



Ground-Fault Protection Analysis for Electrical Installations in a Multi-Story Office Building

M. Solehan¹, Novia Utami Putri²

¹Department of Electrical Engineering, Sekolah Tinggi Teknologi Nusantara Lampung, Indonesia

²Department of Electrical Engineering, Politeknik Negeri Lampung, Indonesia

ARTICLE INFO

Article history:

Received May 13, 2026

Revised Jun 27, 2026

Accepted Jun 30, 2026

Keywords:

ELCB;

ETAP 19.0;

ground-fault protection;

grounding resistance;

protection coordination.

ABSTRACT

Reliable ground-fault protection is essential in multi-story building electrical installations because insulation failure, leakage current, and inadequate grounding may increase the risk of electric shock, fire, and equipment damage. This study evaluates the ground-fault protection system of the One-Stop Service Office Building in Bandar Lampung, Indonesia. Field measurements were conducted at 15 grounding points using the three-point fall-of-potential method with a Kyoritsu 4105A earth resistance tester. The installed residual current devices, locally configured as Earth Leakage Circuit Breakers (ELCBs), were assessed against PUIL 2020, IEC 60364, IEC 60479-1, and IEC 61008-1 requirements. Protection coordination and single line-to-ground fault behavior were further analyzed using ETAP 19.0. The measured grounding resistance ranged from 0.93 Ω to 6.21 Ω , with an average value of 2.56 Ω . Twelve grounding points, or 80% of the measured locations, complied with the 5 Ω maximum limit, whereas G-12, G-14, and G-15 exceeded the standard with values of 5.28 Ω , 5.85 Ω , and 6.21 Ω , respectively. The installed 30 mA ELCBs were suitable for personnel protection; however, type AC devices were still used on circuits supplying non-linear loads such as UPS and variable-frequency drives. Several toilet socket circuits were also found without residual current protection. The ELCB-MCB coordination was selective for low-level leakage currents, although simultaneous operation may occur around 160 A. Corrective actions include installing parallel rod electrodes, applying bentonite-based soil treatment, replacing type AC RCDs with type A devices on non-linear circuits, and implementing six-month preventive testing.

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Corresponding Author:

M. Solehan,

Department of Electrical Engineering, Sekolah Tinggi Teknologi Nusantara Lampung,

Jl. Pulau Damar Gg. Sapta Marga Kel. Way Dadi Baru Kec. Sukarama Bandar Lampung, Indonesia, 35131

Email: solehan.mahasiswa@sttnlampung.ac.id

INTRODUCTION

Electrical installations in multi-story buildings require a protection system capable of maintaining continuity of service while ensuring personnel safety and equipment reliability. In low-voltage distribution systems, ground faults may occur due to insulation degradation, conductor contact with exposed conductive parts, moisture, or failure of connected equipment. If such faults are not detected and interrupted properly, leakage current may create hazardous touch voltage, increase the probability of electric shock, and initiate thermal stress that can lead to fire or equipment damage [1], [2].

Ground-fault protection is commonly implemented through a combination of grounding systems and residual current protective devices. The grounding system provides a low-impedance path for fault current and stabilizes the reference potential of exposed conductive parts, whereas residual current devices detect the imbalance between phase and neutral conductors and disconnect the circuit when the residual current exceeds a specified threshold [3]. In personnel protection applications, 30 mA residual current devices are widely used because they provide additional protection against electric shock under low-voltage installation requirements [4].

However, the effectiveness of ground-fault protection depends not only on the nominal rating of the installed protective devices, but also on the actual grounding resistance, device type, operating characteristics, load profile, and coordination with overcurrent protection devices. Modern building loads such as uninterruptible power supplies, variable-frequency drives, LED drivers, and other power electronic equipment may generate distorted residual currents and high-frequency components. Previous studies reported that residual current devices may experience changes in tripping behavior under harmonics and high-frequency residual currents, indicating that device selection must consider the waveform characteristics of the protected circuit [5], [6].

