

METHOD FOR REDUCING ARRESTER GROUNDING RESISTANCE IN DISTRIBUTION SUBSTATIONS TO MINIMIZE THE OCCURRENCE OF GROUND POTENTIAL RISE (GPR)

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ABSTRACT

An effective arrester grounding system in distribution substations is crucial for safely discharging lightning currents and preventing dangerous Ground Potential Rise (GPR). At the PD.0431 (160 kVA) Distribution Substation, the measurement results showed a grounding resistance value of 6.7Ω , which exceeded the maximum limit of 5Ω according to the 2011 PUIL standard. This condition indicates a risk of equipment damage and safety hazards in the form of high touch and step voltages. This study used field experiments and computational simulation methods. Improvements were made by modifying the grounding system configuration by adding parallel rod electrodes. The effectiveness of the method was analyzed by comparing resistance measurements before and after the repair using an Earth Tester. Safety risk analysis was carried out by simulating the distribution of GPR, touch voltage, and step voltage using CYMGrd software, assuming a lightning fault current of 1000 A. The implementation of the addition of four rod electrodes successfully reduced the grounding resistance from 6.08Ω to 1.97Ω , thus meeting the standard. Simulations show that this improvement successfully reduces GPR by 52.7 % (from 359.14 V to 169.71 V). A more significant reduction occurs in the immediate safety parameters, namely the touch voltage decreased by 73.9 % (from 427.96 V to 111.48 V) and the step voltage decreased by 74.7% (from 297.05 V to 75.12 V). The post-improvement ground potential contour also shows a more even and gentle distribution. This study proves that optimizing the grounding configuration by adding parallel electrodes is an effective method to reduce resistance and, more critically, drastically mitigate the risk of human safety hazards due to GPR. This method is recommended as a practical solution to improve system reliability and personnel safety at distribution substations with similar conditions.

Keywords : Grounding resistance, Ground Potential Rise (GPR), Distribution Substation, Arrester, PUIL 2011

1. INTRODUCTION

The electric power distribution system, which delivers power from generating plants to consumers through transmission lines(Paul et al., 2024), substations, and medium-voltage overhead lines(Swain et al., 2022), is a critical infrastructure vulnerable to disruptions(Rachunok & Nateghi, 2020). Among the various types of disruptions, lightning strikes occupy a significant position as a non-technical threat. To mitigate the impact of lightning surges, the installation of arresters supported by an effective grounding system is essential(Nunes, 2023). The grounding system not only functions to channel lightning currents safely to the ground but also serves as a protective foundation for maintaining reliable operation and equipment safety(Permal et al., 2020).

The primary threat from improperly managed lightning discharges is *Ground Potential Rise* (GPR)(Taryo et al., 2025). GPR is a phenomenon where the electrical potential at a ground electrode increases drastically and unevenly compared to the surrounding reference ground(Putra et al., 2023). This local potential rise creates a dangerous voltage gradient across the ground surface, triggering two major safety risks: *touch voltage* (the danger of touching equipment in contact with the ground)(Hu et al., 2024), and *step voltage* (the danger resulting from the voltage difference between two standing points)(Fitriani et al., 2024). Therefore, the performance of the grounding system directly correlates with the level of human safety around the distribution substation(Farooq et al., 2021).

The key to a grounding system's performance lies in its resistance value. The 2011 PUIL standard sets a maximum grounding resistance limit for distribution substations of 5 ohms(Putra et al., 2024). High resistance impedes the flow of lightning current to the ground, causing surge energy to seek alternative paths(Yani et al., 2024). This can trigger reflected waves that propagate to metal equipment, increasing the risk of overvoltage and insulation damage. In other words, exceeding the standard ground resistance not only reduces the effectiveness of the arrester but can actually exacerbate the effects of GPR and turn the protection system into a source of danger.

Based on initial measurements at the PD 0431 Distribution Substation, it was found that the arrester grounding resistance value had exceeded the permitted limit. This finding indicates the installation's vulnerability to protection failure during a lightning strike, as well as a potential safety threat to personnel and the surrounding community. This condition implies that the design or implementation of the existing grounding system is no longer adequate, requiring technical intervention to improve soil characteristics or electrode configuration.

Therefore, this research is focused on analyzing and proposing an effective and applicable method for reducing grounding resistance at the PD 0431 Distribution Substation. The goal is to restore the performance of the arrester protection system to standard, thereby minimizing the risk of equipment damage due to lightning surges. Furthermore, this research is directed at mitigating the potential for GPR, which ultimately aims to improve the level of life safety by reducing the dangers of touch voltage and step voltage at the distribution substation location.

