as the consumers in the industrial region, using its substations: 110/6/6 kV, 110/35/6 kV, 110/6 kV, and 35/6 kV. It distributes electrical energy through 26 transformers with a total capacity of 2500-63000 kVA, using both overhead and underground cables [6].

1.2 Problem Statement

This thesis aims to assess the status of the grounding equipment and connections between grounding elements within the 12 substations of the Erdenet LLC Electric Plant, including 110/35/10 kV, 110/6 kV, and 35/6 kV. The grounding resistance and soil resistance data and images of dug-up grounding grids of the 12 substations are provided using this data the following analyses were conducted.

The objective is to analyze the given measurements and offer recommendations, as well as to summarize and evaluate the actual performance of the grounding equipment. It will provide future-oriented recommendations focused on the substation at the open-pit mine.

Measuring the resistance of high-voltage substations' grounding grid, identifying the risk of corrosion in grounding grid's metal structures at substations (110, 35, and 6 kV), visually assessing grounding grid, and delivering comprehensive evaluations. Based on the results, select appropriate measurements and recommend necessary improvements in grounding structures.

1.3 Scope of thesis

Within the ownership of the electrical department, the 110/6/6kV, 110/35/6kV, 110/6kV, and 35/6kV substations the following examination and analysis were performed.

1. Analyze the condition of the grounding grid and its corrosion state and thickness.

2. Provide recommendations for conducting specific measurements of grounding conditions, with particular emphasis on substations like those at open-pit mine.

3. Visibly identify grounding elements in the substations and mark any exposed connections to prevent corrosion while also providing diagrams.

4. By utilizing the processed data to make recommendations for future grounding grid improvement and geological location.

Measurements and analysis were performed on the following substations.

№	Substation name	Voltage level [kV]
1	RP-1,2 (РП - 1,2 ГК)	110/6/6
2	RP-9 (РП - 9. КСИ)	110/6/6
3	TSRP-2 (ЦРП - II Подъём)	110/35/6
4	TSRP-3 (ЦРП - III Подъём)	110/6
5	TSRP-4 (ЦРП - IY Подъём)	110/6
6	TSRP-1 TETS (ЦРП- 1. ТЭЦ)	35/6
7	TSRP-5 (ЦРП- 5. РМЗ)	35/6
8	TSRP-7 (ЦРП- 7 НСОВ)	35/6
9	TSRP-10 (ЦРП- 10 ХВОСТ)	35/6
10	TSRP-1 (ЦРП- I Подъём)	35/6
11	TSRP-4/1 (ЦРП-4/1 РОР)	35/6
12	TSRP-4/2 (ЦРП-4/2 РОР)	35/6

Table-1. Substation name and voltage levels

2. Theoretical background

2.1 Short Circuit

A short circuit is an unintended connection between two or more points in an electrical circuit, for example, 3 phases, line to line, line to line to ground, and line to ground faults. Short circuit fault is always avoided because it is a low-resistance path for current flow. This path bypasses the intended load or resistance in the circuit, causing an excessive current to flow, potentially leading to overheating, equipment damage, or electrical hazards such as fires or electric shocks [9].

2.1.1 AC Short Circuit Fault Types

In a 3-phase system, faults can occur between different lines and the ground. Understanding the nature of these faults is crucial in designing protective measures.

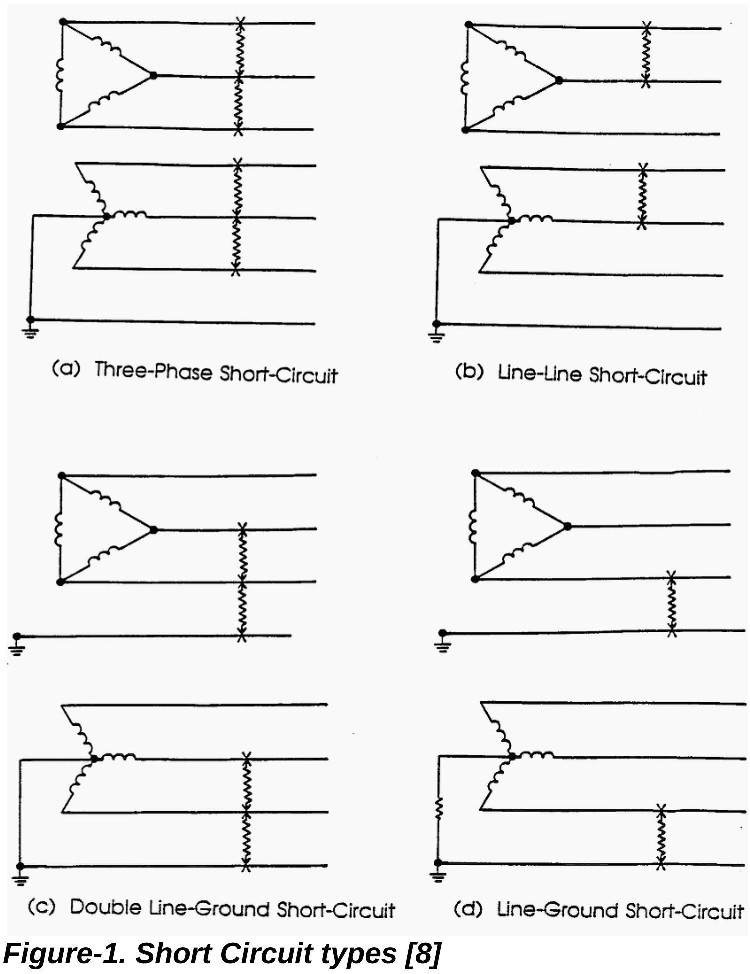

Figure-1. Short Circuit types [8]

Line-to-line faults, as shown in figure-1 (b), occur more frequently than three-phase faults and typically produce approximately fault currents that are 87% of three phase fault current. Since this type of fault creates an imbalance across the three phases, its fault current is rarely calculated because it doesn't represent the maximum fault current possible [8].

Line-to-ground faults, as depicted in figure-1(d), are the most frequently occurring faults and generally cause the least disruption to the system. The current in the faulted phase may range from nearly zero up to a value just above that of a three-phase fault. Accurately determining the current magnitude for line-to-ground faults requires specialized symmetrical component calculation techniques.

Grounding conductors conduct this high current for relay protection fault clearing time. Depending on the fault clearing time and maximum allowable temperature of the conductor the cross-sectional area and maximum fault current the grounding grid is calculated [8].

A three-phase fault as shown in figure-1(a), refers to a situation where all three conductors are physically connected with no impedance between them, similar to being secured tightly together. In a balanced, symmetrical system, the fault current magnitude remains equally distributed across all three phases [8].

Although this type of fault is relatively rare, its results are used to select protective devices because it typically produces the highest short-circuit current values.

Line-to-line-to-ground faults, illustrated in figure-1(c), often start as line-to-ground faults and then expand to involve a second phase conductor. This creates an unbalanced fault condition. The fault current magnitudes for double line-to-ground faults are generally higher than those for line-to-line faults but lower than those for three-phase faults. Calculating these currents necessitates symmetrical components analysis. The impedance plays a significant role in the calculations and should be accurately determined [9].

2.2 Step and Touch Voltage

Step voltage refers to the surface potential difference experienced by a person walking a distance of 1 m without contacting any grounded object with their feet.

Touch voltage represents the potential difference between ground potential rise (GPR) and the surface potential where a person stands while touching a grounded structure with their hand [1].

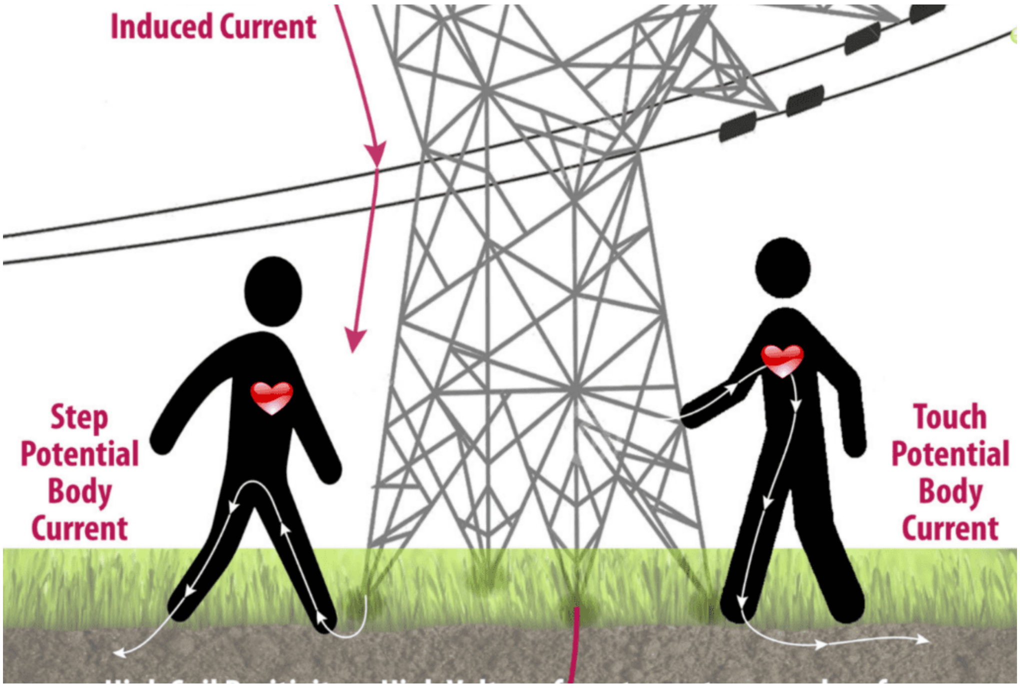

Figure-2. Step and Touch voltage visualization [10]

The impact of electric current on the human body varies based on factors like duration, magnitude, and frequency. Exposure to currents at frequencies of 50 Hz or 60 Hz poses significant risks, potentially leading to conditions like ventricular fibrillation, which can halt blood circulation. Even small currents around 0.1 A can prove lethal [1].

2.3 Soil Resistivity

Soil resistivity is one of the most important parameters for grounding systems' performance. It describes soil resistivity as how resistive the soil is to the flow of electricity. Generally low soil resistance is preferred for almost all grounding systems. Most soils can behave as a conductor of resistance and as a dielectric. With the exception of high-frequency and steep-front waves that penetrate highly resistive soil, the charging current remains negligible in comparison to the leakage current. In such cases, the earth can be conceptualized as a purely resistive entity.

The soil resistivity surrounding ground electrodes may experience alterations due to the flow of current from electrodes in the nearby soil. The thermal characteristics and moisture content of the soil play pivotal roles in determining whether a current of specific magnitude and duration induces significant drying, consequently amplifying the effective soil resistivity [11].

The electrical resistance of soil depends on many factors such as soil composition, moisture content, and sand content. Therefore, the electrical resistance of soil may remain stable or vary greatly.

Soil Type	Average Resistivity (Ω·m)
Surface organic soil	100 - 5000
Mud	200-10000
gravel sand mixture	5000-100000
Limestone	500-10000
Shale mud	2000-200000
Rocky sand	100000
Igneous/Volcanic Rock	50-50000
Biogenic soil	1000-10000

Table-2. Average soil resistivity [4]

2.3.1 Moisture and chemical content

Soil resistance is significantly influenced by moisture and salt content, as its primary electrical conductivity is determined by the electrolyte composition. Variations in weather, season, soil depth, and freezing conditions can lead to substantial changes in soil resistance. The table illustrates the relationship between soil resistance characteristics and moisture content [12].

Moisture content [%]	Resistance [Ω*cm]
0	$1000 \cdot 10^6$
2.5	250000
5	165000
10	53000
15	21000
20	12000
30	10000

Table-3. Soil resistivity relationship between moisture content [12]

The table shows that soil without moisture acts as an insulating material, with a resistivity of 1000 × 10^6 Ω·cm. However, when the moisture content exceeds 15%, the soil's resistance drastically decreases by around 100,000 times to approximately 13,000–21,000 Ω·cm. The following table presents the resistivity of sandy mud with 15% moisture content at 17℃, in relation to its chemical salt content.

Salt Content [%]	Resistance [$\Omega \cdot cm$]
0.0	107000
0.1	1800
1.0	460
5.0	190
10.0	130
20.0	100

Table-4. Soil resistivity relationship between salt content [13]

The table reveals that soil with 15% moisture but no salt has a resistance of 10,700 Ω·cm. However, with just a 1% salt content, the resistance dramatically drops to 460 Ω·cm. When the salt content increases to 5%, the resistance decreases further to just 190 Ω·cm [13].

2.3.2 Temperature effect

When the ground is not frozen, the increase in soil temperature reduces its electrical resistance by almost following a linear law. However, when the soil temperature reaches 0°C and the ground starts to freeze, the resistance increases to ρ = 30,000 Ω·cm. As the freezing process continues and the temperature decreases to around -15°C, the resistance further increases to ρ = 330,000 Ω·cm. The presence of 15.2% moisture in the clay loam significantly impacts soil resistance, which rises with decreasing temperature, as shown in Table 5 [11].

Temperature	Resistivity (Ω·cm)	Temperature (°F)
20°C	7,200	68°F
10°C	9,900	50°F
0°C (Water)	13,800	32°F
0°C (Ice)	30,000	32°F
-5°C	79,000	23°F
-15°C	330,000	14°F

Table-5. Soil resistivity in the relationship between temperature [11]

2.3.3 Seasonal effect

Soil Resistivity depends on its composition, moisture content, temperature, salt concentration, and other factors. Thus, it varies seasonally and annually, affected by phenomena like dry weather, rainfall and freezing leading to periodic changes. Each region's soil resistivity characteristics are essential for accurately designing and calculating grounding systems.

Grounding system resistance with electrodes shows seasonal and annual variations depending on soil depth. For instance, at the topsoil 0.9 meter and deeper layers 3 meter, variations occur based on moisture and frost depth. Figure 3.15-a illustrates this concept. Installing 3/4-inch galvanized iron pipes in rocky or clay soil stabilizes the soil moisture around the grounding electrodes. Additionally, placing the electrode 0.3 meters deep ensures minimal annual or seasonal fluctuations in grounding system resistance [8].

