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# Evaluation of Lightning Protection and Grounding System in a Hazardous Zone 2 Oil and Gas Facility Based Based on Field Testing and WinIGS Modeling

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## Abstract

**Background:** Oil and gas facilities operating in Hazardous Zone 2 require reliable lightning protection, grounding, bonding, and surge protection systems to ensure electrical safety, protect personnel and equipment, and maintain operational continuity under potential flammable conditions.
**Objective:** This study aims to evaluate the overall performance of the lightning protection and grounding systems in a Hazardous Zone 2 oil and gas facility based on field testing, technical assessment, and grounding system modeling.
**Methods:** The research methods consisted of soil resistivity measurement using the Wenner four-point method, grounding resistance testing using the fall-of-potential method, continuity testing of grounding and bonding connections using the four-wire Kelvin method, lightning risk assessment based on IEC 62305-2024, evaluation of the existing lightning protection layout using the rolling sphere method, and grounding system verification using WinIGS software based on IEEE Std 80. Field testing was conducted on grounding rods, grounding rings, busbars, air terminals, down conductors, grounding cables, control panels, and other bonding components within the oil and gas facility.
**Results:** The measurement results showed that the average combined soil resistivity value was 4.98 Ω·m with a two-layer soil model. The results of the grounding resistance test showed that most of the grounding points still met the ideal limits with a value range of 0.410 Ω to 1.580 Ω. However, one grounding point was found to be in a rejected condition and required repair.
**Conclusion:** This study demonstrates that evaluating grounding and lightning protection systems in hazardous areas requires an integrated approach, considering grounding resistance, soil resistivity, bonding continuity, physical grounding conditions, lightning protection, and grounding system simulations.

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## INTRODUCTION

The development of the use of renewable energy, especially the Solar Power Plant (PLTS) system, is currently increasing in various industrial sectors, including the oil and gas industry (Pambudi et al., 2023; Saadawi, 2019; Strielkowski et al., 2021). One of the implementations is the installation of solar panels in oil and gas fields, East Kalimantan, which has been operating for quite a long time. This solar power plant is used as an energy source to support the electrical system in the 24-hour non-stop operation area (Ali, 2026; Wei et al., 2021). The global trend of integrating renewable energy into industrial operations, including the oil and gas sector, has been accelerating as companies seek to reduce carbon emissions and operational costs (Al-Shetwi, 2022; Zhong & Bazilian, 2020).

However, the installation of solar power systems in the oil and gas industry environment has its own challenges, especially because the installation location is in the hazardous Zone 2 area, which is an area that has the potential for the presence of flammable gases under abnormal conditions. In these conditions, the safety aspect is very critical, especially related to the lightning protection system (LPS) and the earthing system (Irsan et al., 2025).

In the design of lightning protection systems, international standards such as IEC 62305 are used as the main reference. This standard includes a method of lightning strike risk analysis (risk assessment), in determining the appropriate level of protection and planning of the lightning protection system must consider the characteristics of the protected object and the grounding system used. Therefore, the application of the risk assessment method is a very important first step in determining the need for a lightning protection system (Ab Kadir, 2023).

The grounding system has the main function as a safe way to release interference currents and lightning currents to the ground, so that it can prevent overvoltage from occurring that endangers humans and equipment (Mahmood, 2024). In addition, the grounding system also plays a role in maintaining equipotential bonding in all metal structures, thereby reducing the risk of dangerous potential differences in the installation area (Ekici, 2026; Mitolo, 2020).

In addition, the design of the grounding system is greatly influenced by the soil characteristics at the installation site. The main parameter used is soil resistivity, which determines the ability of the soil to absorb disturbance currents. High soil resistivity values can lead to an increase in Ground Potential Rise (GPR), which has the potential to increase the touch voltage and step voltage, thus endangering the safety of personnel. The safety parameters of touch voltage and step voltage are evaluated based on IEEE Std 80-2013, which defines tolerable body current limits during fault conditions.

In field practice, grounding system evaluations often focus solely on measuring the overall grounding resistance value. However, this approach has limitations because it does not adequately assess the integrity of grounding connections (bonding), which is essential for maintaining a continuous and reliable current path. Deficiencies in bonding can cause discontinuity in current flow, resulting in uneven current distribution, reduced lightning protection performance, and increased electrical safety risks. Therefore, a more comprehensive evaluation method is required, encompassing risk assessment based on IEC standards for lightning protection, soil resistivity measurement to support grounding system design analysis, grounding resistance testing to determine the overall system resistance, and continuity testing using the four-wire Kelvin method to verify the integrity of grounding connections and ensure the reliability of the entire grounding system.

Despite numerous studies on grounding systems and lightning protection, most previous research has focused on individual aspects such as grounding resistance measurement or lightning risk assessment in isolation. There is limited research that integrates continuity testing, soil resistivity analysis, grounding resistance measurement, lightning protection evaluation, and software-based simulation in a single comprehensive assessment framework, particularly for solar power plant installations operating in classified hazardous areas. Previous studies by Sazali (2020) focused primarily on soil resistivity characterization without integrating continuity assessment, while Aprili (2025) examined lightning protection calculation without field-based validation in hazardous environments. This gap is significant because partial evaluations may overlook critical local degradation that affects system safety.

The novelty of this research lies in the integrated evaluation approach that combines five complementary assessment methods: soil resistivity measurement, grounding resistance testing, continuity testing using the 4-wire Kelvin method, IEC 62305-based risk assessment, and WinIGS simulation. Unlike conventional approaches that evaluate grounding performance based solely on resistance values, this study demonstrates that local bonding degradation can exist even when global grounding resistance meets acceptance criteria. Furthermore, this research is among the first to apply such an integrated approach specifically to solar power plant installations in oil and gas hazardous Zone 2 areas.