Grounding performance is also strongly influenced by soil resistivity, electrode configuration, corrosion, moisture, and seasonal variation. Several studies have shown that grounding resistance can be reduced by increasing the number of electrodes, improving electrode configuration, or applying low-resistivity materials such as bentonite-based soil treatment [7], [8]. Therefore, field measurement remains necessary because design assumptions may differ from the actual condition of the installed grounding network.

The One-Stop Service Office Building in Bandar Lampung is a multi-story public service building with a relatively complex low-voltage distribution system. Although the building is equipped with ELCB and MCB protection devices, a comprehensive evaluation of grounding resistance, residual current protection suitability, and ELCB-MCB coordination has not been systematically reported. This study addresses that gap by evaluating: (1) the compliance of grounding resistance values with PUIL 2020 and IEC 60364 requirements; (2) the suitability of installed ELCB types and sensitivities for protected circuits; (3) the coordination behavior between ELCB and MCB devices under selected fault-current scenarios; and (4) corrective recommendations for grounding and residual current protection improvement.

The main contribution of this study is an integrated field-based assessment of ground-fault protection in a multi-story office building by combining grounding resistance measurement, residual current device evaluation, and ETAP-based protection coordination analysis. The results provide practical recommendations for improving electrical safety and preventive maintenance in public building installations.

RESEARCH METHODS

Research Object and Study Location

This study was conducted at the One-Stop Service Office Building in Bandar Lampung, Indonesia. The object of evaluation was the low-voltage electrical installation system, focusing on grounding resistance, residual current protection, and protective device coordination under ground-fault conditions. The observed installation consisted of a 20 kV incoming supply, a 1600 kVA distribution transformer, a main distribution panel, several sub-distribution panels, final circuits, grounding electrodes, and installed Earth Leakage Circuit Breakers (ELCBs) [9].

The research used a field measurement and simulation-based approach. Field measurement was applied to obtain actual grounding resistance and leakage-current

conditions, whereas simulation was used to evaluate single line-to-ground fault behavior and protection coordination. The overall research procedure consisted of: (1) preliminary inspection of the electrical installation; (2) identification of grounding and protection points; (3) grounding resistance measurement; (4) leakage-current and ELCB data collection; (5) ETAP-based modeling; (6) protection coordination analysis; and (7) formulation of corrective recommendations.

Measurement Instruments

The main instrument used for grounding resistance measurement was a Kyoritsu 4105A earth resistance tester. The instrument was used to measure grounding resistance at selected grounding points using the three-point fall-of-potential method. Leakage-current observation was supported by a Hioki 3290 clamp meter. In addition, the electrical network was modeled and analyzed using ETAP 19.0 to perform load-flow analysis, short-circuit analysis, and protective device coordination [10].

The measured parameters consisted of grounding resistance, leakage current, installed ELCB rating, ELCB sensitivity, MCB rating, panel location, and grounding point condition. The collected technical data were compared with PUIL 2020, IEC 60364, IEC 60479-1, IEC 61008-1, and IEEE Std 81-2012 requirements [11].

Grounding Resistance Measurement Procedure

Grounding resistance was measured at 15 grounding points representing the main grounding system, panel grounding, utility grounding, roof panel grounding, parking-area panel grounding, and lightning protection grounding. The measurement was performed using the three-point fall-of-potential method. In this method, the grounding electrode under test was connected to the earth tester, while two auxiliary electrodes were installed as the current electrode and potential electrode.

The potential electrode was positioned at approximately 61.8% of the distance between the electrode under test and the current electrode. This position was selected to obtain a representative resistance value and reduce the influence of overlapping resistance areas. Each grounding point was measured three times, and the average value was used as the final grounding resistance value. The average resistance was calculated using (1).

$$R_{avg} = \frac{R_1 + R_2 + R_3}{3} \quad (1)$$

where (R_{avg}) is the average grounding resistance, and (R_1), (R_2), and (R_3) are the first, second, and third measurement results, respectively. The compliance status of each grounding point was determined by comparing the measured resistance value with the maximum allowable grounding resistance limit of 5 Ω according to PUIL 2020. A grounding point was classified as compliant when its average resistance was less than or equal to 5 Ω , and non-compliant when its average resistance exceeded 5 Ω .