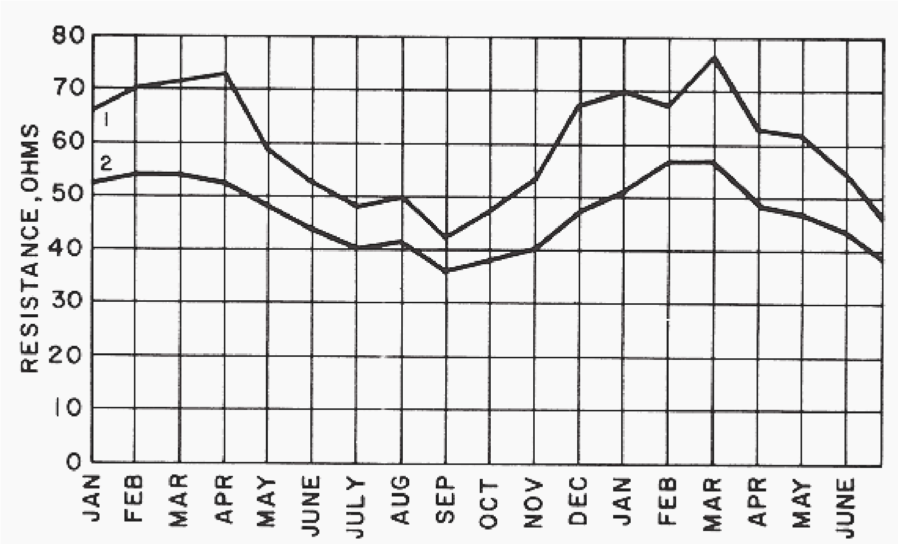

Figure-3. Soil resistivity in relation to season [8]

Curve 1 is 0.9-meter-deep buried electrode

Curve 2 is 3-meter-deep buried electrode

2.3.4 Chemical treatment of soil

In challenging environments where driving deeper ground rods isn't possible due to underlying hard rock or similar obstacles, chemical treatment of the soil can effectively reduce grounding electrode resistance. Selecting appropriate treatment chemicals requires careful consideration of the potential corrosive effects on electrodes, as well as adherence to environmental regulations [8].

2.3.4.1 Selecting Treatment Chemicals:

- **Magnesium Sulfate**: This is the least corrosive option and provides effective results.
- **Copper Sulfate and Rock Salt**: Copper sulfate offers a moderate level of corrosion resistance, while rock salt is cost-effective and can significantly improve resistance if applied in a trench around the electrode (see Figure 5).

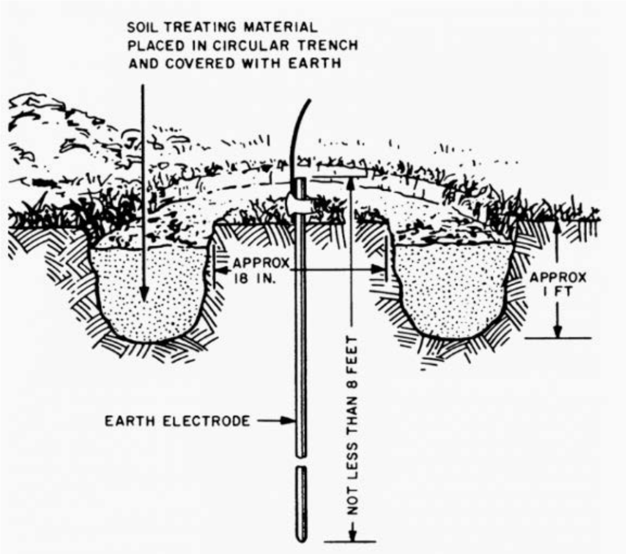

Figure-4. Soil chemical treatment [8]

It is crucial to note that soluble sulfates can damage concrete structures and should be kept away from building foundations. An alternative method involves backfilling around the electrode with specialized conductive concrete products like bentonite.

2.3.4.2 Impact of Electrode Length and Diameter:

- **Electrode Length**: Increasing the length of the grounding rod can substantially decrease resistance. Doubling the length can reduce resistance by approximately 40%. For instance, Figure 1 illustrates this reduction, where longer electrodes yield lower resistance values [8].

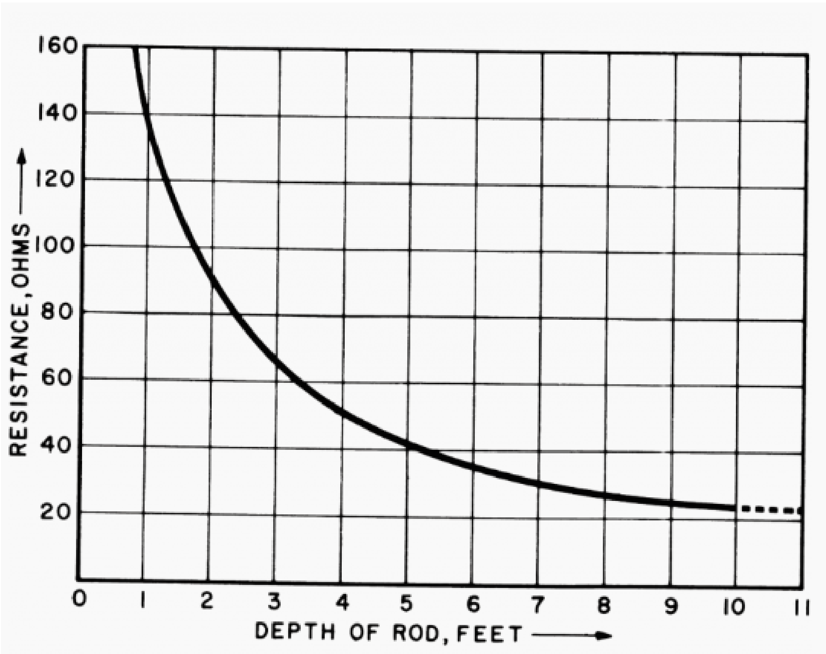

Figure-5. Resistance relationship between electrode depth [8]

* **Electrode Diameter**: Although increasing the diameter of the electrode decreases resistance, the effect is minimal compared to length. Doubling the diameter generally reduces resistance by only around 10%, as shown in Figure 2. Therefore, increasing the diameter is advisable only when the rod must penetrate hard terrain.

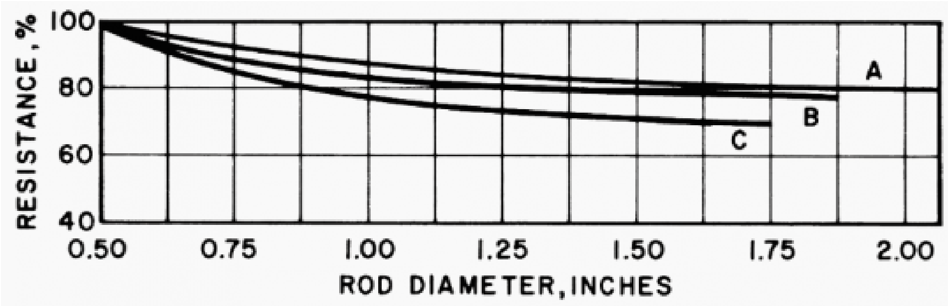

Figure-6. Soil resistivity relationship between rod diameter [8]

Using Multiple Rods:

Installing multiple grounding rods effectively reduces resistance because each rod acts as a parallel resistance. However, the overall resistance is not reduced exactly by half of each individual rod's resistance due to interactions between the rods. Practical reduction values can be inferred from Figure 4 [8].

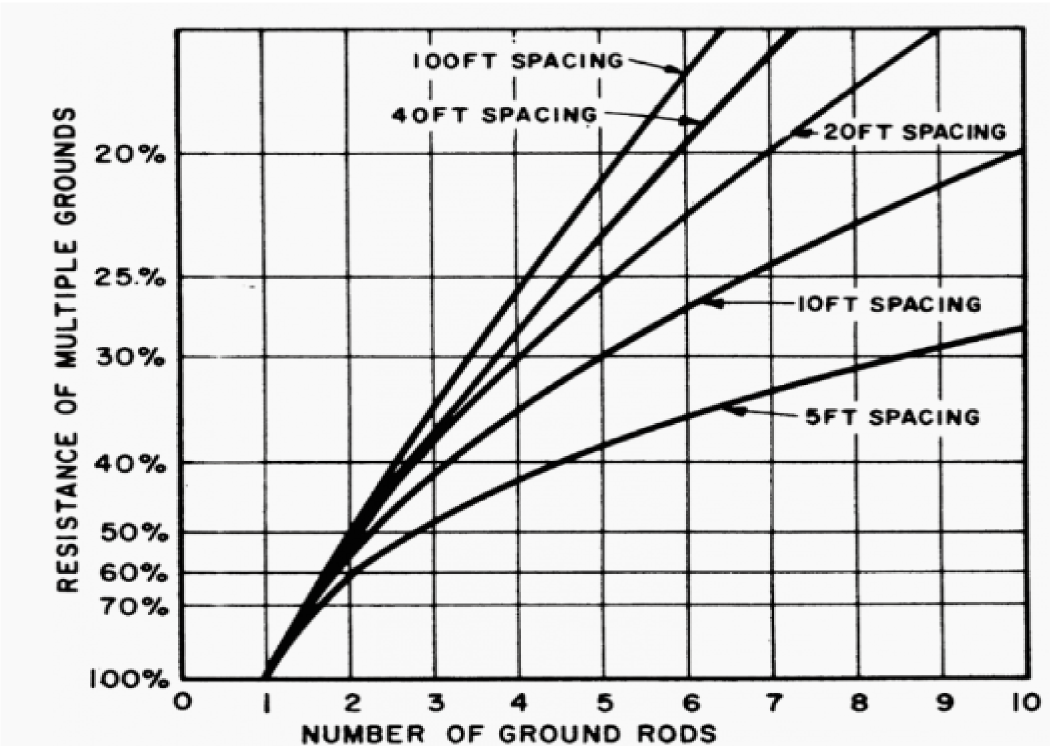

Figure-7.1. Soil resistivity relationship between number of electrodes [8]

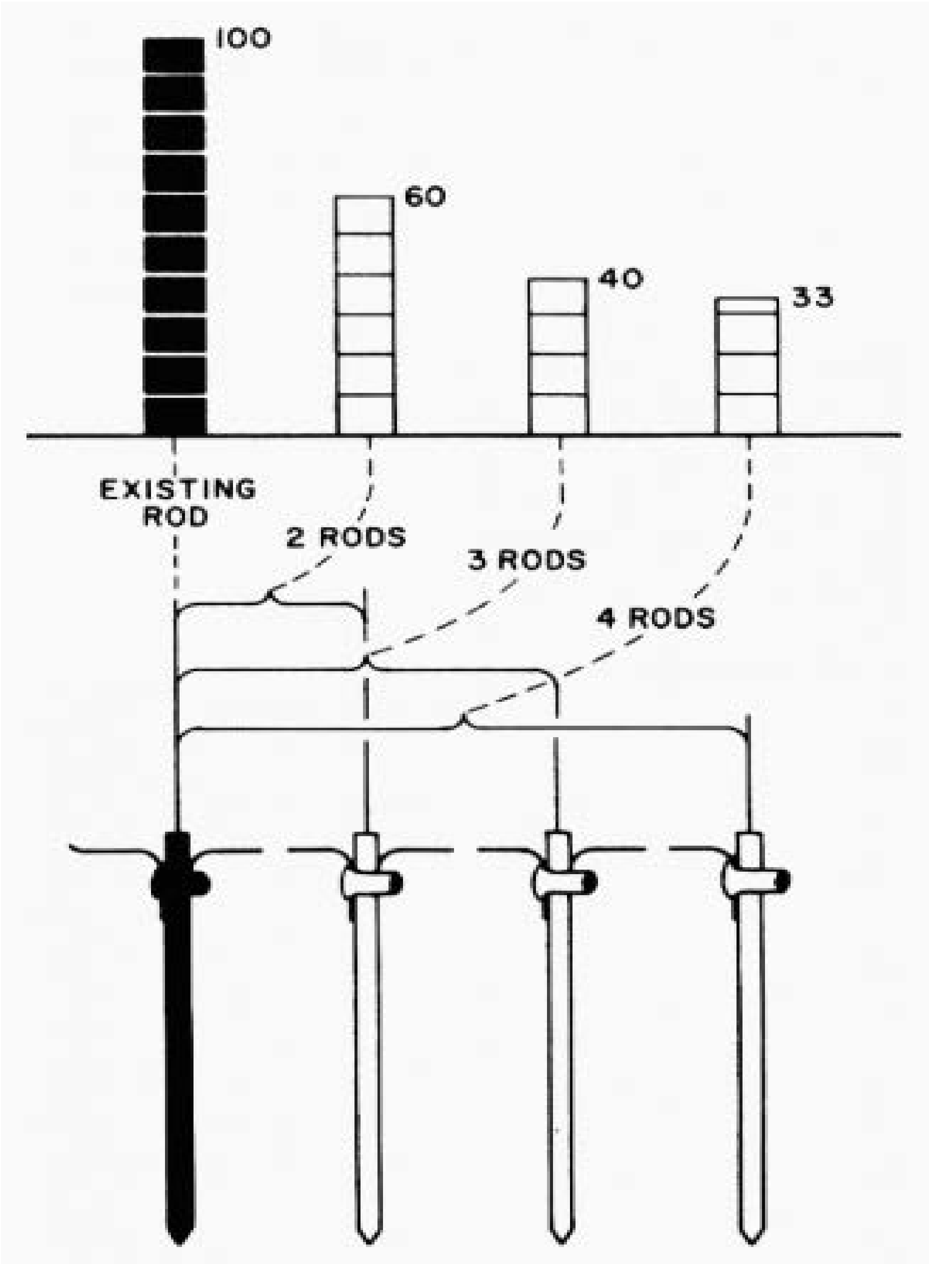

Figure-7.2. Soil resistivity relationship between number of electrodes [8]

Chemical Treatment and Seasonal Variation:

Chemical treatment can stabilize resistance by reducing the seasonal fluctuations caused by periodic soil wetting and drying. Figure 6 illustrates these variations. However, due to the gradual leaching of chemicals by natural drainage, this is not a permanent solution. The treatment needs periodic replenishment, which depends on soil porosity and rainfall.