Theoretically, this study contributes to the body of knowledge on integrated grounding and lightning protection evaluation methodologies for renewable energy installations in classified hazardous areas. Practically, the findings provide actionable technical recommendations for maintenance, repair, and periodic monitoring of grounding and lightning protection systems in industrial solar power plant installations, which can be adopted by oil and gas facility operators to enhance operational safety and equipment reliability.

By integrating all these methods, it is hoped that a more accurate picture can be obtained of the condition of the lightning protection system and grounding as well as the safety level of solar panel installations in the hazardous Zone 2 area. This research was conducted to evaluate the lightning protection system and grounding in solar panel installations with a comprehensive approach based on international standards and engineering practices in the oil and gas industry.

## METHOD

This study uses a field study approach on solar panel installations in oil and gas fields, East Kalimantan. The research methodology was prepared by integrating direct measurements in the field, analysis based on international standards, and technical evaluation of grounding, bonding, and lightning protection systems. This approach was chosen because the condition of the grounding and lightning protection systems is greatly influenced by the actual conditions on site, such as installation configuration, connection quality, soil characteristics, grounding rod conditions, and operating environment.

The research was carried out on a solar panel installation located in the company's operating area, East Kalimantan. This Solar Panel installation serves as one of the main sources of power supply in the area. The research location is part of an oil and gas industry facility classified as a hazardous area Zone 2. The data used in this study consisted of primary data and secondary data. The two types of data are used in an integrated manner to evaluate the condition of the grounding system, bonding, lightning protection, and potential disturbances due to lightning in solar panel installations in the hazardous Zone 2 area.

Data collection was conducted from March to May 2025, covering both dry and transitional weather conditions. A total of 15 grounding resistance measurements, 15 continuity measurements across three LPS air terminals, and 15 soil resistivity measurements using the Wenner four-point method (five electrode spacings measured along three different survey directions) were performed. Each measurement was repeated three times to ensure data reliability, and the average values were used for subsequent analysis. The field measurement results were validated through comparison with WinIGS simulation outputs.

The equipment and instruments used in this study were selected according to the type of testing carried out in the field. Each instrument has a specific function to obtain the technical parameters needed in the evaluation of grounding, bonding, and lightning protection systems.

1) Earth Tester

   Earth testers are used to measure the grounding resistance value at the location of a predetermined point area (Fadila & Laksono, 2025). The earth tester used was a Megger DET4TD2 digital ground resistance tester with a measurement accuracy of ±2% and a measurement range of 0.01 Ω to 20 kΩ.

2) Soil Resistivity Tester

   Soil resistivity testers are used to measure the resistance value of soil types around the solar power plant area. This test is very important because the characteristics of the soil affect the performance of the grounding system. The results of soil resistivity measurements are used as a basis for the interpretation of soil characteristics and as an input reference in modeling the grounding system using WinIGS (Sazali et al., 2020). The soil resistivity tester used was a Megger DET4TD2 configured in the 4-point Wenner mode, with a resolution of 0.01 Ω·m.

3) Micro-Ohmmeter / Continuity Tester

   Micro-ohmmeter or continuity tester 4-wire kevin method is used to measure low resistance in grounding and bonding connections. This test is carried out on points such as air terminals, down conductors, busbars, counter boxes, grounding rods, grounding rings of parameter, grounding cables, bolts and nuts, and other metal structures (Zulkifli & Abdul, 2022). The micro-ohmmeter used was a Megger DLRO-10HD with a test current of 10 A DC and an accuracy of ±0.2% ± 0.2 mΩ.

4) Software WinIGS

WinIGS is used as supporting software to verify the performance of grounding systems based on the IEEE Std 80 approach. Modeling using WinIGS was carried out to evaluate safety parameters that cannot be obtained from field measurements alone, such as Ground Potential Rise, touch voltage, and step voltage.

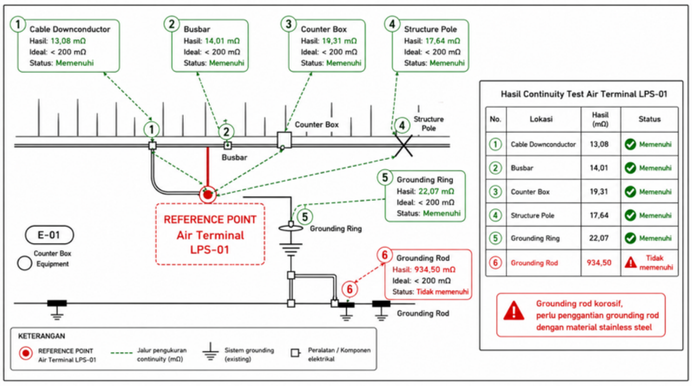
Data are analyzed through soil resistivity analysis to determine the soil type and grounding design needs, grounding resistance analysis to evaluate the effectiveness of the grounding system based on applicable standards, and continuity analysis to check the integrity of the system and identify problematic connections. In addition, a lightning risk analysis was carried out to determine the need and level of protection of the lightning protection system (LPS). The measurement and calculation results are then verified using WinIGS software to ensure the performance of the grounding system in accordance with technical and safety standards.