2. RESEARCH METHOD

The research on reducing the arrester grounding resistance at the 20 kV Distribution Substation PD.0431 was motivated by the high frequency of lightning strikes at the location, which increases the vulnerability to disturbances and the potential for *Ground Potential Rise* (GPR). The initial stage of the research began with field observations and a comprehensive literature study. Observations were conducted to ensure the selection of the right location, while the literature study was used to collect relevant references and previous methods, in order to build a strong theoretical foundation.

Next, an initial grounding resistance measurement was performed as baseline data. This measurement used the three-point method (*Fall of Potential Method*) with a 4015A Digital Earth Teste(Putra et al., 2025), in accordance with applicable measurement standards. The results of this initial measurement were then analyzed to determine the improvement strategy. Based on the analysis, the chosen improvement method was the addition of a *driven rod* electrode. The design of this electrode configuration was calculated using the Dwight Formula (based on IEEE Std 81-2012) to predict the final resistance value theoretically (IEEE Power and Energy Society - Substations

Committee, 2012). This prediction is important to determine the optimal number, depth, and spacing between electrodes before physical implementation.

After the repair method was implemented in the field, repeat measurements were performed to verify the resistance reduction. To assess safety aspects, a Ground Potential Rise (GPR) analysis was performed using CYMGrd simulation software. This simulation aims to model the distribution of ground potential after the repair, in order to evaluate the effectiveness of the system in mitigating the risks of touch voltage and step voltage.

- For one electrode rod, it is implanted perpendicularly.

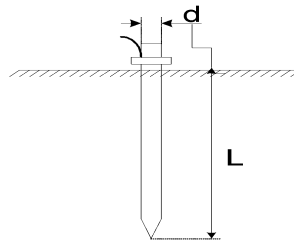


Figure 1. The rod electrode is implanted perpendicularly

$$R = \frac{2}{2\pi L} \ln \ln \left(\frac{2L}{r} \right) \quad (1)$$

- For four electrode rods implanted perpendicularly (placed anywhere)

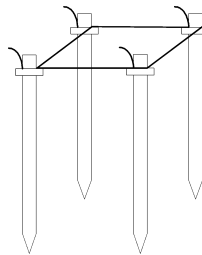


Figure 2. Four electrode rods are implanted perpendicularly.

$$R = \frac{2}{2\pi L} \ln \ln \left(\frac{2L}{\sqrt[4]{2^{1/2} a^3} r} \right) \quad (2)$$

3. RESULTS AND DISCUSSIONS

Based on initial measurements using the three-point method with *the 4015A Digital Earth Tester*, data obtained showed that the arrester grounding resistance value at the PD.0431 Distribution Substation (160 kVA Transformer) was 6.7 Ω . This result has exceeded the maximum limit of 5 Ω set in the 2011 PUIL standard, as summarized in Table 1.

Table 1. Results of arrester grounding resistance measurements

Substation Code	Soil Type	Location	Resistance Ω
PD. 0431	Clay	Jl. Silaberanti	6.7

The high resistance value is due to the characteristics of the location. This substation sits on clay soil, which tends to be damp due to the rainy season. Literature indicates that clay soils have a wide range of resistivity, generally in the range of 20 - 100 Ωm . Initial measurements of 6.7 Ω indicated that the existing ground electrode configuration was no longer adequate for the soil resistivity conditions at the location.

To design an effective solution, a calculation analysis is performed to predict the electrode requirements as described in Table 2. This calculation refers to the Dwight Equation (UB. Dwight). This equation models the grounding resistance for one or more *driven rod electrodes* installed in parallel. For a single driven rod electrode, the grounding resistance can be estimated using formula (1), using one driven electrode rod:

Table 2. Field Parameters

Parameter	Mark	Unit
ρ : Clay Resistivity	20 to 100	Ωm
ρ : Assumed soil resistivity	35	Ωm
L: Length of embedded stem	10	m
d : Electrode rod diameter	0.02	m
r : Radius of the electrode rod	0.01	m

Table 3. Results of Arrester Grounding Resistance Comparison

PUIL 2000 Standard	Measurement (Ω)	Calculation (Ω)
5	6.7	4.84

Table 3. The results of the initial calculation analysis using the Dwight Equation for the arrester grounding system at the PD.0431 Distribution Substation (160 kVA) produced a higher value than the field measurement results of 6.7 Ω . This difference may occur because the assumption of soil parameters in theoretical calculations (such as homogeneous resistivity) has not fully represented the actual conditions in the field, which are more complex. However, both the measurement results (6.7 Ω) and the initial calculation results have both exceeded the maximum limit of 5 Ω set in the 2011 PUIL standard. This condition confirms that the existing grounding system is inadequate and requires immediate repair intervention.