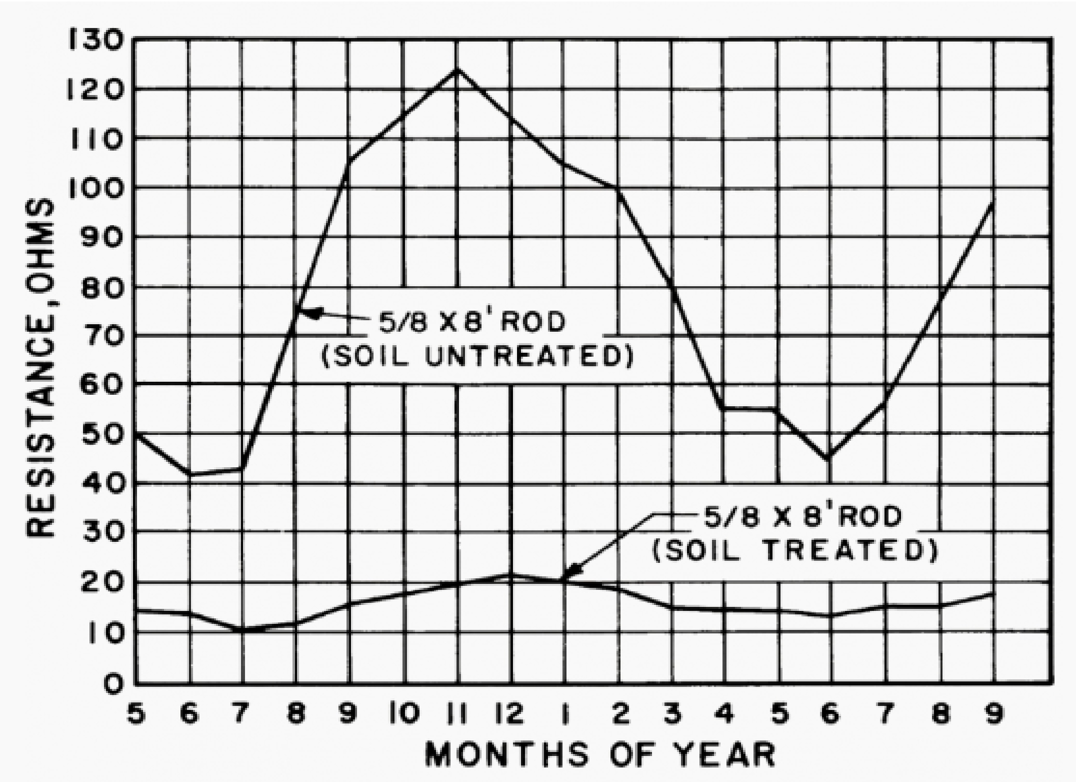

Figure-8. Soil resistivity difference between chemically treated and untreated soil [8]

2.3.5 Uniform soil model

A uniform soil model can be utilized instead of multilayer models whenever two-layer or multilayer computational tools are unavailable. However, estimating an upper bound of errors in relevant grounding parameters remains challenging due to soil heterogeneity. When the resistivity contrast between different soil layers is moderate, an average soil resistivity value can be used as a first approximation to establish an order of magnitude [11].

Arithmetic Averaging of Resistivity:

In cases where resistivity variations are within an acceptable range, a uniform soil resistivity estimate can be derived by taking the arithmetic average of measured apparent resistivity data using the following equation: [1]

$$\rho_{a(avg)} = \frac{\rho_{a(1)}+\rho_{a(2)}+\rho_{a(3)}+\dots+\rho_{a(n)}}{n} \quad (1)$$

Where:

$\rho_{a(1)} + \rho_{a(2)} + \rho_{a(3)}+\dots+\rho_{a(n)}$	is apparent resistivity data
N	is total number of measurements

Limitations of the Uniform Soil Model:
Most soils deviate significantly from the uniform soil model criteria. The resistivity of soil varies greatly due to differing moisture levels, mineral composition, and temperature, making it challenging to apply a uniform soil model accurately [11].

2.3.6 Two-layer soil model

The model assumes an abrupt change in soil resistivity at the boundary between the two layers. The reflection factor K, which quantifies the resistivity difference between the layers, is calculated using the following equation.

$$K = \frac{\rho_2 - \rho_1}{\rho_1 + \rho_2} \tag{2}$$

where

ρ_1 is the resistivity of the upper soil layer (Ω·m),

ρ_2 is the resistivity of the lower soil layer (Ω·m).

IEEE Std 81-1983 provides methods to determine the equivalent resistivities of the upper and lower soil layers, along with the thickness of the upper layer.
These methods typically involve the Wenner four-pin or driven rod soil resistivity measurements [1].

2.4 Methods to Measure Grounding Grid Resistance

Earth resistance testing involves the quantification of a grounding system's resistance relative to the Earth. This examination is conducted to ascertain the efficacy and safety of the grounding system.
Precise measurements of ground resistance are instrumental in detecting and rectifying potential complications, such as insufficient grounding or elevated soil resistivity. These complications can potentially impede the optimal performance of electrical systems.
The methodologies for conducting earth resistance testing are outlined in the IEEE Standard 81.

2.4.1 two-point (dead earth) method

The dead earth method, also known as the Two-electrode method, serves as a practical solution for measuring earth resistance in situations where additional test electrodes cannot be accommodated. This method becomes particularly relevant when space constraints or other limitations preclude the use of conventional testing approaches.

In instances where a substantial metallic water pipe network is available, it can serve as a viable alternative for evaluating the earth resistance of an existing electrode. The extensive coverage of the water system typically results in minimal resistance, rendering it conducive to accurate measurements.

However, it's crucial to note that the dead earth method is applicable only under specific conditions. Firstly, the water-pipe system must be entirely metallic, ensuring negligible resistance. Additionally, the electrode under evaluation should be in proximity to the piping system to facilitate effective testing.

The dead earth method should be considered as a last resort for earth resistance measurement when conventional testing methods are impractical or unavailable. Its utilization is contingent upon the fulfillment of the aforementioned criteria, making it a viable option only under specific circumstances [14].

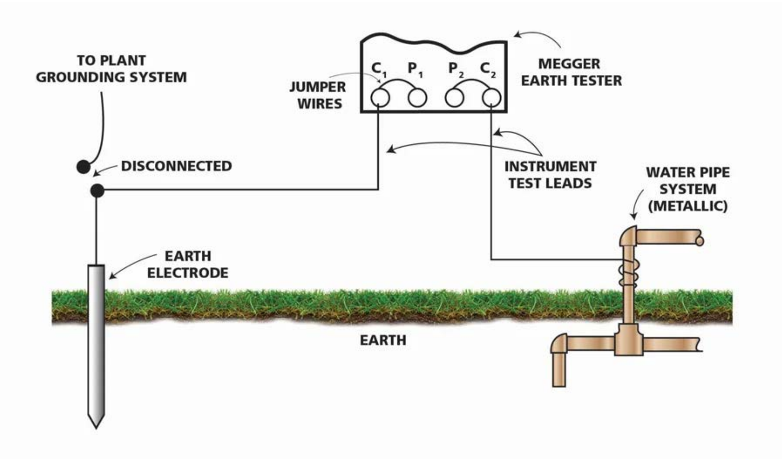

Figure-9. Dead Earth method scheme [14]

2.4.2 three-point (Fall-of-potential) method

The 3-point method, often referred to as the “fall of potential” method, involves the ground electrode under examination and two other electrically independent test electrodes, typically denoted as P (Potential) and C (Current). These test electrodes may possess a higher ground resistance (lesser “quality”), but they must remain electrically independent from the electrode under examination. An alternating current is introduced through the outer electrode C, and the voltage is measured at an intermediary point between them using the inner electrode P. The ground resistance is then computed internally by the test equipment using Ohm’s Law [14].

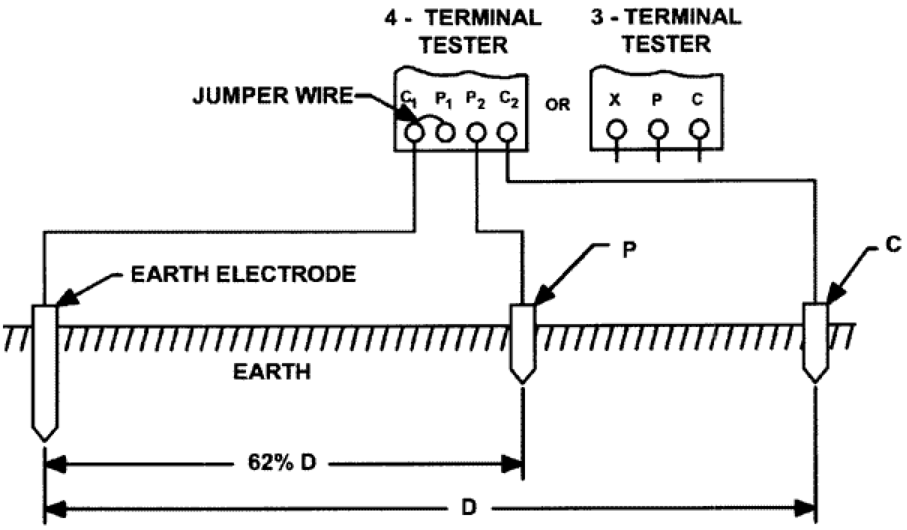

Figure-10. Fall Potential method scheme [14]

During a measurement, the objective is to place the auxiliary test electrode C at a sufficient distance from the ground electrode under examination such that the auxiliary test electrode P lies outside the effective resistance areas of both the ground system and the other test electrode (refer to Figure 9). If the current test electrode, C, is positioned too closely, the resistance areas will overlap, resulting in a significant variation in the measured resistance as the voltage test electrode is relocated. If the current test electrode is appropriately positioned, there will be a 'flat' resistance area (or very nearly so) somewhere between it and the ground system, and any alterations in the position of the voltage test electrode should only result in minor changes in the resistance figure [15].

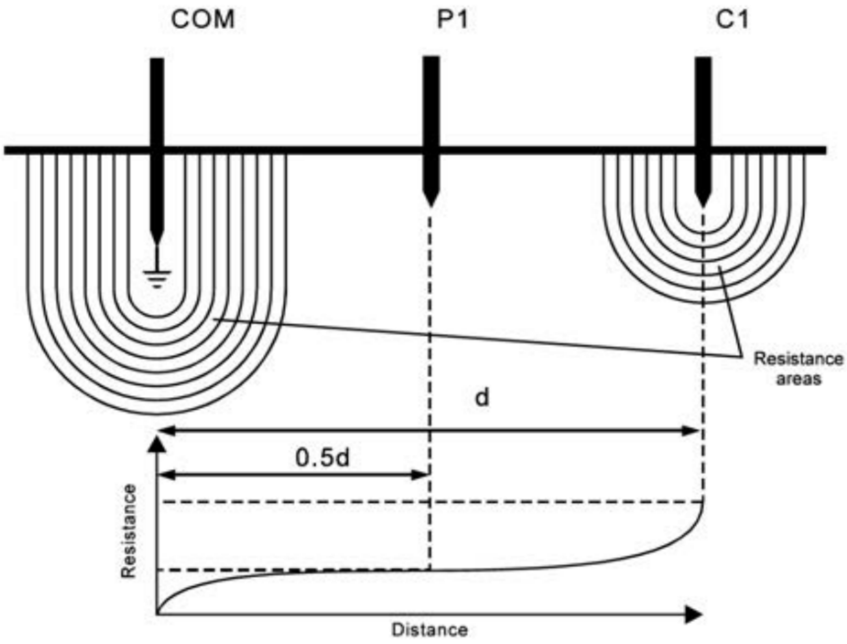

Figure-11. Fall Potential method electrode placement scheme [15]

The instrument is connected to the ground system under examination via a short test cable, and a measurement is taken. The accuracy of the measurement can be influenced by the proximity of other buried metallic objects to the auxiliary test electrodes. Objects such as fences, building structures, buried metal pipes, or even other grounding systems can interfere with the measurement and introduce errors. It is often challenging to determine a suitable location for the test stakes based solely on a visual inspection of the site, so it is always advisable to conduct more than one measurement to ensure the accuracy of the test.

Measurements are plotted on a curve of resistance vs. distance. Correct earth resistance is read from the curve for the distance that is roughly 62% of the total distance between C1 and C2. There are three basic types of the fall-of-potential method: Full fall-of-potential: A number of tests are made on different spaces of P and a full resistance curve is plotted.
Simplified fall-of-potential: Three measurements are made at defined distances of P and mathematical calculations are used to determine the resistance.
61.8 Rule: A single measurement is made with P at a distance of 61.8% (62%) of the distance between C1 and C2.

2.4.3 Wenner four-pin resistivity measuring method

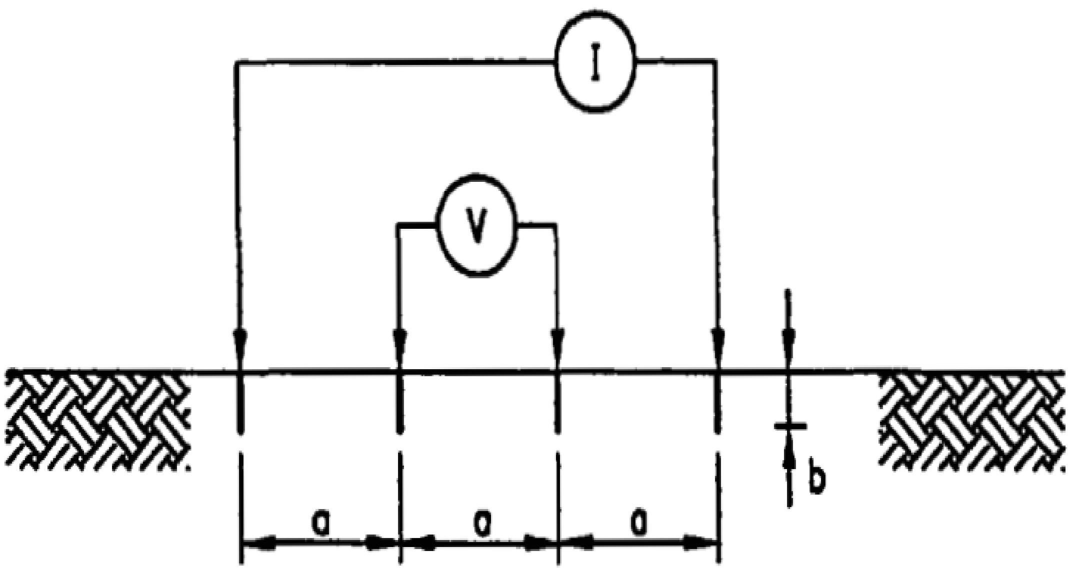

Figure-12. Wenner four pin method scheme [1]

The widely utilized approach for measuring soil resistivity is the Wenner alpha four-pin method. This technique involves positioning four pins equidistantly, passing a known current through the outermost electrodes, and registering the voltage across the inner electrodes [1].