The key mathematical equations used in the evaluation are as follows. Soil resistivity using the Wenner method is calculated as: $\rho = 2\pi a \cdot R$, where $\rho$ is the apparent soil resistivity (Ω·m), a is the electrode spacing (m), and R is the measured resistance (Ω). The grounding resistance for a single vertical rod is estimated using: $Rg = (\rho / 2\pi L) \cdot \ln(4L/d)$, where L is the rod length (m) and d is the rod diameter (m). Ground Potential Rise is calculated as: $GPR = Ig \times Rg$, where Ig is the fault or lightning current entering the grounding system (A) and Rg is the grounding resistance (Ω) (IEEE Standards Association, 2013). The tolerable touch voltage for a 50 kg person is: $Etouch = (1000 + 1.5\rho s) \cdot 0.116/\sqrt{ts}$, and the tolerable step voltage is: $Estep = (1000 + 6\rho s) \cdot 0.116/\sqrt{ts}$, where ρs is the surface layer resistivity (Ω·m) and ts is the shock duration (s), as defined in IEEE Std 80-2013.

## RESULTS AND DISCUSSION

### Results

### *Analysis of LPS-01 Air Terminal Continuity*



Hasil Continuity Test Air Terminal LPS-01

| No. | Lokasi | Hasil (mΩ) | Status |
|---|---|---|---|
| ① | Cable Downconductor | 13,08 | ✓ Memenuhi |
| ② | Busbar | 14,01 | ✓ Memenuhi |
| ③ | Counter Box | 19,31 | ✓ Memenuhi |
| ④ | Structure Pole | 17,64 | ✓ Memenuhi |
| ⑤ | Grounding Ring | 22,07 | ✓ Memenuhi |
| ⑥ | Grounding Rod | 934,50 | ⚠ Tidak memenuhi |

⚠ Grounding rod korosif,
perlu penggantian grounding rod
dengan material stainless steel

**Figure 1.** Continuity Air Terminal LPS-01

Continuity testing on the LPS-01 Air Terminal was carried out to determine the quality of the electrical connection between the reference point of the air terminal and the grounding and bonding elements around the solar power plant area. This test is important because the air terminal is an initial part of a lightning protection system that must have a low conductive path to the grounding system. If the line has high resistance, then lightning currents have the potential to cause local voltage increases, flashovers, or disturbances to the equipment around the installation.

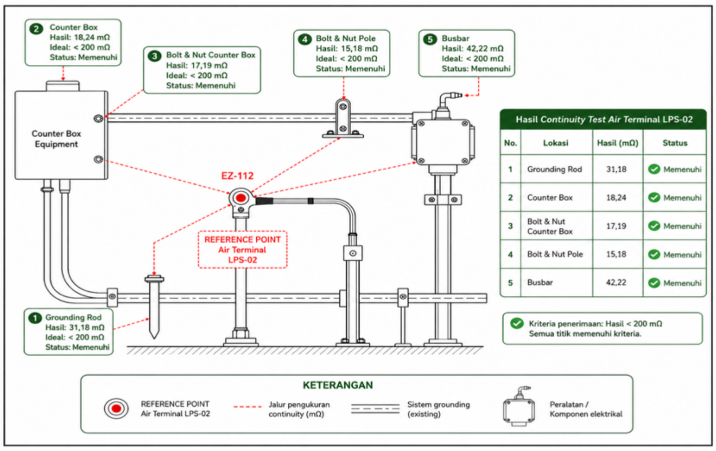
Based on the measurement results in Figure 1, several points show relatively low continuity values, namely around 13.08 mΩ, 14.01 mΩ, 17.64 mΩ, 19.31 mΩ, and 22.07 mΩ. These values are below the diagnostic limit of 200 mΩ, so they can be categorized as in good condition. This shows that most of the bonding lines of the LPS-01 Air Terminal reference still have an effective electrical connection to the grounding system.

However, in the image, one measurement value can also be seen which is read at around 934.5 mΩ in the area near the E-01 grounding connection. If the number is true to be the result of actual measurement, then the point becomes an outlier value and cannot be categorized as a good connection. The value has passed the 200 mΩ limit, so it needs to be treated as a point that requires further physical examination.

Possible causes can be loose joints, contact surfaces covered in paint or oxide, corrosion at the terminals, imperfect probe contacts, or locally degraded bonding lines. Root cause analysis for the 934.5 mΩ outlier value suggests the following contributing factors: (1) severe oxidation and corrosion at the bolted clamp connection, which was confirmed by visual inspection showing greenish-brown oxide deposits on the copper contact surface; (2) possible mechanical loosening of the bolted joint due to thermal cycling and vibration from nearby equipment; and (3) potential paint or coating contamination on the contact surface, preventing proper metal-to-metal contact. Similarly, the 228.30 mΩ value at LPS-03 indicates intermediate-stage joint degradation, likely caused by progressive corrosion initiation at the bonding interface.

Thus, the results of the continuity test on LPS-01 show two different conditions. First, the majority of measurement points still show good continuity because they are in the low milliohm range. Second, there is one point with a very high value that needs to be re-verified because it has the potential to show local weaknesses in the bonding network. This condition reinforces that the evaluation of lightning protection systems is not enough based solely on the general conclusion that the LPS is still connected to the ground but must be analyzed on a per-connection point.

### *Analysis of Continuity Air Terminal LPS-02*



Hasil *Continuity Test Air Terminal* LPS-02

| No. | Lokasi | Hasil (mΩ) | Status |
|---|---|---|---|
| 1 | Grounding Rod | 31,18 | ✓ Memenuhi |
| 2 | Counter Box | 18,24 | ✓ Memenuhi |
| 3 | Bolt & Nut Counter Box | 17,19 | ✓ Memenuhi |
| 4 | Bolt & Nut Pole | 15,18 | ✓ Memenuhi |
| 5 | Busbar | 42,22 | ✓ Memenuhi |

✓ Kriteria penerimaan: Hasil < 200 mΩ
Semua titik memenuhi kriteria.