This high resistance phenomenon is exacerbated by environmental conditions. Measurements were conducted at a location with clay soil that was humid due to the rainy season. Although humidity generally reduces soil resistivity, the existing single-electrode configuration was still unable to achieve safe resistance values. This indicates that a technical solution is needed to overcome the limitations of the existing system, regardless of weather conditions.

Therefore, a repair design was carried out by adding rod electrodes, which are installed in parallel to form a grid configuration with the existing electrodes. The analysis begins by calculating the performance of one additional electrode using the Dwight Equation. As a result, the resistance value obtained is still outside the standard limits. Therefore, the simulation is continued by increasing the number of electrodes. Based on the equation for the parallel arrangement (equation 2), the calculation with four grounding electrodes produces a theoretical resistance value of 1.68 Ω .

The final value of 1.68 Ω has met and is even far within the tolerance limit of the PUIL 2011 standard (0–5 Ω) added. This configuration of four parallel electrodes is theoretically able to expand the contact area with the ground and create a more effective grounding path, so that it can flow fault currents (especially lightning currents) more efficiently. Achieving this value shows that the method of adding electrodes in parallel is a feasible and effective solution to reduce the grounding resistance of distribution substations in similar soil conditions.

Table 4. Calculated Grounding Resistance Values

PUIL Standard 2011	Calculation Results Grounding Resistance (Ω)	
	1 Electrode Rod	4 Electrode Rods

5	4.84	1.68
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Based on the implementation of the addition of rod electrodes in the field, the results of the arrester system grounding resistance measurements showed a significant decrease, as presented in Table 5. Measurements were carried out on two tested configurations: the old system with 1 rod electrode and the repair system with 4 electrode rods installed in parallel.

Table 5. Grounding Resistance Values from Field Measurements

PUIL 2000 Standard	Grounding Resistance Measurement Results (Ω)	
	1 Electrode Rod	4 Electrode Rods
5	6.08	1.97

The data confirms that increasing the number of electrodes is inversely proportional to the final resistance value. The 4 electrode configuration successfully reduced the resistance from 6.08 Ω to 1.97 Ω , which meets and is well within the safe limits of the PUIL standard (maximum 5 Ω). This downward trend is clearly visualized in Figure 1, which shows a curve of the relationship between increasing the number of electrodes and the resulting resistance.

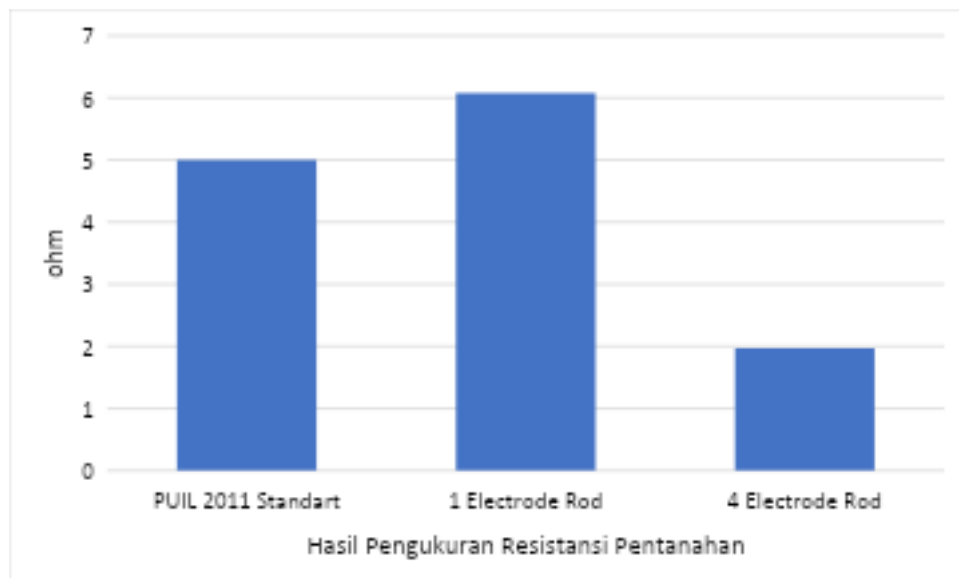


Figure 1. Graph of grounding resistance reduction with field measurements.

It should be noted that there is a difference between the resistance value from the previous theoretical calculation (1.68 Ω) and the actual measurement result (1.97 Ω). This difference is normal and can be caused by several field factors, such as variations in inhomogeneous soil resistivity, imperfect electrode depth and contact conditions, or the influence of higher soil moisture during the rainy season. This moisture factor is actually beneficial because it reduces soil resistivity, thus contributing to the achievement of lower resistance values.