Equipment Setup: Four electrodes, typically metal pins or rods, are inserted into the ground in a straight line. These electrodes are evenly spaced apart, forming a geometric shape resembling a square or rectangle. The distance between the electrodes depends on the depth of investigation and the desired resolution.

Current Injection: A known electrical current is introduced into the soil through the outermost electrodes (the two outer pins). This current flows through the soil between these electrodes [11].

Voltage Measurement: Simultaneously, the voltage drop is measured across the inner electrodes (the two inner pins). This voltage drop occurs due to the resistance of the soil through which the current is passing. The voltage measurement reflects the resistance of the soil between the inner electrodes.

Calculation: Using Ohm's law (V = IR), where V is voltage, I is current, and R is resistance (in this case, soil resistivity), the resistivity of the soil can be calculated. The formula used for this calculation considers the geometry of the electrode array and the measured voltage and current values [1].

$$\rho_a = \frac{4\pi a R}{1+\frac{2a}{\sqrt{a^2+4b^2}}-\frac{a}{\sqrt{a^2+b^2}}} \qquad (3)$$

Where

Ra is the apparent resistivity of the soil in Ohm*m. A and b are respectively electrode distance and depth in the soil.

2.4.4 Clamp-on method

The 3-point method necessitates the disconnection of all earth electrode connections prior to the test, whereas induced frequency tests can be conducted while the system is operational. Clamp-on testing, also referred to as the stateless method of earth testing, offers a straightforward approach to earth resistance measurement, eliminating the need for additional test electrodes.

To assess earth resistance using this method, two clamps are placed around the electrode under examination. One clamp applies voltage to the electrode, while the other measures the resulting current flowing through the ground. By analyzing the voltage and current readings, the ground resistance can be determined utilizing Ohm’s law.

This technique proves particularly effective in scenarios where a series-parallel resistance path is present. For instance, in systems featuring a parallel earth network where the objective is to measure the earth resistance Rx alongside n earth electrodes in parallel, the tester is clamped onto the electrode undergoing testing. As voltage is induced, the current flows through the test electrode and distributes among the remaining electrodes in parallel [16].

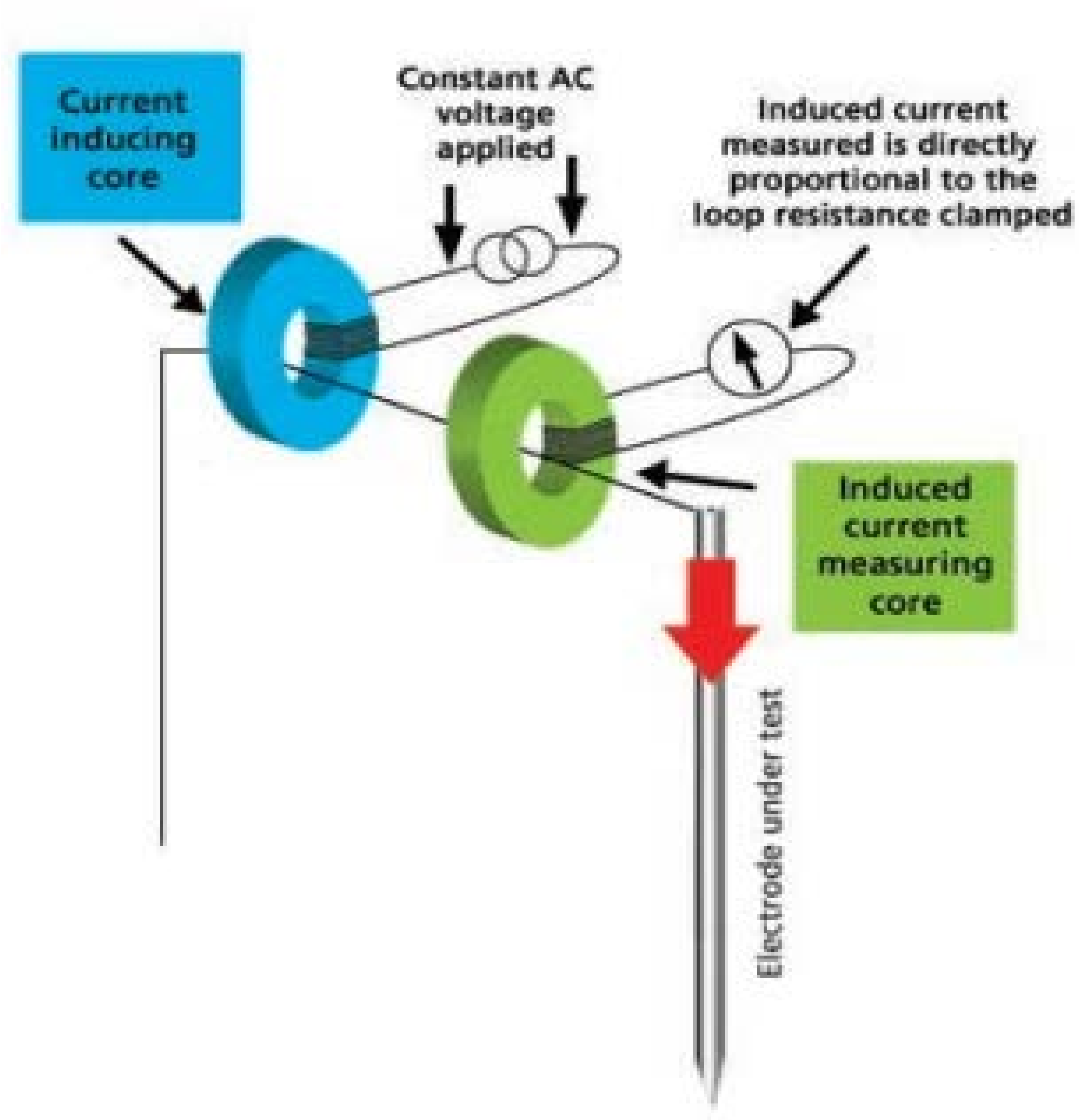

Figure-13. Clamp-on method scheme [16]

2.4.5 Selecting grounding Electrode location

A low-resistance grounding electrode relies heavily on finding soil with low resistivity in a location where electrodes can be effectively driven into the ground. Two primary approaches can be used for site selection.

2.4.5.1 Methodology for Unfavorable Locations

To establish a low-resistance electrode in an area with suboptimal conditions, arrange straight lines spaced 3 meters apart across the site. Along one line (a-b-d-c as shown in Figure 11), drive four stakes into the ground at 3-meter intervals but no deeper than 15 centimeters. Measure the resistance (R) between stakes b and c using a method for determining soil resistivity.

Subsequently, shift the stakes along the line to points b-c-d-e, c-d-e-f, and so forth, continuing to test until the entire line has been evaluated. Move to the adjacent line and repeat this procedure until the entire site is covered. The location yielding the lowest resistance value (R) will have the lowest specific soil resistance down to a depth of 3 meters and will likely be the best position for the grounding electrode.

2.4.5.2 Surveying for Greater Depth

If results influenced by the average soil resistivity down to 6 meters are desired, conduct a survey using lines spaced 6 meters apart and stakes driven 6 meters apart. Although this requires more time, such surveys can significantly improve grounding system reliability by identifying areas with optimal soil resistivity.

2.4.5.3 Testing on Paved Surfaces

Tests can also be performed on paved surfaces using a ground resistance tester with high-resistance test circuits.

By following this systematic site selection approach, it is possible to identify the most favorable location for grounding electrodes, thereby achieving a low-resistance grounding system.

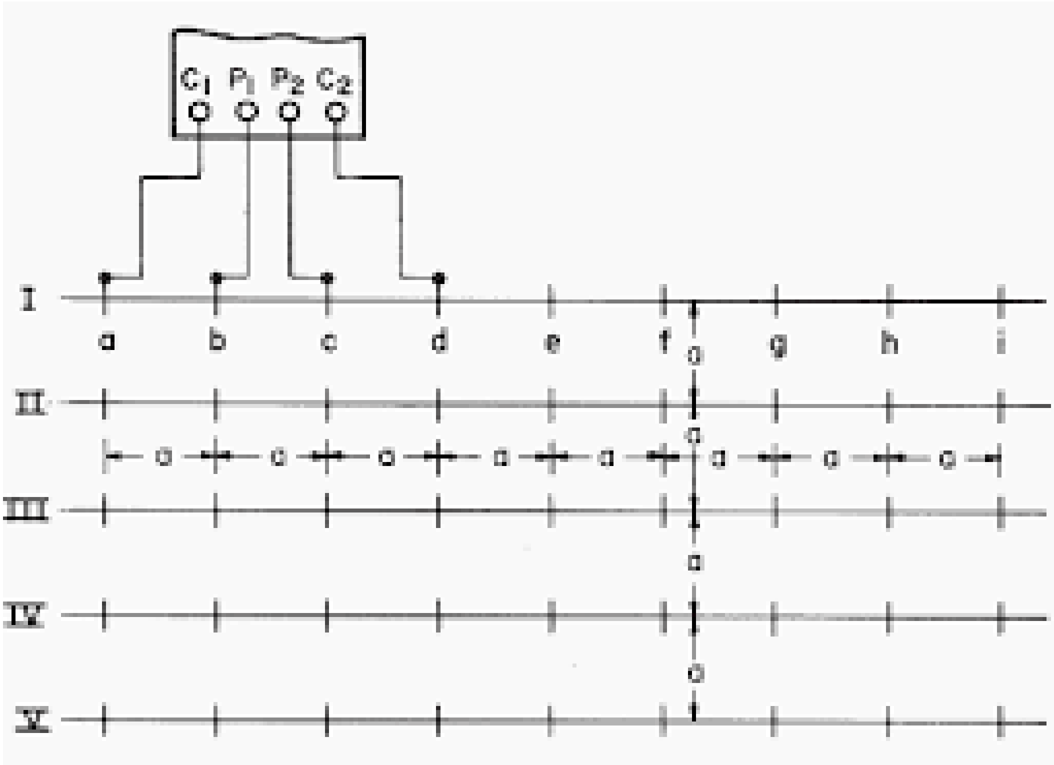

Figure-14. Electrode location testing scheme [14]

2.5 Conductor Selection

2.5.1 Conductor sizing selection

The short time temperature rises in a ground conductor, or the required conductor size as a function of conductor current. These equations evaluate the ampacity of any conductor for which the material constants are known, or can be determined by calculation [1].

$$I = A_{mm^2}\sqrt{\frac{TCAP*10^{-4}}{t_c\alpha_r\rho_r}\cdot ln(\frac{K_o+T_m}{K_o+T_a})} \qquad (4)$$

Where

I is the rms current in kA

Amm2 is the conductor cross section in mm^2

Tm is the maximum allowable temperature in °C

Ta is the ambient temperature in °C

Tr is the reference temperature for material constants in °C

αo is the thermal coefficient of resistivity at 0°C in 1/°C

αr is the thermal coefficient of resistivity at reference temperature Tr, in 1/°C ρr is the resistivity of the ground conductor at reference temperature Tr, in μΩ*cm

Ko is 1/αo or (1/αr) – Tr, in °C

tc is the duration of current in s

TCAP is the thermal capacity per unit volume from Table I, in J/(cm^3-°C)

The ampacity of the conductor equation can be rearranged to give the required conductor size as a function of conductor current.

$$A_{mm^2} = I \cdot \frac{1}{\sqrt{\frac{TCAP*10^{-4}}{t_c \alpha_r \rho_r} \cdot ln(\frac{K_o+T_m}{K_o+T_a})}} \quad (5)$$

The formula can further be simplified as follows in English units.

$$A_{kcmil} = I \cdot K_f \sqrt{t_c} \quad (6)$$

Where:

Akcmil is the area of conductor in kcmil

I is the rms fault current in kA

tc is the current duration in s

Kf is the constant from Table 2 for the material at various values of T, (fusing temperature or limited conductor temperature based on 11.3.3) and using ambient temperature (Ta) of 40 "C.

Equation (4), (5), (6) were taken from reference [1]. The constants can be looked up from also reference [1].

The conductor size is usually selected larger than the area that is based on fusing because of these reasons:

- The conductor must possess sufficient durability to endure anticipated mechanical stresses and corrosive influences throughout the prescribed lifespan of the grounding installation.
- The conductor should have a high enough conductance to prevent any possible dangerous voltage drop during a fault, for the life of the grounding installation
- The conductor's temperature should be limited. Usually, conductors and connections situated in proximity to flammable materials should adhere to stricter temperature constraints.

2.5.2 Average corrosion value

Assuming the surface of the grounding metal has uniform corrosion, the average annual corrosion rate can be calculated using the following formula.

$$ACV = 10 \cdot \frac{\Delta W}{d \cdot A \cdot t} \quad (7)$$

Where

ACV	Average corrosion value;	$[\frac{mm}{year}]$
ΔW	Mass reduction due to corrosion	[gram]
d	Density of the metal	[gr/cm^3]
A	Area of metal	[cm^2]
T	Work lifespan	[year]

3. Literature Review

Reference [1] discusses a comprehensive guide for ensuring safety in the grounding of AC substations. It primarily focuses on outdoor AC substations, encompassing distribution, transmission, and power plant substations. The methodologies outlined in the standard are also applicable to the indoor components of these substations.

Reference [3] proposes a simple hand calculation-based formula for finding grounding mesh resistance. The proposed method in this paper simplifies calculations through a formula derived from the numerical moment method and the concept of current images. It accounts for parameters like conductor size, mesh size, and grid depth. It provides accurate results across a range of conditions. The paper also compares the proposed formula with other known formulas and computer simulated grounding grid resistance. The new formula showed a small error margin compared to the computerized analysis method (2.36% at 0.25m depth, decreasing to 0.13% at 1m depth). This contrasts with the existing formulas, which generally became less accurate as grid depth increased. Overall, the document provides a comprehensive solution for accurately calculating substation grounding grid resistance using a simpler approach that outperforms other widely recognized methods.