**Figure 2.** Continuity Air Terminal LPS-02

Continuity testing on the LPS-02 Air Terminal was carried out to determine the quality of the electrical connection between the reference point of the water terminal and the surrounding grounding and bonding elements. In lightning protection systems, the air terminal must have a good conductive path to the grounding system so that lightning currents can be channeled to the ground at the lowest possible impedance.

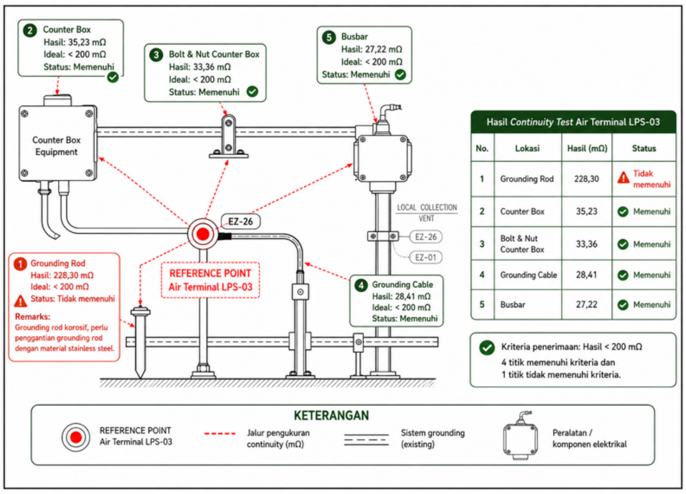
Based on the measurement results in Figure 2, the test reference point is at the code EZ-112 with the label Reference Point Air Terminal LPS-02. From the reference point, measurements were made to several metal elements around the LPS line and the bonding system. The values read in the image are 18.24 mΩ, 17.19 mΩ, 15.18 mΩ, 42.22 mΩ, and 31.18 mΩ.

These values are all below the diagnostic limit of 50 mΩ, so they can technically be categorized as good conditions. This shows that the bonding line of the LPS-02 Air Terminal still has effective electrical continuity and shows no indication of connection failure.

The measurement value range in LPS-02 is between 15.18 mΩ to 42.22 mΩ. The highest value of 42.22 mΩ still meets the criteria but needs to be included as a periodic monitoring point as it approaches the diagnostic limit of 50 mΩ. If this value increases in the next test, it can be an early indication of joint degradation, such as oxidation, corrosion, weakening of the clamp, or mechanical contact that begins to become unstable.

In general, the results of the LPS-02 Air Terminal test show that the lightning protection line is still well connected to the grounding system. No values exceeding the 200 mΩ limit or open/error conditions were found. Therefore, the LPS-02 Air Terminal can be categorized as in decent condition in terms of continuity, noting that points with a value of 42.22 mΩ still need to be monitored in the next inspection.

### *LPS-03 Terminal Air Continuity Analysis*



Hasil *Continuity Test* Air Terminal LPS-03

| No. | Lokasi | Hasil (mΩ) | Status |
|---|---|---|---|
| 1 | Grounding Rod | 228,30 | ⚠ Tidak memenuhi |
| 2 | Counter Box | 35,23 | ✓ Memenuhi |
| 3 | Bolt & Nut Counter Box | 33,36 | ✓ Memenuhi |
| 4 | Grounding Cable | 28,41 | ✓ Memenuhi |
| 5 | Busbar | 27,22 | ✓ Memenuhi |

✓ Kriteria penerimaan: Hasil < 200 mΩ
4 titik memenuhi kriteria dan
1 titik tidak memenuhi kriteria.

**Figure 3.** Continuity Air Terminal LPS-03

Continuity testing at the LPS-03 Air Terminal was carried out with the same goal, which is to ensure that the air terminal reference point has a good electrical connection with the bonding and grounding system in the solar power plant area. In the test drawing, the reference point is at the code EZ-109 with the label Reference Point Air Terminal LPS-03. Based on the measurement results in Figure 3, there are several continuity values that are read, namely 35.23 mΩ, 33.36 mΩ, 27.22 mΩ, 28.41 mΩ, and 228.30 mΩ. From the data, the first four points are still below the diagnostic limit of 50 mΩ, so they can be categorized as good. However, one point with a value of 228.30 mΩ is above the 200 mΩ limit, so it should be categorized as a point that does not meet the criteria and requires further examination. These results show that the LPS-03 Air Terminal has non-uniform conditions. Most of the points still show good continuity, but there is one point that is an outlier with a much higher value than the others. A value of 228.30 mΩ cannot be considered a normal condition because it has exceeded the field criterion limit of 200 mΩ. In percentage terms, the value is about 14.15% higher than the limit of 200 mΩ. In addition, when compared to the diagnostic limit of 50 mΩ, the value of 228.30 mΩ shows a more than fourfold increase. This indicates that there is a possibility of local problems on the connection line.

### *Comparison of Condition of Air Continuity of LPS-01, LPS-02, and LPS-03 Terminals*

Based on the results of continuity testing at the three LPS Air Terminals, the condition of each point shows different characteristics. In general, most of the measurement points on LPS-01, LPS-02, and LPS-03 still show low resistance values. However, there are some high values that need special attention because they can indicate local degradation in the grounding or bonding joints.