After confirming that the resistance value has met the standard, the next critical step is to evaluate the safety aspect by analyzing the Ground Potential Rise (GPR) potential. This analysis was performed using CYMGrd software simulations for two scenarios: a system with four electrodes at a depth of 3 meters and a system with a depth of 10 meters. The simulations were performed assuming a lightning fault current of 1000 Amperes flowing into the ground.

Table 6. Ground Potential Rise (GPR)

Research Description	GPR	Touch Voltage	Step Voltage
	Volts (V)		
Before Repair	359.142	427.962	297.05
After Repair	169.712	111.482	75.12

The data in Table 6 shows a very significant decrease in the three safety parameters after the improvement of the grounding system with the addition of 4 electrode rods. The GPR value decreased by 52.7% (from 359.142 V to 169.712 V). A more drastic decrease occurred in the direct hazard parameters to humans. Touch Voltage decreased by 73.9% (from 427.962 V to 111.482 V), and Step Voltage decreased by 74.7% (from 297.05 V to 75.12 V).

The decrease in these values is directly due to the decrease in grounding resistance from 6.08 Ω (1 bar) to 1.97 Ω (4 bars). Based on Ohm's law, this 67.6% decrease in resistance causes the potential arising at the ground electrode (GPR) to also decrease proportionally for the same fault current. The new parallel electrode configuration also creates a more even and gentle distribution of ground potential, so that the voltage gradient at the ground surface, which is the source of the danger of step voltages, decreases drastically. A visualization of this potential distribution is shown in Figure 2. The potential contour before the repair (Figure 2a) shows a very steep gradient and a high potential area concentrated around a single electrode point. In contrast, the contour after the repair (Figure 2b) shows a wider, smoother distribution pattern and a much lower maximum potential value. This visual difference strengthens the conclusion that the new grounding system has succeeded in improving grounding effectiveness and distributing fault energy better.

Overall, the simulation analysis proves that the grounding system repair not only successfully meets the resistance standards but also substantially improves the safety level of the site. The post-repair touch and step voltage values (111.482 V and 75.12 V) have been at a much safer level, which significantly reduces the risk of serious injury or fatality for operation and maintenance personnel around the PD.0431 Distribution Substation.

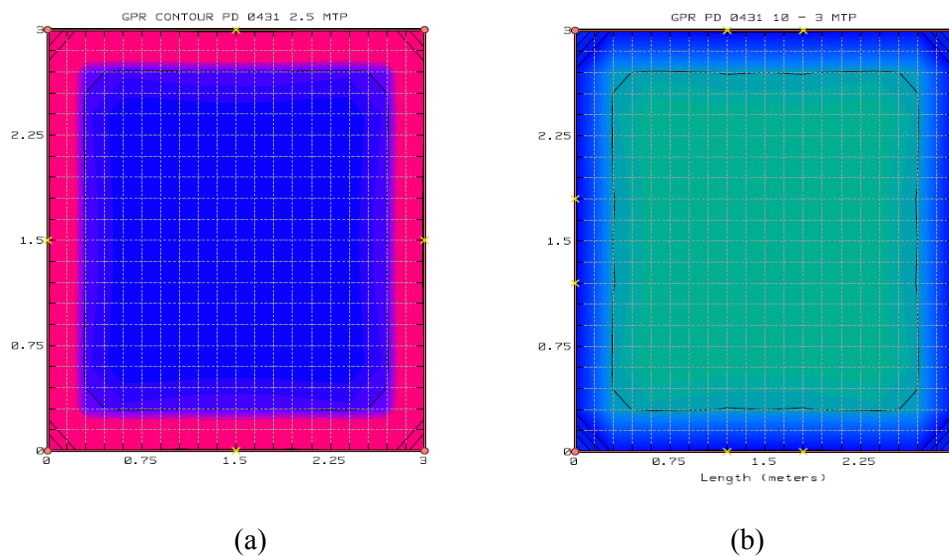


Figure 2. Contour (a) assumption before repair and (b) after repair of the grounding system

4. CONCLUSION

Based on the research conducted, it can be concluded that the method of adding rod electrodes in parallel successfully reduced the arrester grounding resistance at the PD.0431 Distribution Substation from 6.08 Ω to 1.97 Ω . This result has met the PUIL 2011 technical standard, which requires a maximum resistance value of 5 Ω . This system configuration improvement proves that physical optimization of the grounding system is an effective solution to overcome high ground resistance at locations with moist clay soil characteristics. Furthermore, the reduction in resistance has a direct and significant impact on improving safety. Simulations show that the system improvement successfully reduced the Ground Potential Rise (GPR) by 52.7 %, as well as reducing the touch voltage and step voltage by 73.9% and 74.7%, respectively. Thus, this study not only focuses on the technical compliance aspect but also confirms that effective grounding is a critical step in protecting humans from the dangers of electric shock, while improving the reliability of the electric power distribution system as a whole.

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