Reference [4] discusses an alternative design substation grounding in areas of high ground resistance. It discusses various methods for designing a substation earthing system without modifying the soil properties with additives or adding a grounded cavity to achieve low resistance.

Reference [5] focuses on grounding methodologies for direct current (DC) systems in industrial park distribution networks featuring both AC and DC power. The choice of an appropriate grounding method is crucial as it affects fault detection and clearance, insulation levels, relay protection reliability, and interference with communication and signal systems.

Reference [6] examines the verifying grounding grid continuity in power systems to ensure safety and performance. It presents the AC current injection method as a practical approach for continuity testing. This technique involves injecting AC current into the grounding grid and measuring voltage drops at various points. By analyzing the resultant voltage profiles, continuity issues or defective connections within the grounding grid can be accurately identified. The paper discusses these matters by detailing the method's application, highlighting its effectiveness in assessing the integrity of grounding connections. Furthermore, it provides simulation results and field test data, demonstrating that this approach can reliably pinpoint faults, thus ensuring the grid's reliability and enhancing overall safety.

4. Methodology

The Electrical Department of the Erdenet Mining Corporation every 10-year conducts inspection of the grounding electrodes and grids in their substations and electrical infrastructure. Last inspection was conducted in 2018. This evaluation involved thoroughly analyzing the condition of the grounding grid, assessing corrosion levels, and identifying any potential damages. Corrosion on the grounding grid was discovered and measured, and corrective actions were taken, including the removal of corrosion and addressing any detected issues. Specifically, some ribbon-shaped grounding conductors had developed holes, which were identified and treated during this inspection.

The grounding grid resistance testing of this is 3 electrode methods.
From the following figure we can see all substations grounding grid resistivity measurements.

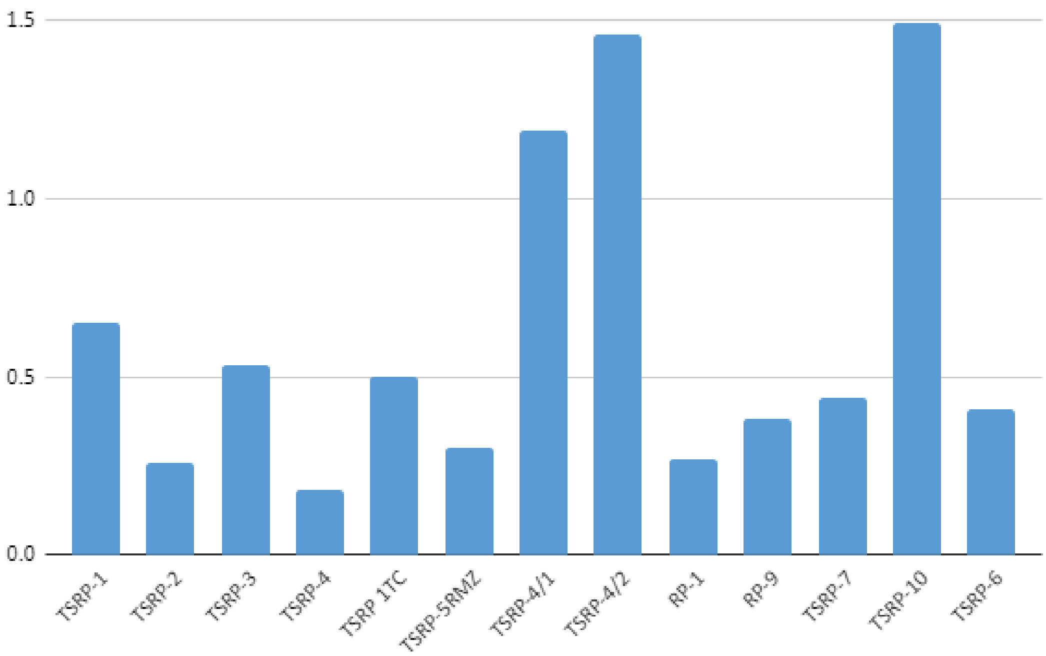

Figure-15. Substation grounding grid resistance [Ω]

4.1 Substation soil resistivity

The soil resistance near Erdenet Mining Corporation's 110/35.6 kV high voltage substations was measured using Werner's four-pin method, with electrode distances set at 1 meter, 3 meters, and 6 meters. These distances were selected considering the specific natural environment of Erdenet's soil properties. According to the IEEE 80-2000 standard, the soil at all high voltage substations should be considered as a double-layered type. Following this standard, the grounding electrode depth should be at least 3 meters below ground.

Measurement locations were selected near the substations, ensuring that the influence of nearby overhead transmission lines and other live power objects was negligible. However, other infrastructures built atop almost all the substations' grounding grids posed significant challenges in accurately measuring the grounding grid's resistance.

Soil resistance was measured at eight substations using three different measuring devices: Megger, an American product, and the Russian-made MRU101 and “Φ4103” meters. The original electrical plan drawing for the 110/35/6kV and 110/6kV substations that are in work for more than 40 years were looked up and found. The electrical drawing was made in 1974. From the drawing that soil resistivity was initially considered to be 100 ohm-meters. The grounding grid resistance was specified to be less than 0.5 ohms for 110 kV and less than 4 ohms for 35 kV. In the following figures soil resistance measurements are shown.

The below table shows measured grounding resistances near 8 substations. Using different soil resistance measuring devices.

Measuring Point	Distance [meter]	Megger	MRU101	“Φ4103”
TSRP-1	1	77.4		
	3	269.3		
	6	327.1		
TSRP-2	1	75.6	74.5	
	3	37.4	47.1	
	6	29.01	32	
TSRP-3	1			23.8
	3			50.8
	6			79.1
TSRP-4	1			79.1
	3			130.9
	6			203.4
TSRP-1 TETS	1		31.5	
	3		41.7	
	6		28	
TSRP-5	1		37.9	
	3		65	
	6		78.1	
TSRP-4/1	1		35.3	
	3		55.2	
	6		93.5	
TSRP-4/2	1		90.7	
	3		90	
	6		104	

Table-6. Substation resistance measurement using multiple tool

Measured Substations	1 meter	3 meters	6 meters
TSRP-1	77.4	269.3	327.1
TSRP-2	75.6	37.4	29
TSRP-3	23.8	50.8	79.1
TSRP-4	79.1	130.9	203.4
TSRP-1 TETS	31.5	41.7	28
TSRP-5	37.9	65	78.1
TSRP-4/1	35.3	55.2	93.5
TSRP-4/2	90.7	90	104
RP-1	167.04	266.58	366.6
RP-9	62.3	58.4	61.2
RP-7	63.5	83	130
TSRP-10	31.7	66.1	55.3
TSRP-6	45.5	135	160
Average	63.17	103.80	131.95

Table-7. Soil resistance values with different depth

The graph below provides a graphical representation of Table 7. The graph illustrates a clear correlation as the depth of the electrode increases, so does the soil resistance.

A notable observation from the graph is that TSRP-1 and RP-1 exhibit similar soil resistance values, ranging from approximately 320 to 370 ohms. This is significantly higher compared to the other values.

On the other hand, TSRP-4, TSRP-7, and TSRP-6 present moderate resistance levels, fluctuating between roughly 130 to 200 ohms. This places them in the middle range of the observed soil resistances.

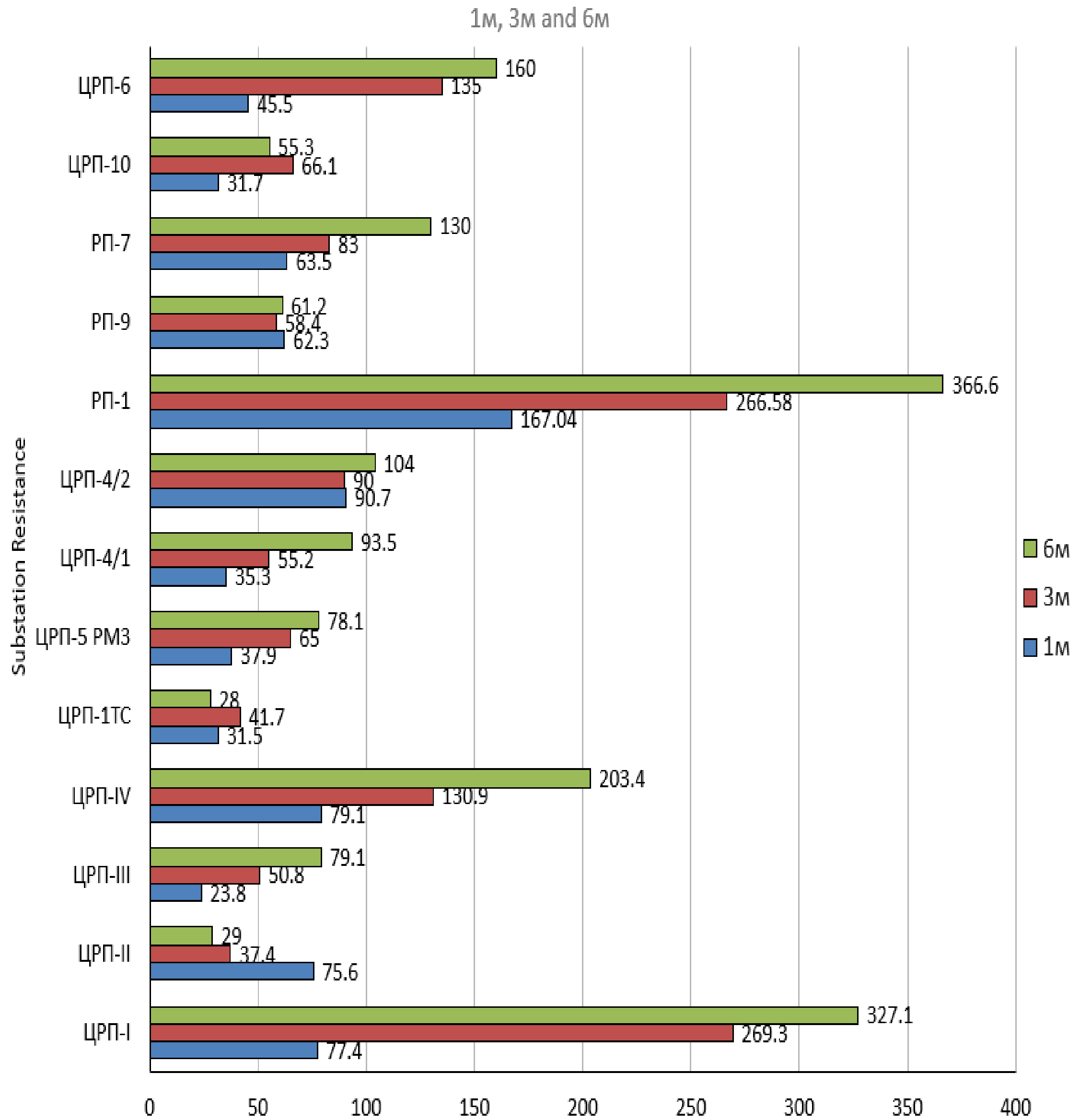

Figure-16. Soil resistance values with different depth

From Figure-16 we can see that the TSRP-6, TSRP-4, TSRP-1 and RP-9 substations' soil resistance is noticeably higher than the rest of the of the substations. Also from figure 15 we can see TSRP-4/1, TSRP-4/2 and TSRP-10 substations' grounding grid resistance is much higher than the rest of the substations' grid resistance. Even though the soil resistance of these substations are not that high compared to the rest of the substations. Therefore, actions to improve the soil resistance should be implemented near the mentioned substations. For example, one way to improve the soil resistance is by chemical treatment using magnesium sulfate. Because magnesium sulfate is the least corrosive solvent, the grounding grids already have been corroded severely. Chemical treatment should be done around every 4 years.

4.2 Grounding grid corrosion

The Erdenet Mining Corporation, along with its Electrical Department, has been operational for approximately 40 years. Over this period, the grounding grids have been gradually deteriorating due to corrosion. The following graphs illustrate the extent of this corrosion, indicating the amount of material that has been lost as a result.
The following figures show the corrosion visually.

Figure-17. Podiem-3: 110/6kV substation 1st transformer deep neutral grounding

Figure-18. Podiem-3: 110/6kV substation grounding grid outer belt conductor

Figure-19. TSRP-1 Zest TETS 110/6/6kV substations' C phase belt input grounding

Figure-20. RP-1. 110/6/6kV substation's 2nd transformers deep grounding

The corrosion width and thickness were measured using the corrosion data here the following graphs visualize the corrosion graphically.

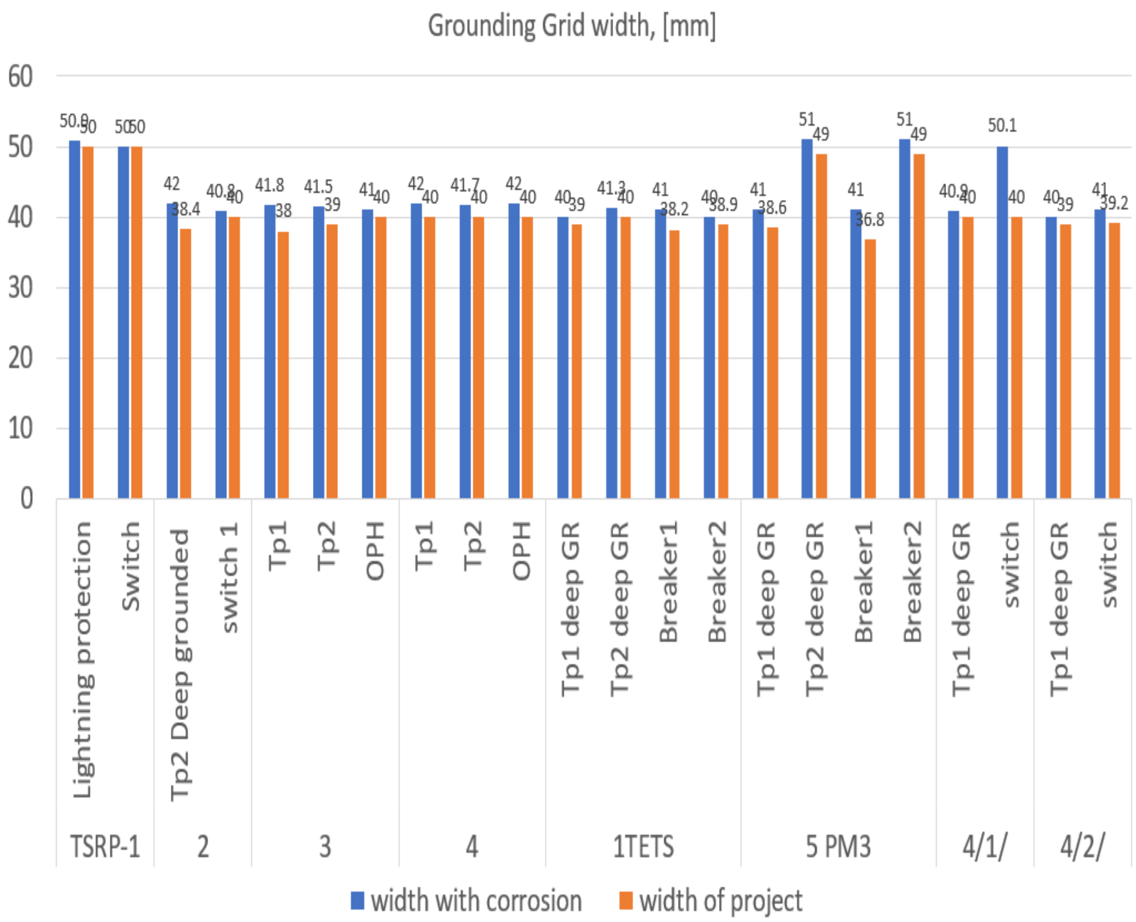

Figure-21. Grounding grid's width, corrosion

This graph presents a comparison between corroded and cleaned grids, showcasing that the majority of grid widths are approximately 40 mm. Regarding thickness, there isn't a substantial difference between the corroded and cleaned grids, with a variance of approximately 0.8 to 2 mm.