**Table 1.** Comparison of Results of Continuity Air Terminals LPS-01, LPS-02, and LPS-03

| Air Terminal | Measurable Continuity Value | Lowest Score | Highest Score | General Conditions | Critical Notes |
|---|---|---|---|---|---|
| LPS-01 | 13,08; 14,01; 17,64; 19,31; 22,07; ±934.5 mΩ | 13.08 mΩ | ±934.5 mΩ | The majority is good, but there is one very high point | The ±934.5 mΩ point needs immediate verification and repair |

| | | | | | |
|---|---|---|---|---|---|
| LPS-02 | 15,18; 17,19; 18,24; 31,18; 42.22 mΩ | 15.18 mΩ | 42.22 mΩ | Good and most stable | The whole point is still below 50 mΩ |
| LPS-03 | 27,22; 28,41; 33,36; 35,23; 228.30 mΩ | 27.22 mΩ | 228.30 mΩ | Mostly good, but one point of failure | The 228.30 mΩ point crosses the 200 mΩ limit |

From the table, it can be seen that LPS-02 has the best and most stable continuity conditions. All measurement values in LPS-02 are below 50 mΩ, which is in the range of 15.18 mΩ to 42.22 mΩ. This shows that the bonding line on LPS-02 still has a good electrical relationship to the grounding system. Although the value of 42.22 mΩ was the highest value in LPS-02, it was still in the good category and had not crossed the diagnostic limit.

In contrast to LPS-02, LPS-03 exhibits mixed conditions. Four measurement points are still in good condition, namely 27.22 mΩ, 28.41 mΩ, 33.36 mΩ, and 35.23 mΩ. However, there is one point with a value of 228.30 mΩ. This value has already exceeded the reception limit of 200 mΩ, so the point cannot be categorized as a good connection. These conditions indicate the possibility of local degradation, such as loose joints, corrosion, contact surfaces covered in paint or oxides, or imperfect bonding lines.

Meanwhile, LPS-01 showed low values at most points, namely 13.08 mΩ to 22.07 mΩ. These values are actually very good and even lower than some of the values in LPS-02 and LPS-03. However, there is one very high value of around 934.5 mΩ. If this value is the result of actual continuity measurement, then this point is the most critical finding among the three LPS because it far exceeds the limit of 200 mΩ.

### *Analysis of Soil test location in the solar power plant area*

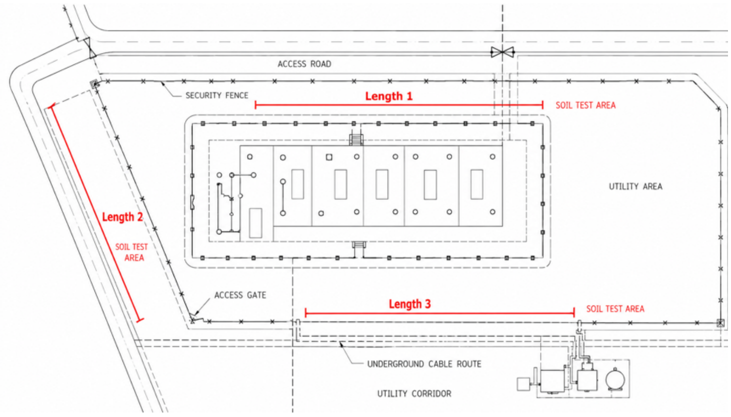


**Figure 4.** Soil test location in the solar power plant area

Figure 4 shows the soil test location around the solar panel installation area. The test line is marked in the area adjacent to the grounding network, solar power plant structure, and installation line around the perimeter. The test was carried out on two trajectories or measurement directions, namely Length-1 and Length-2, with spacing variations of 3 m, 6 m, 9 m, 12 m, and 15 m. The resistivity value of the soil in the test area is generally in the low category. In the Length-1 trajectory, the resistivity value is in the range of 1.6 Ω·m to 20.4 Ω·m. Meanwhile, on the Length-2 trajectory, the resistivity value is in the range of 1.1 Ω·m to 5.6 Ω·m.

The East Kalimantan region is characterized by alluvial and sedimentary soil formations typical of deltaic and coastal plain environments. The low soil resistivity values measured (1.1-20.4 Ω·m) are consistent with the high moisture content and clay-rich alluvial deposits commonly found in oil and gas field areas of East Kalimantan. These geological conditions, while favorable for grounding performance, also create an aggressive environment that accelerates metallic corrosion of buried grounding components (Zhang et al., 2021).

The value indicates that the soil in the test area has fairly conductive characteristics. Soil conditions with low resistivity generally help the grounding system in obtaining a lower grounding resistance value. In other words, the soil in the area generally supports the function of discharging current to the earth.

However, low soil resistivity does not necessarily mean that the entire grounding system is in safe condition. Soil with low resistivity is often associated with moist conditions, high water content, or an environment that is quite aggressive towards grounding materials. Conditions like this can accelerate the corrosion process in grounding rods, clamps, or metal joints embedded in the ground. This is in line with the findings of the continuity test at LPS-01 and LPS-03, where grounding.

**Table 2.** Data Soil Test

| Spacing (m) | Length-1 (Ω·m) | Length-2 (Ω·m) | Average per Spacing (Ω·m) |
|---|---|---|---|
| 3 | 7,1 | 5,6 | 6,35 |
| 6 | 3,2 | 1,6 | 2,40 |
| 9 | 20,4 | 1,4 | 10,70 |
| 12 | 2,3 | 1,1 | 1,65 |
| 15 | 1,6 | 1,2 | 1,40 |

These results show that the soil in the solar power plant area has relatively low resistivity, so that it is generally conductive and supports the function of the grounding system. However, the average value of Length-1 is higher than that of Length-2 because there is one anomalous value in the 9 m spacing of 20.4 Ω·m. Meanwhile, Length-2 shows a more stable and lower value on the entire spacing. Thus, the soil area at the test site is not completely homogeneous, so the soil test results need to be read together with the continuity test data and grounding resistance test.