ELCB and MCB Evaluation

The installed ELCBs were evaluated based on rated current, residual operating current, device type, protected circuit, and installation location. ELCBs with a sensitivity of 30 mA were assessed as personnel protection devices, whereas higher-sensitivity settings were evaluated in relation to fire protection and upstream protection functions. The suitability of ELCB type was also examined, particularly for circuits supplying non-linear loads such as uninterruptible power supplies and variable-frequency drives.

The coordination between ELCB and MCB was evaluated by comparing the operating characteristics of both devices under several ground-fault current scenarios. The analysis considered low-level leakage current, rated residual current, multiples of residual operating current, overload current, and high short-circuit current. The coordination was

classified as selective when the protective device closest to the fault operated first without causing unnecessary upstream disconnection. If both devices operated within a very close time interval, the condition was identified as a possible simultaneous tripping zone.

ETAP Modeling and Simulation

The electrical distribution system was modeled in ETAP 19.0 based on available single-line diagram and field data. The model included the utility source, 20 kV/400 V transformer, main distribution panel, sub-distribution panels, final circuits, grounding system, circuit breakers, and residual current protection devices. The main system parameters used in the simulation were a 1600 kVA transformer capacity, 6% transformer impedance, 20 kV/400 V voltage level, 1250 kVA total load, 0.85 lagging power factor, and 25 kA utility short-circuit current [12].

Three simulation studies were performed. First, load-flow analysis was conducted to verify voltage profile and load distribution. Second, short-circuit analysis was performed using IEC 60909-based calculation to estimate single line-to-ground fault current at selected buses. Third, protective device coordination was analyzed using the Star View feature to examine the operating relationship between ELCB and MCB devices.

The single line-to-ground fault current was calculated conceptually using the symmetrical component approach shown in (2).

$$I_{LG} = \frac{3V_{phase}}{Z_1 + Z_2 + Z_0 + 3Z_f} \quad (2)$$

where (I_{LG}) is the single line-to-ground fault current, (V_{phase}) is the phase voltage, (Z_1), (Z_2), and (Z_0) are the positive-, negative-, and zero-sequence impedances, and (Z_f) is the fault impedance.

Data Analysis

The data analysis was performed in three stages. First, the grounding resistance data were analyzed statistically using minimum, maximum, average, and compliance percentage values. The compliance percentage was calculated using (3).

$$C = \frac{N_c}{N_t} \times 100\% \quad (3)$$

where (C) is the compliance percentage, (N_c) is the number of compliant grounding points, and (N_t) is the total number of measured grounding points.

Second, the installed ELCBs were evaluated by comparing their rating, residual operating current, device type, and protected circuit characteristics with relevant installation and safety standards. Third, ETAP simulation results were compared with the field measurement data to identify critical points requiring corrective action. The final recommendations were prioritized based on safety risk, non-compliance level, installation criticality, and ease of implementation.

RESULTS AND DISCUSSION

Electrical System Description

The evaluated building is supplied by a 20 kV utility network through a 1600 kVA distribution transformer with a 20 kV/400 V voltage ratio, Dyn11 vector group, ONAN cooling type, and 6% impedance. The low-voltage distribution system consists of a main distribution panel (MDP), several sub-distribution panels (SDPs), final circuits, utility panels, grounding electrodes, and residual current protection devices installed at selected circuits.

The installed protection system combines miniature circuit breakers (MCBs) for overcurrent and short-circuit protection with Earth Leakage Circuit Breakers (ELCBs) for residual current protection. The ELCBs installed in personnel protection circuits have a residual operating current of 30 mA, while the upstream protection uses a higher residual current setting for fire-risk mitigation. This configuration is technically appropriate in principle because low-level leakage currents must be detected before they develop into hazardous touch voltage or thermal faults.

Grounding Resistance Measurement Results

Grounding resistance was measured at 15 grounding points using the three-point fall-of-potential method. Table 1 presents the measured grounding resistance and compliance status of each point based on the 5 Ω maximum limit specified in PUIL 2020.