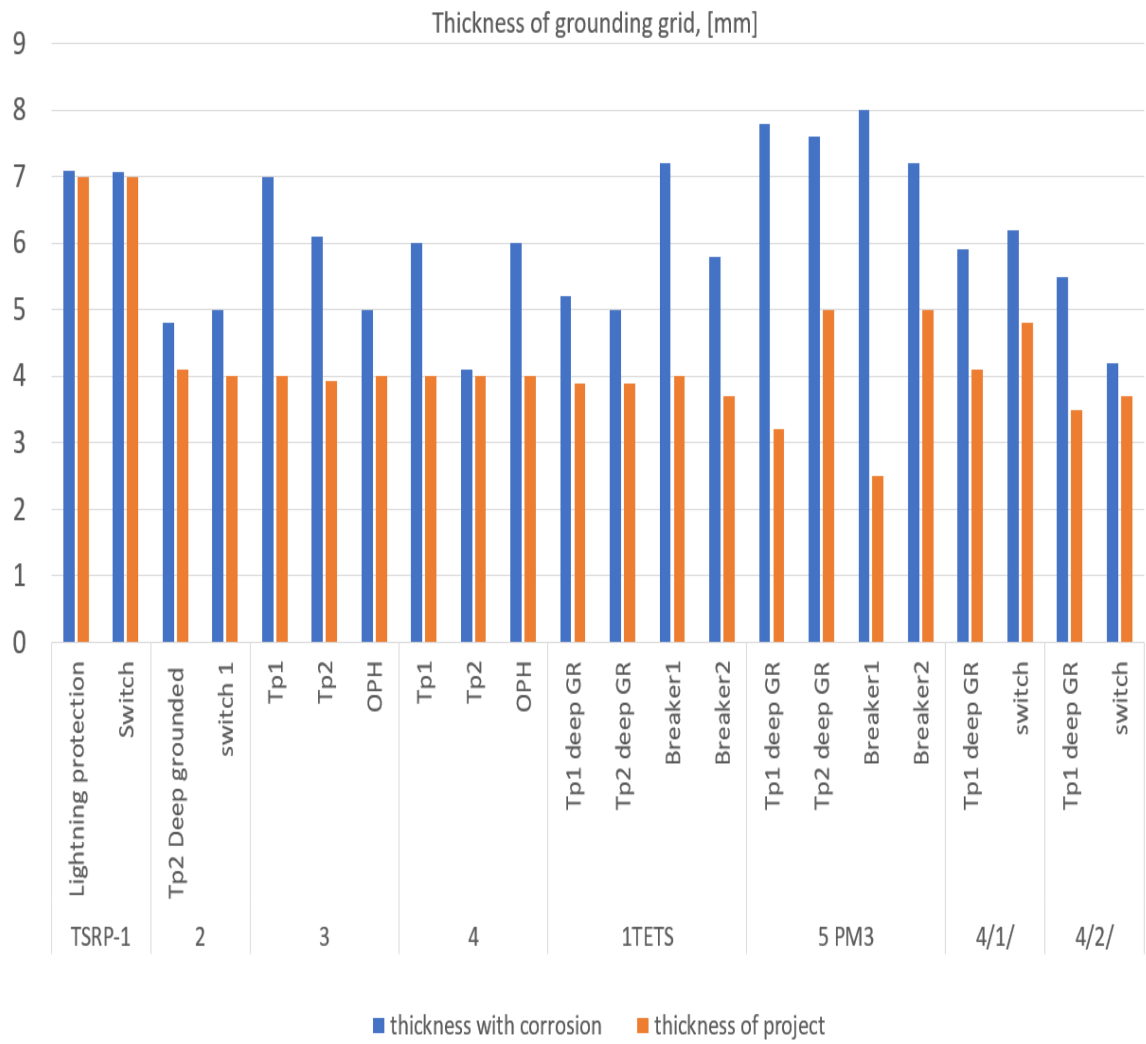

Figure-22. Grounding grid's clear thickness and corroded thickness

However, concerning thickness, the contrast between the corroded and cleaned grids is more significant, relative to their own thickness. Although the disparity ranges from approximately 1.5 to 5 mm, when viewed as a percentage, it spans from 1% to 44%. Notably, TSRP-1 TETS substations breaker-1 grounding exhibits the highest percentage variance.

Lastly we have an area comparison and reduction graph due to corrosion. Using this data and using equation (7) the annual average corrosion value is calculated.

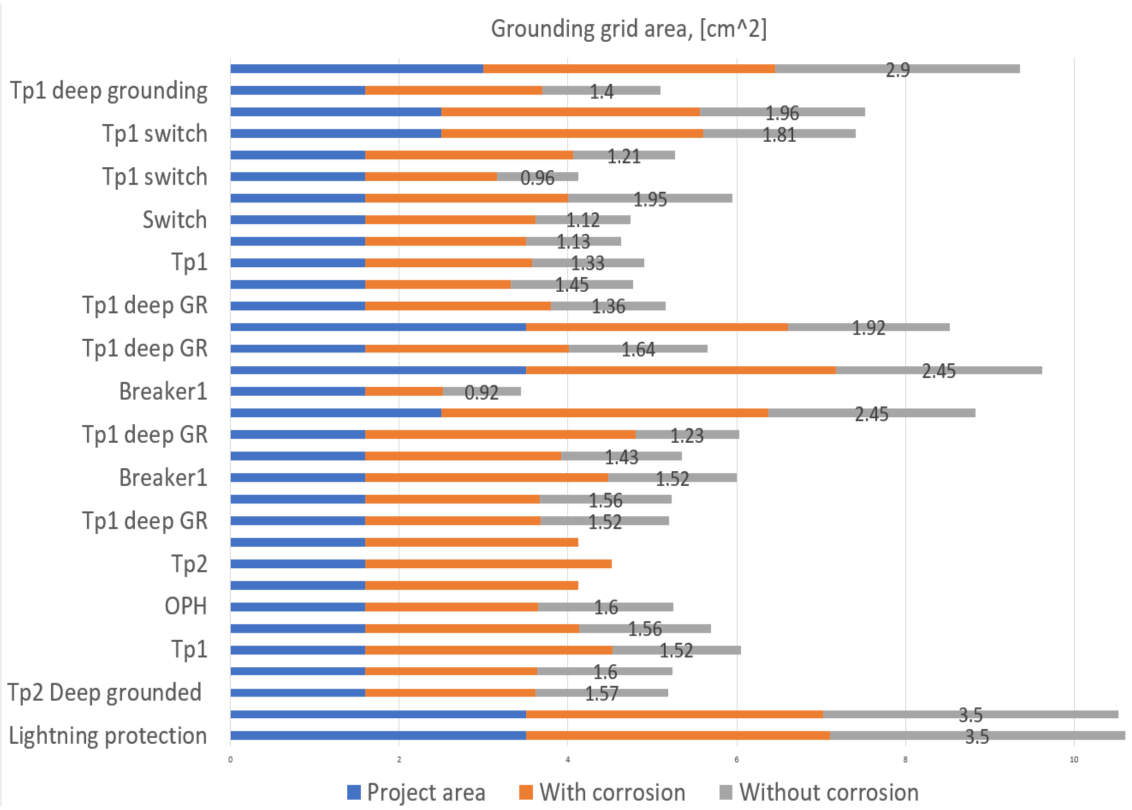

Figure-23. Grounding grid's clear area and corroded area

	Substation	Average corrosion value, [mm / year]; Half mass corrosion time, [year]				
		Power transformer neutral grounding		Circuit Breaker, Switch	Surge protector	Potential fence and its connection
		Transformer-1	Transformer-2			
1	TSRP-1			0.00175, 2000		0.002, 1750
2	TSRP-2		0.1025 24.39			
3	TSRP-3	0.075, 26.666			0.025, 80	
4	TSRP-4					
5	TSRP-1 TETS	0.0325, 60	0.025, 78	0.08, 23.125		
6	TSRP-5	0.115, 13.91	0.065, 38.46	0.015, 66.66		
7	TSRP-4/1	0.045, 45.55		0.035, 8.57		
8	TSRP-4/2	0.05, 35		0.0125, 148		
9	TSRP-7		0.025, 100	0.05, 40		
10	TSRP-10			0.0475, 1.5789		
11	RP-1		0.12, 16.25			

12	RP-9	0.06, 41.66				
13	TSRP-6	0.0325, 56.92	0.05, 40			0.0375, 6.666

Table-8. Average Corrosion Value, Half mass corroding time

From here we can see that the most extreme cases are TSRP-5 110/35/6kV with an ACV of 0.115 at power transformer 1 and TSRP-2 110/35/6kV with ACV of 0.1025 at power transformer 2. By using the Average corrosion value, the time in years, till half the mass of the conductors corroded away. The time till half the mass corrodes away varies from short as 1.5 years to 2000 years. Within the next 2 to 40 years these substations' grounding grid should be replaced completely TSRP-10's circuit breaker switch, RP-1's transformer-2 grid, TSRP-4/2's transformer-1 grid, TSRP-5's both transformer grid, TSRP-4/1's circuit breaker switch, TSRP-1's Circuit breaker switch, TSRP-3's transformer-1 grid and TSRP-2's transformer-2's grid.

5. Result

In addition to the soil resistance data, the grounding resistance values for the substation's lightning protection and two power transformers were provided for the period from 2013 to 2023. By analyzing this data, we can observe how the resistance of the grounding has changed over time.