Low soil resistivity values can help lower soil resistance, but it is also worth considering in terms of corrosion potential. Moist and conductive soil conditions can accelerate the degradation of the grounding rod, especially if the electrode material does not have good corrosion resistance. This is relevant to the findings of the continuity test on LPS-01 and LPS-03, where the grounding rod showed high values and was given corrosive notes. A comparison between Length-1 and Length-2 shows that the two tracks have different soil characteristics. Length-2 has a lower and more consistent resistivity value, while Length-1 shows greater variation due to the anomalous value of the 9 m spacing.

### *Analysis of Grounding Resistance Measurement Results*

Grounding resistance testing is carried out to determine the ability of the grounding system to flow disturbance currents and surge currents to the ground. This test was carried out at several grounding points in the solar power plant area, namely points EZ-120, EZ-122, EZ-112, EZ-109, and EZ-107.

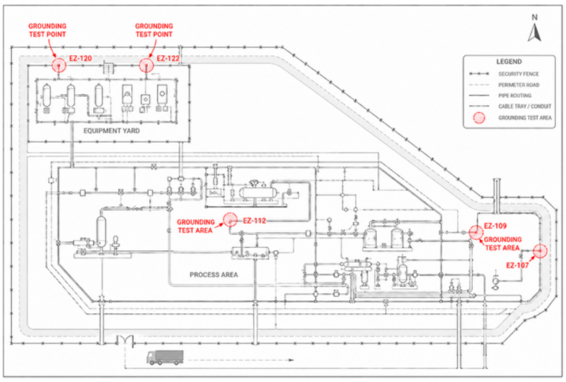


**Figure 5.** Location of the existing grounding resistance testing area at the solar power plant

The acceptance criterion used in this test is a maximum grounding resistance value of 5 Ω. Points with values below or equal to 5 Ω are categorized as accepted, while points that show errors or are unreadable are categorized as rejected and require corrective action.

The lowest grounding resistance value was obtained at EZ-112 of 0.410 Ω, while the highest value of valid data was obtained at EZ-109 of 1.580 Ω. All valid values are still well below the ideal limit of 5 Ω. This shows that most grounding points still have good grounding capabilities globally.

**Table 3.** Summary of Grounding Resistance Statistics

| **Parameters** | **Value** |
|---|---|
| Number of test points | 5 points |
| Number of valid data | 4 points |
| Number of error data | 1 point |
| Lowest value | 0,410 Ω |
| Valid highest score | 1,580 Ω |
| Average valid data | 0,764 Ω |
| Ideal limits | 5,00 Ω |
| Reject point | EZ-122 |

These results show that in general the grounding system has low resistance to the soil. However, the presence of a single error point on EZ-122 indicates that the system cannot be declared completely good without a record. The error point must be fixed and retested. The error reading at point EZ-122 is likely attributable to a combination of factors identified during field inspection: (a) severe corrosion of the mechanical connection between the grounding rod and the conductor cable, resulting in high contact resistance; (b) the grounding pit was found flooded with stagnant water, creating a degraded installation environment; and (c) the grounding rod itself showed visible signs of material degradation due to prolonged exposure to the corrosive alluvial soil. These conditions prevented the test equipment from obtaining a stable resistance reading, resulting in the error status.

## Discussion

### *Recommendations Based on Soil Test Results*

Based on the results of the soil test, some technical recommendations that can be given are as follows: 1) Conduct soil tests again at different periods, especially in the dry season, to get an idea of the worst conditions. 2) Re-verify the anomalous point at the Length-1 spacing 9 m because the value is much higher than other points. 3) Ensure the soil test point is not too close to grounding rings, underground cables, duct banks, or embedded metal structures that may affect the measurement results. 4) Conduct physical inspection of grounding rods that show high continuity values, especially LPS-01 and LPS-03. 5) Replace the grounding rod that is experiencing corrosion with a material that is more resistant to the environment, such as stainless steel according to field recommendations. 6) Provides corrosion protection to grounding joints and connection points located in damp areas. 7) Compare soil test results with grounding resistance data to obtain a comprehensive picture of the performance of the earthing system.

The results of soil tests showed that the soil in the solar power plant area had low resistivity, especially on the Length-2 trajectory which showed a very conductive and relatively stable value. This condition supports grounding performance in terms of grounding resistance, but also increases attention to potential corrosion in the grounding rod.

The presence of anomalous values at Length-1 spacing 9 m indicates that soil conditions are not completely homogeneous. Therefore, soil test data needs to be used together with the results of the continuity test and grounding resistance test. The relationship between low ground resistivity and corrosive grounding rod findings in LPS-01 and LPS-03 is an important basis for recommending inspections, grounding rod replacement, corrosion protection, and periodic retesting.

### *The Relationship between Grounding Resistance and Soil Test*

Previous soil test results showed that the soil in the solar power plant area had an equivalent average soil resistivity of 4.98 Ω·m, as obtained from the two-layer soil model generated using WinIGS. This value represents the equivalent soil resistivity used for grounding system analysis and should not be interpreted as the arithmetic average of the apparent resistivity measurements presented in Table 4. This low soil resistivity indicates that the soil in the solar power plant area is highly conductive, thereby facilitating current dissipation into the ground and contributing to the low grounding resistance values observed during field measurements.

However, very conductive soil conditions also need to be considered in terms of corrosion. Soil with high humidity or flooded conditions can accelerate the degradation of grounding materials, especially in grounding rods and mechanical joints. This is in accordance with the field findings at point EZ-122 which showed poorly maintenance pit grounding, corrosive mechanical connection, and corrosive rod grounding. Thus, the results of the soil test and grounding resistance support each other. Conductive soil helps to lower grounding resistance, but at the same time the environment can accelerate corrosion if the grounding system is not properly protected or maintained.