Table 1. Grounding Resistance Measurement Results

Grounding Point	Location	Average Resistance (Ω)	Status
G-01	Transformer electrode	0.93	Compliant
G-02	MDP panel	1.06	Compliant
G-03	SDP floor 1-4	1.45	Compliant
G-04	SDP floor 5-8	1.53	Compliant
G-05	SDP floor 9-12	1.89	Compliant
G-06	Basement panel	1.62	Compliant
G-07	Utility panel	2.15	Compliant
G-08	Grounding ring	1.19	Compliant
G-09	Genset area	2.85	Compliant
G-10	Cooling tower	3.43	Compliant
G-11	AC chiller panel	4.15	Compliant
G-12	Roof panel	5.28	Non-compliant
G-13	Parking panel B1	4.83	Compliant
G-14	Parking panel B2	5.85	Non-compliant
G-15	Lightning grounding	6.21	Non-compliant

The measured grounding resistance ranged from 0.93 Ω to 6.21 Ω , with an average value of 2.96 Ω . The lowest resistance was recorded at G-01, which represents the transformer grounding electrode, while the highest resistance was found at G-15, which represents the lightning protection grounding point. Of the 15 measured points, 12 points complied with the 5 Ω requirement, resulting in an 80% compliance rate.

The non-compliant grounding points were G-12, G-14, and G-15, with resistance values of 5.28 Ω , 5.85 Ω , and 6.21 Ω , respectively. These results indicate that the grounding system is generally acceptable, but localized degradation exists at several critical points. The high value at G-12 may be associated with limited electrode depth, higher soil dryness at the roof-related grounding path, or increased conductor-path resistance. The high value at G-14 is consistent with field inspection findings indicating corrosion at the electrode connection. Meanwhile, G-15 requires higher priority because it is associated with the lightning protection system, where a low-impedance discharge path is essential to reduce the risk of dangerous potential rise during lightning events.

The measurement results confirm that grounding performance must be assessed based on actual field conditions rather than design assumptions alone. Soil resistivity, moisture content, electrode depth, electrode spacing, corrosion, and connection quality may significantly affect the final resistance value. Therefore, periodic grounding measurement is required, particularly for outdoor, basement, parking, and lightning protection grounding points.

ELCB Suitability Evaluation

The installed ELCBs consist of Schneider Electric and ABB devices with type AC characteristics. The 30 mA ELCBs installed in final circuits are suitable for additional

personnel protection because this sensitivity level is commonly applied to reduce electric-shock risk in low-voltage installations. The upstream protection with a higher residual current setting is also acceptable when used for fire protection and selective protection coordination.

However, two technical issues were identified. First, type AC ELCBs are still used in circuits supplying non-linear loads such as uninterruptible power supplies (UPSs), variable-frequency drives (VFDs), and other power electronic equipment. This configuration is not optimal because type AC residual current devices are intended primarily for sinusoidal alternating residual currents. Non-linear loads may produce pulsating DC components, distorted waveforms, and high-frequency residual currents that can affect residual current device operation [5]–[8]. Therefore, type A ELCBs are recommended for circuits containing UPSs, VFDs, LED drivers, and other converter-based loads.

Second, several toilet socket circuits on floors 7–10 were not protected by ELCBs. This condition should be corrected because socket circuits in wet or humid areas have a higher electric-shock risk. The absence of residual current protection in these circuits reduces the overall safety level of the building installation. Therefore, 30 mA ELCBs should be installed on these circuits as a priority corrective action.

ELCB-MCB Coordination Analysis

The coordination between ELCB and MCB was evaluated under several fault-current scenarios. Table 2 summarizes the expected operating behavior of the ELCB and MCB combination used in the evaluated final circuit.