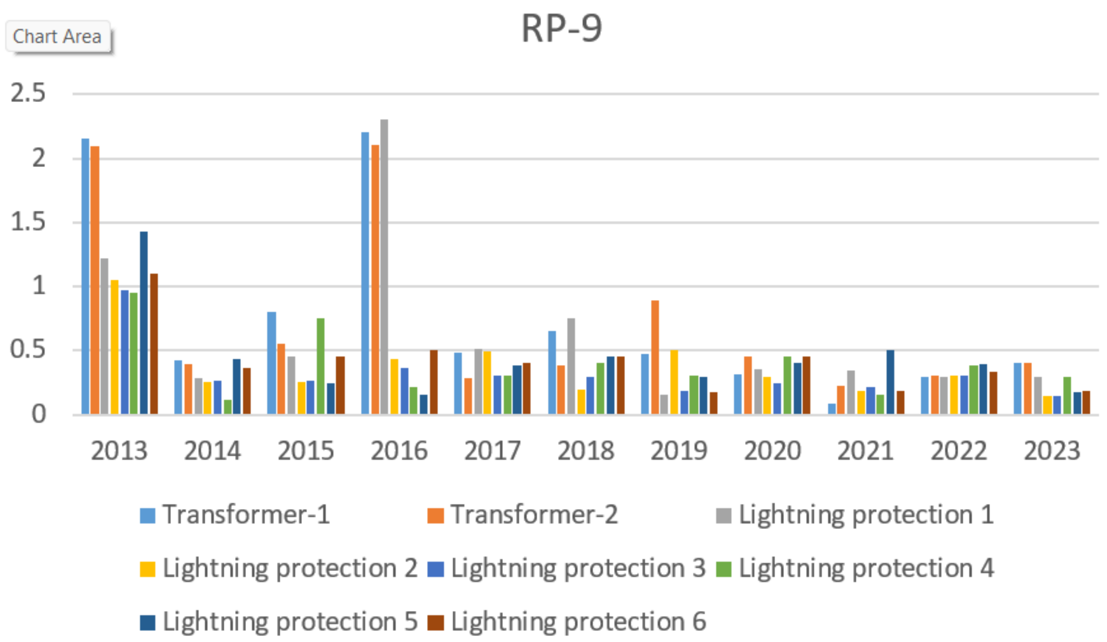

Figure-24. RP-9 substations' grounding equipment resistance in Ω

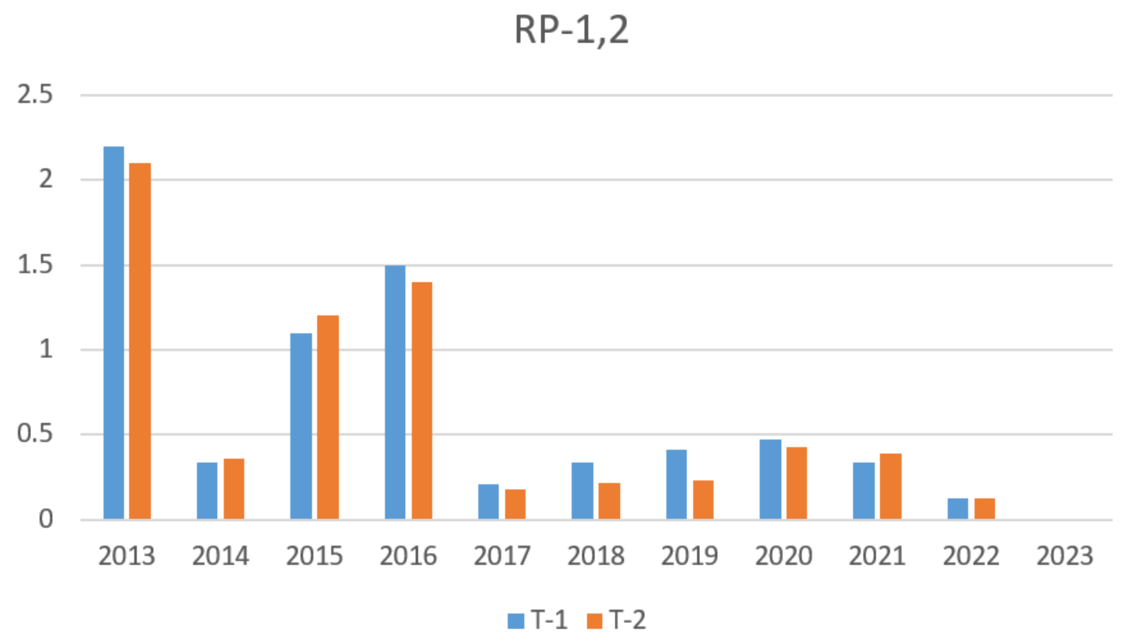

Figure-25. RP-1,2 substations' grounding equipment resistance in Ω

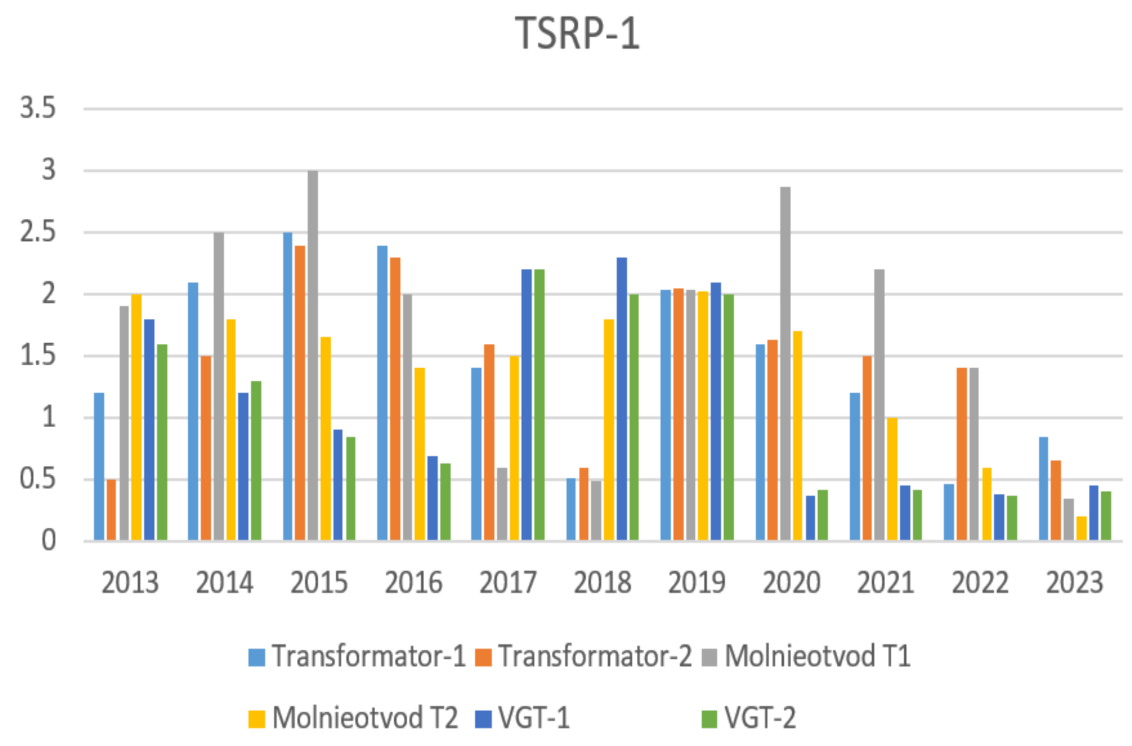

Figure-26. TSRP-1 substations' grounding equipment resistance in Ω

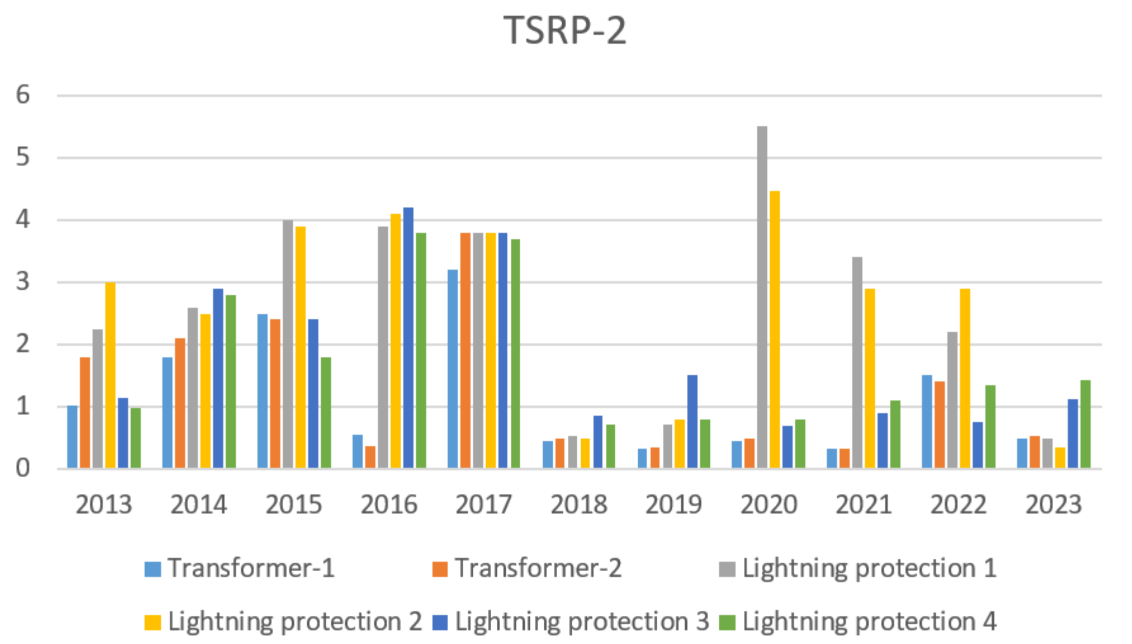

Figure-27. TSRP-2 substations' grounding equipment resistance in Ω

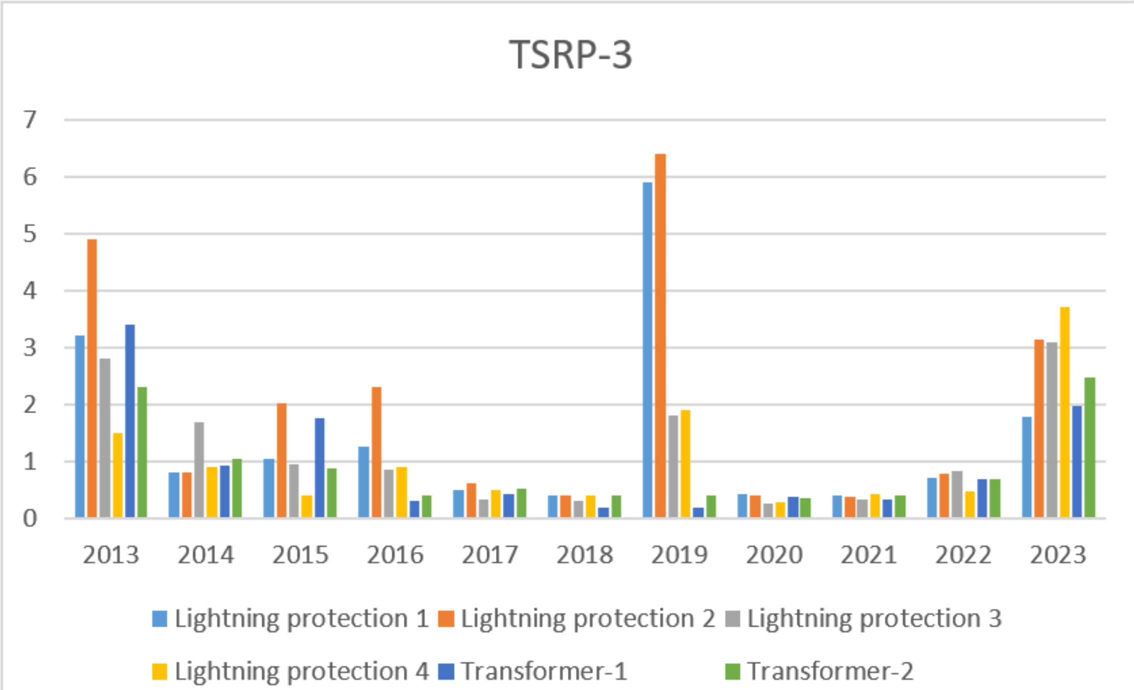

Figure-28. TSRP-3 substations' grounding equipment resistance in Ω

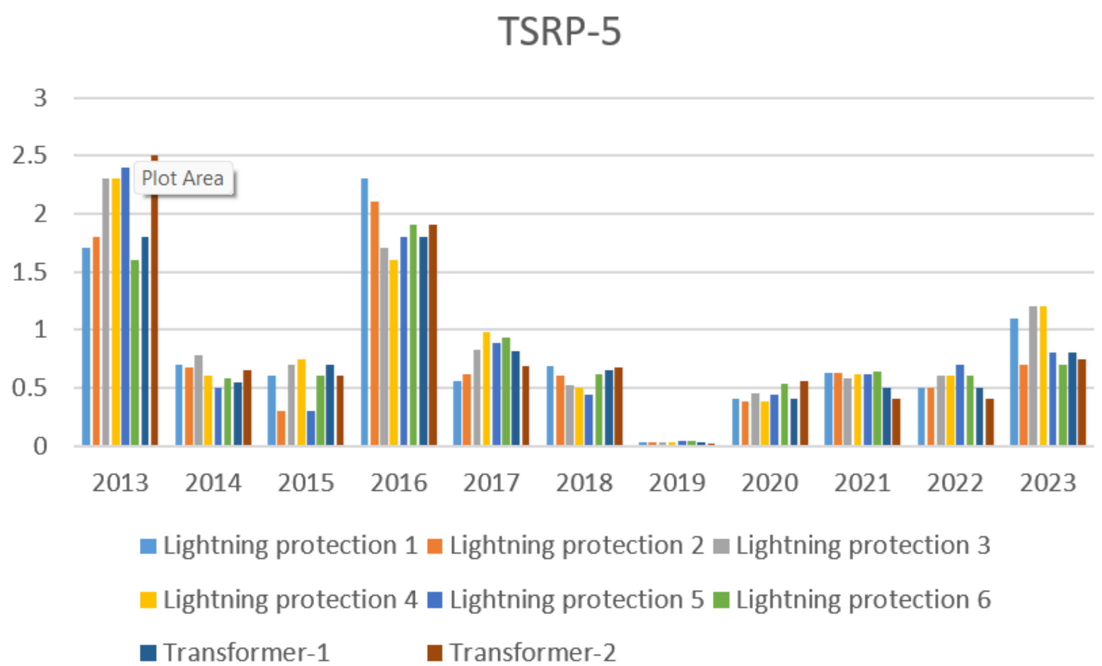

Figure-29. TSRP-5 substations' grounding equipment resistance in Ω

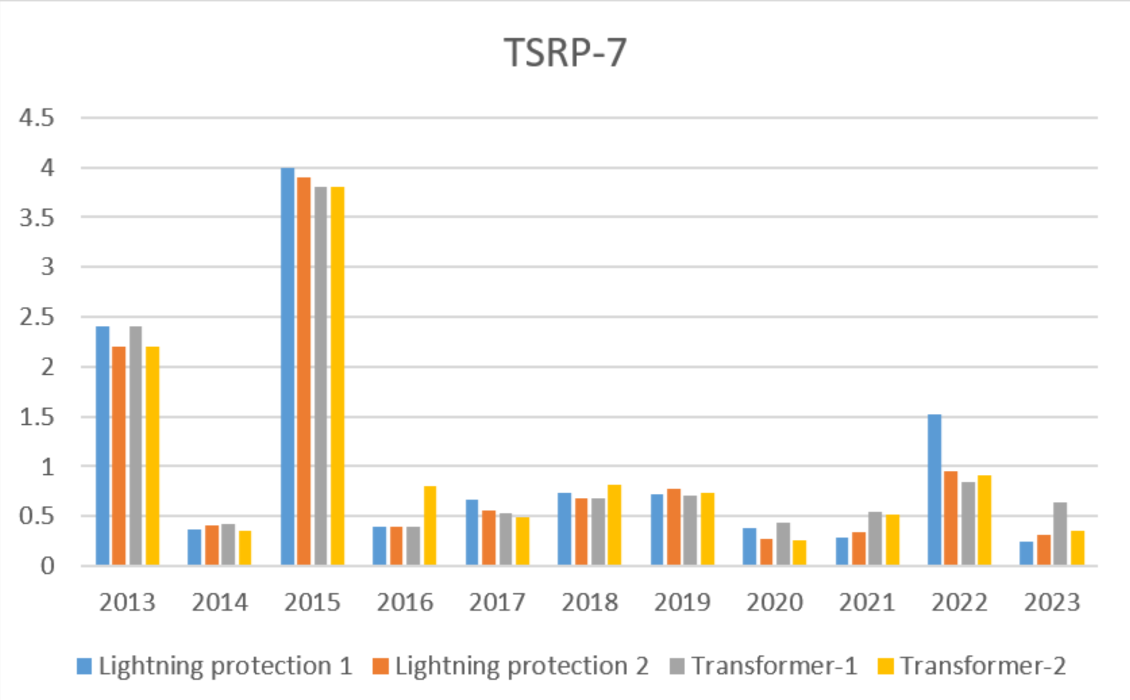

Figure-30. TSRP-7 substations' grounding equipment resistance in Ω

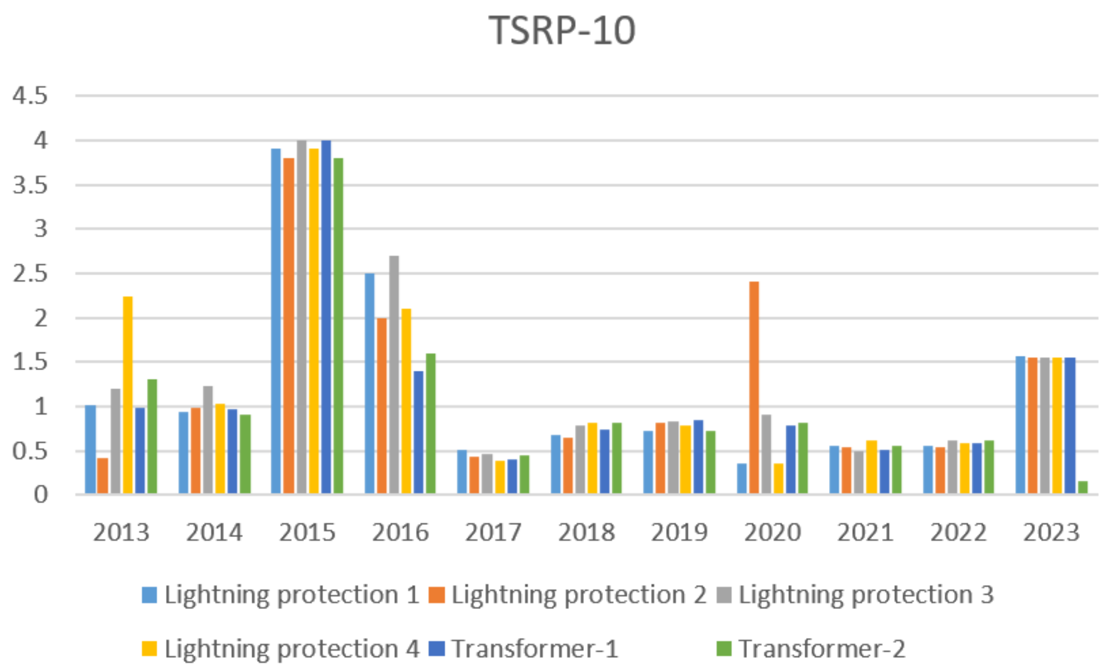

Figure-31. TSRP-10 substations' grounding equipment resistance in Ω

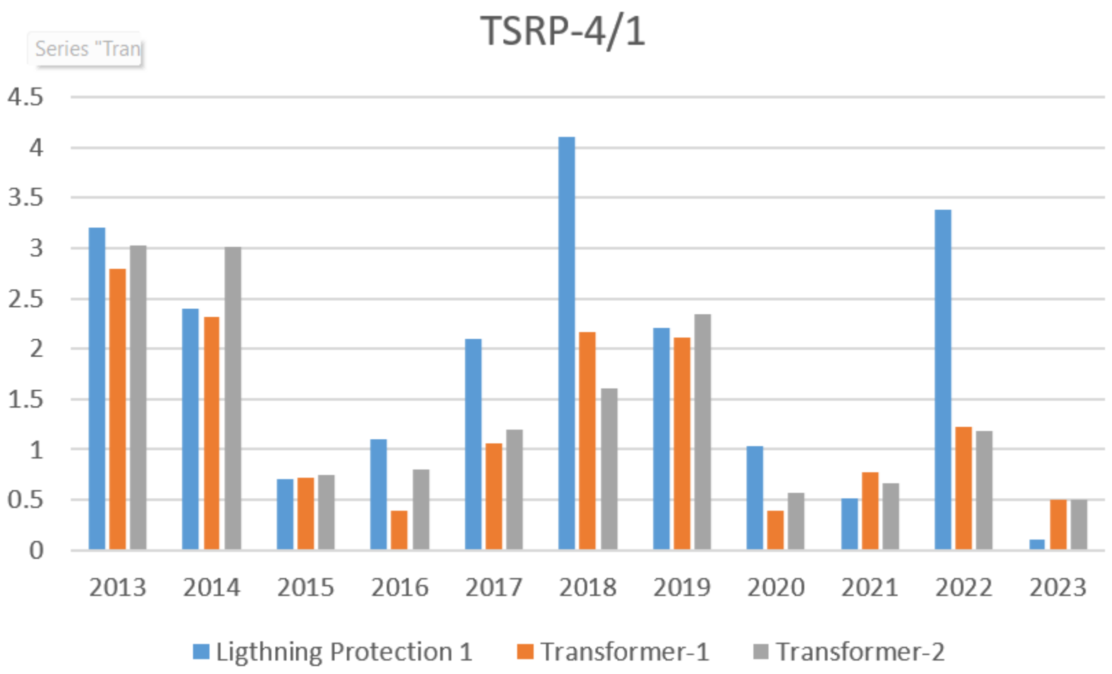

Figure-32. TSRP-4/1 substations' grounding equipment resistance in Ω

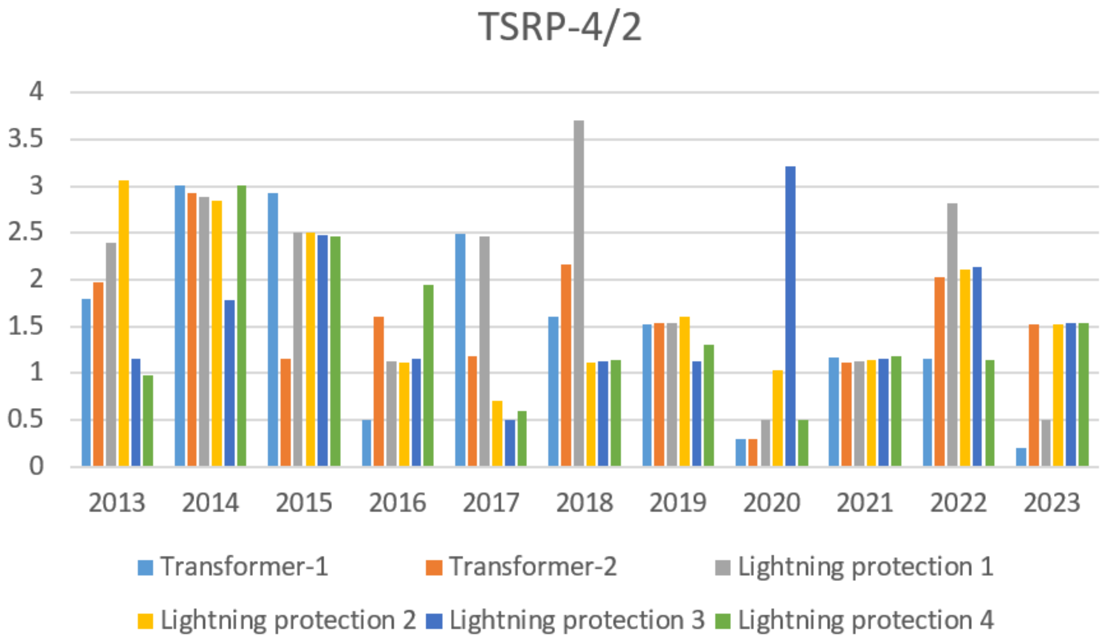

Figure-33. TSRP-4/2 substations' grounding equipment resistance in Ω

Almost all values are below 4Ω which is the limit for the grounding equipment of the substations however lightning protections has higher nominal resistance of 10Ω. Almost all values are under 4Ω means the grounding system is in normal operative condition. But regular routine check is necessary. Every 10 years the electrical department digs up and examines the grounding grid that routine check should be done at least every four years.

6. Discussion

The Erdenet Mining Corporation operates 13 substations, each with grounding equipment and infrastructure. The resistance values for these substations are as follows: 0.4-3.7Ω for 110/6kV substations and 0.2-3.9Ω for 35/6kV substations. These values indicate compliance with both international and Mongolian standards.

However, despite a grounding resistance of 0.26Ω, the TSRP-2 110/35/6 substation has experienced severe corrosion in 2018, resulting in the grounding grid split into two pieces. Similarly, the TSRP-3 substation, with a grounding resistance of 0.53Ω, has seen mechanical tearing of the outermost ring of the grounding grids. Furthermore, the neutral grounding of the second power transformer at the TSRP-3 substation has been punctured.

The soil at the locations of the 13 substations of the Erdenet Mining Corporation has resistance values of 31.7-167.04Ωm at a depth of 1 meter, 37-266.5Ωm at 3 meters, and 29-366Ω*m at 6 meters. These values suggest that the soil is suited for the grounding purposes of the 13 substations. However improvement of soil resistance is still neeeded.

6.1 Ampacity calculation

The short circuit current ampacity is determined by calculating the clean, rust-free cross-sectional area, using equation (4), with a fault clearing time assumed to be 0.5 seconds. In the graph, it's evident that the TSRP-1 substation records the highest short circuit current, approximately 14kA. Meanwhile, the TSRP-1, 2, 3, 4, and 1 TETS substations exhibit values around 6kA. The remaining substations range from 3.5kA to 11.5kA.

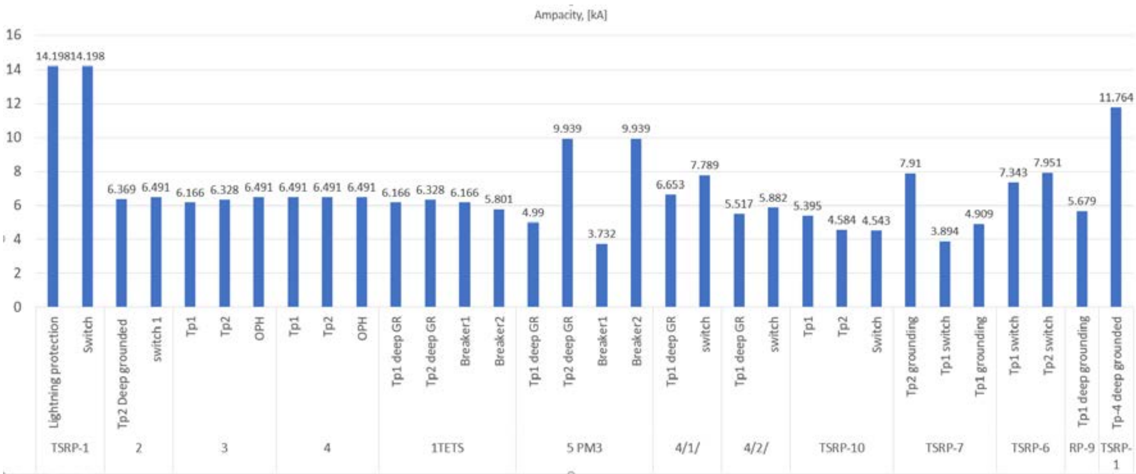

Figure-34. Substations grounding equipment max ampacity

7. Conclusion