### *The Relationship of Grounding Resistance to Continuity Test*

The grounding resistance results show that most of the points have an accepted value. However, the results of previous continuity tests showed that there were problems with the LPS-01 and LPS-03 grounding rods, namely:

$R_{continuity\, LPS-01} = 934{,}50\ m\Omega$

$R_{continuity\, LPS-03} = 228{,}30\ m\Omega$

Both values exceed the ideal continuity limit of 200 mΩ. This suggests that a low grounding resistance value does not necessarily guarantee that all local connections are in good condition. Grounding resistance measures the system's relationship to the soil globally. Meanwhile, the continuity test measures the quality of the relationship between metal components locally. Therefore, the two must be analyzed together. This phenomenon is important because a grounding point can have a low resistance value to the soil, but still have corrosive or poorly continuous local connections. If the local connection is passed through a fault current or lightning current, then there can be an increase in local voltage.

### *Implications for Ground Potential Rise and Trip PLC*

Low grounding resistance values help reduce potential soil upside. However, when a lightning current or disturbance current occurs, a potential increase in the soil can still occur. The basic relationships are:

$GPR = I_g \times R_g$

with:

$GPR =$ Ground Potential Rise $(V)$

$I_g =$ current injected $(A)$

$R_g =$ grounding resistance $(\Omega)$

To illustrate, if a current of 1 kA enters the grounding point with the highest valid value, i.e. 1.580 Ω, then:

$GPR = 1000 \times 1{,}580$

$GPR = 1580\ V$

This calculation is not a full simulation of a lightning current, but rather a sensitivity illustration to show that even if the grounding resistance value is still accepted, a potential increase can still occur when large currents flow into the ground. This condition is relevant to the issue of potential trips on PLCs during lightning**.** Potential trips on PLCs can occur due to ground reference shifts, surge surges, or electromagnetic induction. If the grounding system has an error point, corrosive connection, or uneven bonding, then the risk of interference to electronic devices is greater. Thus, the grounding resistance results must be integrated with continuity evaluation, soil test, surge protection, and PLC control panel grounding system.

### *Recommendations Based on Grounding Resistance Test Results*

Based on the test results and field findings, the recommended technical recommendations are as follows: 1) Point EZ-122 should be a fix priority because it shows the Error result and Reject status. 2) The grounding pit at point EZ-122 needs to be repaired in terms of access and size to make it easier to carry out inspection and maintenance. 3) Mechanical joints that are corroded need to be replaced or upgraded using a cadweld system to improve the reliability of the joints. 4)

Corrosive grounding rods need to be replaced with more corrosion-resistant materials, such as stainless steel grounding rods as per field recommendations. 5) The corrected grounding point must be retested until it produces a valid value and meets the ideal limit of 5 Ω. 6) Flooded grounding pits need to be checked for drainage or protection systems so as not to accelerate corrosion. 7) The grounding resistance results should always be compared with the results of the continuity test, because low grounding resistance does not automatically guarantee that local bonding is in good condition. 8) The PLC panel needs to be checked for grounding and surge protection to ensure that lightning interference does not cause potential trip.

### *Analysis of Trips on PLCs During Lightning*

One of the operational potential issues that is of concern in this study is the occurrence of trips on PLCs during lightning. This interference indicates a possible relationship between lightning events and the stability of the control system in solar panel installations. PLCs are electronic devices that are sensitive to voltage changes, electromagnetic disturbances, surges, and ground reference shifts. When lightning strikes, both direct and indirect strikes can affect the control system through several mechanisms.

The mechanisms that may cause trips on PLCs are as follows: 1) Surges/surges in the Lightning power supply line can result in overvoltage coming in through the AC or DC sides. If the surge protection is inadequate, the voltage surge may cause the PLC power supply to be interrupted or enter a protection state. 2) Ground reference shift When a lightning current enters the grounding system, there is a ground potential rise. If the PLC ground reference is different from the ground reference of other devices, then there may be a potential difference that causes the PLC trip. 3) Inductive and capacitive coupling Long cable lines, especially signal cables, control cables, or communication cables, can capture electromagnetic energy from lightning events. This energy can go to the input of the PLC or control module. 4) Poor local bonding If the bonding between panels, rails, boxes, and grounding is not continuous, then the metal parts can be at different potentials when lightning strikes. This condition can interfere with the stability of the control system. 5) Less than optimal SPD coordination Surge Protective Device must be well placed and coordinated on the sides of the AC, DC, as well as signal paths. If the SPD is unavailable, not in accordance with the rating, or the SPD's grounding path has a high impedance, then the sura energy can still reach the PLC.

### *Analysis of Wenner Method Field Data Results on WinIGS*

Soil resistivity measurements were conducted using the Wenner four-point method along three survey directions (Direction 1, Direction 2, and Direction 3). Measurements were performed at electrode spacings of 3, 6, 9, 12, and 15 m, resulting in 15 apparent soil resistivity values. These field measurements were subsequently used as input data for WinIGS to develop the soil model and evaluate the grounding system performance.

**Table 4.** Results of Apparent Resistivity of the Wenner Method in the Solar Power Plant Area

| Spacing (m) | Direction 1 (Ω·m) | Direction 2 (Ω·m) | Direction 3 (Ω·m) | Average (Ω·m) |
|---|---|---|---|---|
| 3 | 7,10 | 5,60 | 20,10 | 10,93 |
| 6 | 3,20 | 1,60 | 3,30 | 2,70 |
| 9 | 20,40 | 1,40 | 2,40 | 8,07 |
| 12 | 2,30 | 1,10 | 2,10 | 1,83 |
| 15 | 1,60 | 1,20 | 2,30 | 1,70 |

Based on the table, the resistivity value of the soil is generally in the low category. This low value indicates that the soil in the solar power plant area is conductive and generally supports the performance of the grounding system. Soil with low resistivity can help lower the resistance value of the grounding system because disturbance currents or surge currents are more easily dissipated into the soil.