Table 2. ELCB-MCB Coordination Under Selected Fault Current Levels

Fault Current	ELCB Operating Time	MCB Operating Response	Coordination Status
30 mA	< 300 ms	No trip	Selective
150 mA	< 40 ms	No trip	Selective
300 mA	< 30 ms	No trip	Selective
5 A	< 30 ms	> 5000 ms	Selective
63 A	< 30 ms	Approximately 4000 ms	Selective
160 A	< 30 ms	Approximately 10 ms	Possible simultaneous trip
1000 A	< 30 ms	< 5 ms	Acceptable for short-circuit protection

The results show that the ELCB operates first for low-level leakage current and residual current scenarios. At 30 mA, 150 mA, and 300 mA, the MCB does not operate because the current is far below its overcurrent tripping range. Therefore, the ELCB provides the primary protection against leakage current and electric-shock risk.

At 5 A and 63 A, the ELCB still operates faster than the MCB. This condition indicates that leakage and moderate ground-fault currents can be cleared by the residual current protection device before the overcurrent device operates. However, at approximately 160 A, both devices may operate within a relatively close time interval. This condition is identified as a possible simultaneous tripping zone. Although the fault will still be interrupted, the selectivity margin is reduced and nuisance disconnection may occur.

For high short-circuit current, the MCB operates rapidly and provides short-circuit protection. This confirms that the ELCB and MCB have complementary functions: the ELCB detects residual current imbalance, while the MCB interrupts overload and short-circuit current. Therefore, proper coordination must ensure that each device operates according to its protection function without unnecessary upstream interruption.

ETAP Simulation Results

ETAP 19.0 was used to evaluate single line-to-ground fault current at selected buses in the low-voltage distribution system. The simulation was performed using IEC 60909-based

short-circuit calculation. Table 3 presents the simulated line-to-ground fault current and ground-fault protection setting at selected locations.

Table 3. Etap Simulation Results For Single Line-To-Ground Fault Current

Location	Voltage (V)	LG Fault Current (kA)	Maximum GF Setting (A)	Status
MDP bus	400	18.50	850	Acceptable
SDP floor 1-4 bus	395	12.30	480	Acceptable
SDP floor 5-8 bus	392	11.80	460	Acceptable
SDP floor 9-12 bus	389	10.20	395	Acceptable
Basement panel bus	394	11.50	445	Acceptable
Final circuit floor 5 bus	385	8.50	320	Acceptable

The ETAP simulation shows that the single line-to-ground fault current decreases from the MDP bus to the final circuit. The highest simulated line-to-ground fault current was 18.50 kA at the MDP bus, while the lowest value was 8.50 kA at the final circuit floor 5 bus. This trend is expected because downstream impedance increases along the distribution path, reducing the available fault current at downstream buses.

The simulation confirms that the installed protection system is generally capable of detecting and clearing ground-fault conditions. However, the high prospective fault current at the MDP and SDP levels indicates that protective device interrupting capacity and short-circuit withstand capability must be verified periodically. Any replacement of ELCB, MCB, MCCB, or panel components should consider the calculated prospective short-circuit current to avoid under-rated protection devices.

Corrective Action and Improvement Strategy

The improvement strategy focuses on grounding points exceeding the 5 Ω limit, ELCB coverage in wet-area circuits, and ELCB type suitability for non-linear loads. Table 4 presents the recommended corrective actions and priority level.

Table 4. Recommended Corrective Actions

Corrective Action	Priority	Technical Purpose	Recommended Completion
Repair G-15 lightning grounding	Urgent	Reduce lightning discharge impedance	1 month
Replace corroded connection at G-14	Urgent	Restore electrode conductivity	1 month
Improve G-12 roof panel grounding	High	Reduce panel grounding resistance	2 months
Install 30 mA ELCBs for toilet socket circuits	High	Improve personnel protection in wet areas	2 months
Replace type AC ELCBs with type A devices on UPS/VFD circuits	Medium	Improve residual current detection for non-linear loads	6 months
Conduct grounding and ELCB preventive testing	Routine	Maintain protection reliability	Every 6 months

For grounding improvement, additional parallel rod electrodes are recommended at G-12, G-14, and G-15. The estimated equivalent resistance for two similar rod electrodes can be approximated by (4), assuming sufficient electrode spacing and limited mutual resistance effect.

$$R_{eq} \approx \frac{R_1 R_2}{R_1 + R_2} \quad (4)$$

For example, if two electrodes with similar resistance values are installed in parallel at G-12, the equivalent resistance can be reduced from 5.28 Ω to approximately 2.64 Ω under ideal spacing conditions. In practice, the final resistance may be slightly higher due to mutual resistance between electrodes. Therefore, electrode spacing, soil condition, conductor connection quality, and corrosion protection must be considered during installation.