This thesis has systematically evaluated the condition of the grounding systems in the substations of the Erdenet Mining Corporation. The study encompassed soil resistivity analysis, grounding grid corrosion assessments, and grounding resistance measurements. The findings have identified critical insights into the state of the grounding equipment, the environmental factors influencing corrosion, and the overall safety compliance of the substations.

7.1 Grounding System Resistance and Soil Resistivity:

The measured grounding grid resistance values for the substations complied to international and Mongolian standards, with most substations exhibiting values below 4 Ω. However, lightning protection equipment was noted to have a higher nominal resistance threshold of up to 10 Ω. Soil resistivity measurements across the substations varied with depth and location deeper the soil the more the measured soil resistance. Grounding grid soil should be treated to lower its resistance for example chemical treatment of the soil with magnesium sulfate which is the least corrosive approach which should be retreated every 4 years. The routine check that is conducted every 10 years should be done every 4 years. Some of the substations grounding grid should be completely replaced.

7.2 Corrosion Impact

Severe corrosion was evident in substations like TSRP-2 and TSRP-3, where significant mechanical damage was detected in grounding components. This deterioration resulted in grounding splits and perforations that necessitate immediate intervention. The corrosion was quantified using the average corrosion value (ACV), revealing that the TSRP-5 and TSRP-2 substations experienced the highest corrosion rates, indicating critical areas for remediation. The biggest problem that Erdenet Mining Corporation’s grounding grid have is corrosion. Therefore, Sacrificial Anode Protection method is well suited for the protection of the grounding grid of the substations.

7.3 Grounding Grid Ampacity

Ampacity calculations determined that substations like TSRP-1 exhibited the highest short-circuit current ampacity, at approximately 14 kA. Other substations demonstrated ampacity ranging from 3.5 kA to 11.5 kA.

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16. https://eepower.com/

Appendix

ООО "Предприятие Эрдэнэт"
Элекртоцех СЭТЛ

ПРОТОКОЛ № 1

Измерения сопротивления растеканию заземлителей

Дата: 22.04.2013г

Заказчик РП-9 КСИ

Объект ОРУ-110/6/6 кВ　　Заземление контура

Общие сведения

Характер грунта	Состояние погоды		Температура в день Измереня (^{0}C)
	Последние 3 дня	В день измерения	
Суглинник	~~сухая~~ сырая	~~сухая~~ сырая	+5

Результаты измерений:

№	Виды заземлителей и место измерения	Наиб. диаметр заземл. зонда (м)	Расстояние: От испыт. заземл. зонда (м)	Расстояние: От испыт. Заземл до Вспом заземл.	Изм. Сопр. (Ом)	Заключение
1	Молние отвод-1	60	40	20	1,22	в норме
2	Молние отвод-2	60	40	20	1,05	в норме
3	Молние отвод-3	60	40	20	0,97	в норме
4	Молние отвод-4	60	40	20	0,95	в норме
5	Молние отвод-5	60	40	20	1,43	в норме
6	Молние отвод-6	60	40	20	1,10	в норме
7	ЛР-1	60	40	20	2,62	в норме
8	ЛР-2	60	40	20	2,36	в норме
9	Т-1	60	40	20	2,15	в норме
10	Т-2	60	40	20	2,09	в норме
11	СР-1	60	40	20	2,25	в норме
	СР-2	60	40	20	2,56	в норме

Измерение производилось прибором типа:

№	Наименование	Тип	Зав №	Класс точ.	Дата госповерки
	Омметр	MRU-101	–	–	–

Общие заключения Пригоден к эксплуатации.

Протокол проверил
Нач.уч-ка СЭТЛ .... Ю.Лхагватав

Испытание произвели
.... Д.Амгаланбаатар
.... Д.Энхтуяа