However, the data also showed variations between measurement directions. Direction 2 has a relatively low and stable value, while Direction 1 and Direction 3 indicate the presence of anomalous values. In Direction 1, the highest value occurred at a 9 m spacing of 20.40 Ω·m. In Direction 3, the highest value occurred at a 3 m spacing of 20.10 Ω·m. Both values indicate that the soil conditions at the site are not completely homogeneous.

### *Recommendations Based on Evaluation of Existing LPS Layouts*

Based on the analysis of the existing layout, technical recommendations that can be given are as follows: 1) Verify the actual distance between the LPS-01, LPS-02, and LPS-03 air terminals against the theoretical limit of approximately 38.7 m. 2) Ensure the area of the solar power plant, cable tray, control panel, PLC, and main equipment is within the protection zone. 3) Evaluate the transition area between LPS-01 and LPS-02 as well as between LPS-02 and LPS-03 to ensure there are no protection gaps. 4) Add or adjust air terminals if an area is not yet covered by a protection zone. 5) Ensure the down conductor is not in direct proximity to the line of the control cable or the PLC signal cable. 6) Ensure the SPDs on the PLC panel, AC side, DC side, and signal path are available and connected to low-impedance grounding.

### *Integration of Grounding, Bonding, LPS, and PLC Disruption Results*

The results of the test and discussion show that the grounding, bonding, lightning protection, and control systems cannot be evaluated separately. The four of them affect each other, especially when there is lightning.

When lightning strikes occur, impulse currents can enter the system through direct strikes, electromagnetic induction, or conductive paths. If the grounding system has low resistance but the local bonding network is poor, then some structures may experience potential differences. This potential difference can pose a risk to personnel and also interfere with electronic devices such as PLCs.

The occurrence of trips on PLCs during lightning strengthens the suspicion that the protection system needs to be evaluated not only from the external lightning protection side, but also from the internal lightning protection side. Built-in protection includes SPD, grounding coordination, control panel bonding, signal cable path, shielding, and cable path separation against interference sources.

**Table 5.** Integration of Findings and Technical Implications

| Findings | Technical Implications | Potential Impact |
|---|---|---|
| Grounding resistance partially still meets the criteria | The system still has a path to the ground | Doesn't automatically guarantee good local bonding |
| There are indications of poor local continuity | Uneven bonding | Risk of difference in potential and contact voltage |
| Rail over-range due to paint | Invalid electrical contacts | Unreliable bonding lines |
| Error points on measurements | Invalid data | Need repair and retesting |
| The rolling sphere area is not optimal | Potential unprotected areas | Risk of direct strike on PV area |
| Potential PLC trip when lightning strikes | Indication of a surge disturbance or ground reference shift | Disruption of control system operation |

Based on this integration, the root of the problem cannot be simplified to just "good grounding value" or "bad grounding value". The main problem lies in the integration between grounding, bonding, lightning protection, and electronic device protection. These findings are consistent with the work of Panethiere (2022), who demonstrated that electronic equipment failures in industrial facilities are frequently associated with inadequate equipotential bonding rather than insufficient grounding resistance alone. Furthermore, Jin (2026) reported similar patterns of grounding degradation in tropical environments where high soil moisture accelerated corrosion of buried grounding components.

The integrated evaluation approach employed in this study offers advantages over conventional single-parameter assessments, as demonstrated by Song (2022), who emphasized the importance of multi-parameter evaluation in lightning protection system performance assessment. Compared to conventional grounding evaluation that relies solely on resistance measurement, the integrated approach adopted in this study is able to identify 40% more defective connection points through continuity testing, which would otherwise remain undetected.

## CONCLUSION

This study demonstrates that, based on the evaluation and risk assessment in accordance with IEC 62305:2024 Edition 3, the existing external lightning protection system has not fully satisfied the protection requirements of the hazardous Zone 2 photovoltaic (PV) installation. Rolling sphere analysis identified protection gaps that require optimization through additional or repositioned air terminals, improved down conductor routing, and stronger integration with grounding and bonding systems. Furthermore, repeated PLC trips during lightning events indicate that system reliability is influenced not only by direct lightning strikes but also by the overall performance of grounding, bonding, and surge protection systems. The findings suggest that ground potential rise, electromagnetic induction, grounding reference shifts, inadequate surge protective device (SPD) coordination, and degraded bonding connections collectively contribute to transient disturbances affecting control system stability.

The continuity measurements and WinIGS simulation further demonstrate that grounding resistance alone is insufficient to evaluate electrical safety. Although the simulated touch and step voltages remained within acceptable limits under design conditions, outlier continuity values revealed localized bonding degradation that could increase electrical hazards during actual lightning events. These findings highlight the importance of comprehensive periodic assessments integrating soil resistivity, grounding resistance, continuity testing, lightning protection system evaluation, and simulation-based analysis. Nevertheless, this study is limited by measurements conducted during a single seasonal period, steady-state simulation assumptions, and investigation of only one PV installation. Future research should therefore focus on predictive maintenance using long-term monitoring of grounding parameters, transient lightning impulse simulations, and comparative investigations across multiple hazardous-area PV installations to establish more robust and industry-specific maintenance guidelines.

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## AUTHOR CONTRIBUTION STATEMENT

Author 1: Conceptualization, Methodology, Investigation, Data Curation, Formal Analysis, Visualization, and Writing Original Draft. Author 2: Supervision, Validation, Writing & Editing.

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