Bentonite-based soil treatment or other low-resistivity materials may also be applied around the electrode to improve soil conductivity. Previous studies have shown that low-resistivity materials can reduce grounding resistance, although their effectiveness depends on soil resistivity, moisture, grounding configuration, and installation method [9]–[12]. Therefore, the application of soil treatment should be followed by post-installation measurement to verify whether the target resistance has been achieved.

Discussion

The results indicate that the evaluated building has a generally acceptable grounding and residual current protection system, but several localized weaknesses require correction. The 80% grounding compliance rate shows that most grounding points are within the required limit; however, the three non-compliant points cannot be ignored because they are located at critical areas, particularly the lightning grounding system and parking-area panel [13]. A grounding resistance value above 5 Ω may increase touch voltage risk and reduce the effectiveness of fault-current dissipation during abnormal conditions.

The ELCB evaluation shows that the installed 30 mA devices are technically appropriate for personnel protection. Nevertheless, the use of type AC ELCBs on circuits with UPSs and VFDs is a significant technical concern. Power electronic loads may generate distorted residual currents and high-frequency leakage components. Prior studies reported that residual current devices may experience altered tripping behavior under high-frequency residual currents and converter-based load conditions [14]. This supports the recommendation to replace type AC devices with type A devices for circuits supplying non-linear loads.

The coordination analysis confirms that the ELCB operates selectively for low-level residual currents, while the MCB provides overcurrent and short-circuit protection. The possible simultaneous tripping zone around 160 A does not eliminate the protection function, but it indicates that selectivity margin is limited at certain fault-current levels [15]. This condition should be considered during future protection setting review, especially if load capacity is expanded or additional non-linear equipment is installed.

The ETAP simulation supports the field findings by showing that prospective line-to-ground fault current remains significant at both upstream and downstream buses. Therefore, protection reliability depends on the combined performance of grounding resistance, ELCB sensitivity, MCB interruption capability, and device coordination [16]. The proposed corrective actions are expected to improve the safety level of the installation by lowering grounding resistance, expanding residual current protection coverage, and improving device suitability for modern building loads [17].

CONCLUSION

This study evaluated the ground-fault protection system of a multi-story office building by integrating field grounding resistance measurements, ELCB suitability assessment, ELCB-MCB coordination analysis, and ETAP-based single line-to-ground fault simulation. The measurement results at 15 grounding points showed that the grounding resistance ranged from 0.93 Ω to 6.21 Ω , with an average value of 2.96 Ω . Twelve grounding points, or 80% of the measured locations, complied with the 5 Ω maximum limit required by PUIL 2020, while three points, namely G-12, G-14, and G-15, exceeded the standard and require corrective action. The installed 30 mA ELCBs were generally appropriate for personnel protection; however, the use of type AC ELCBs on non-linear load circuits and the absence of ELCB protection on several toilet socket circuits indicate safety gaps that must be addressed. The coordination analysis confirmed that ELCB-MCB operation was selective for most leakage-current scenarios, although a possible simultaneous tripping zone was identified around 160 A. ETAP simulation further showed that the prospective line-to-ground fault current

ranged from 8.50 kA to 18.50 kA across selected buses, confirming the need for adequate interrupting capacity and periodic protection verification. Therefore, the proposed improvement measures include installing additional parallel rod electrodes, applying bentonite-based soil treatment, replacing type AC ELCBs with type A devices for UPS and VFD circuits, installing 30 mA ELCBs in wet-area socket circuits, and implementing preventive testing every six months. Future research should include seasonal grounding measurements and waveform-based residual current testing to evaluate protection performance under varying soil moisture and non-linear load conditions.

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