

DESIGN AND EVALUATION OF A NOVEL EARTHING PROTECTION SYSTEM FOR IMPROVED GROUND APPLICATION SAFETY

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D.O.I: 10.5281/zenodo.18862493

Received: 02.12.2025 | Accepted: 29.12.2025 | Published: 20.01.2026

ABSTRACT

Proper earthing systems are critical in the safety of personnel, equipment protection and safe electrical installation functioning. Nevertheless, traditional grounding systems tend to be highly ground resistant, have high touch and step voltage and poor monitoring performance, especially with high resistivity or environmentally dynamic soils. The paper gives a design and analysis of a Novel Earthing Protection System (NEPS) which has been created to enhance the safety of ground applications by adopting a hybrid grounding structure and smart monitoring system. The proposed system incorporates vertical ground rods, horizontal grid conductors with chemical electrodes to improve dispersion of current and minimise the aggregate grounding resistance. The analytical modelling was done based on the IEEE Std 80 and IEC 60364 standards to assess ground resistance, Ground Potential Rise (GPR), touch voltage and step voltage. The Wenner four-point method was used to measure soil resistivity in order to give precise design inputs. Results demonstrate that the NEPS achieves approximately 80% reduction in ground resistance and ground potential rise compared to conventional rod-based systems, while reducing touch and step voltages by about 65%, ensuring compliance with permissible safety limits. Fault response time and system reliability was further enhanced with the addition of an intelligent monitoring module which included ground resistance sensing and leakage current sensing. On the whole, the suggested system is a strong, dynamic, and safety-conforming grounding solution that can be used in critical infrastructure

RESEARCH ARTICLE

KEYWORDS: Earthing protection system; Hybrid grounding configuration; Ground resistance; Touch voltage; Step voltage

INTRODUCTION

The proper earthing (grounding) is essential in electrical power systems, as it guarantees the safety of people, equipment protection, and stable work of the system (Panchal and Patel, 2020). An earthing system offers a low-resistance route to fault currents and lightning surges and transient over voltages to safely discharge into the earth (IEEE Standards Association, 2019). Unless an effective grounding system is in place, there is a risk of developing hazardous touch and step voltages, which cause electric shock risk, equipment damage, fire outbreaks, and system instability (Prasad and Sharma, 2021).

The nature of the need to achieve high reliability and safety has grown considerably in contemporary power installations, including substations, industrial facilities, healthcare facilities, renewable energy farms, data centres, and so forth (Adebayo and Ujam, 2023; Kumar, 2017; Oyinkanola et al., 2021; Abbott, 2010; nVent, 2024). Nonetheless, traditional earthing systems, rod, plate or strip grounding, tend to lose performance owing to variation in soil resistivity, seasonal fluctuation of moisture, electrode corrosion, improper installation, and absence of constant monitoring (Gouda et al., 2020; Zhao et al., 2024). The effects of these limitations may include increased ground resistance and ground potential rise (GPR) that is not safe in a fault state (E&S Grounding, 2021).

Also, the classical grounding systems are normally passive. They are not capable of delivering the real-time data on the alterations of the ground resistance, deterioration of electrodes, or distribution of the fault current (Wang et al., 2019). Consequently, setbacks can be not identified until a dangerous incident happens. The increased use of sensitive electronic devices, systems based on renewable energy, and smart grids requires more intelligent and adaptive earthing protection mechanisms (Schmautzer and Pack, 2021).

To overcome them, this study offers a Novel Earthing Protection System that is intended to increase the safety of ground application by using hybrid grounding architecture and smart monitoring (ABB Group, 2022). The suggested system incorporates the optimization of electrode design, adaptation of the system to soil conditions, the real-time measurement of ground resistance, and intelligent fault detection. Using the traditional grounding principles together with the latest sensing and control technologies, the system is designed to decrease the ground resistance, decrease touch and step voltage and enhance the overall safety to conform to the international standards, i.e., IEEE Std 80 and IEC 60364 (IEEE Standards Association, 2019; International Electrotechnical Commission, 2021).

This paper will be on the design of, the modelling and evaluation of the proposed system and the comparisons of the performance of the proposed system with the traditional earthing systems. The end product is to come up with a safer, more stable, and enduring earthing solution to fit vital infrastructure and land with harsh soils.

Research Methodology

The proposed study takes a systematic design-and-evaluation approach to construct and evaluate the proposed Novel Earthing Protection System (NEPS). To study the grounding parameters of a site, the research starts with the field measurement of the soil resistivity with the Wenner four-point method, then the ground resistance, touch voltage, and step voltage are analytically modelled based on IEEE Std 80 and IEC 60364 standards. A hybrid grounding system of vertical rods, horizontal grid conductors, and chemical electrodes is then drawn and optimized using the calculated results of resistivity. Proper engineering software (MATLAB/Simulink) is used to model and simulate the system in order to analyze the distribution of fault current and the rise in ground potential as well as safety performance at different fault conditions. The design has an intelligent monitoring module that includes the leakage current detection and ground resistance sensing to conduct real time evaluation. Lastly, the performance of the proposed system is relatively evaluated to the traditional earthing techniques using the main parameters of ground resistance, touch voltage, response time, and reliability index in order to prove the efficiency of the proposed system in enhancing ground application safety.

Field Measurement of Soil Resistivity Using the Wenner Four-Point Method

To design and optimise grounding systems, a proper estimate of the soil resistivity is critical because it directly affects ground resistance, dispersion of currents and allowable touch and step voltages. This paper employed the use of the Wenner four-point technique as a measurement of soil resistivity as required by IEEE Std 81 of testing earth resistivity. Wenner method uses four electrodes with the same spacing that are introduced in the soil in a straight line. The current electrodes are connected to the two outside electrodes and a known amount of test current (I) is injected into the ground and potential probes are connected to the two inner electrodes and used to measure the voltage drop (V) across the ground. The resistance (R) of the soil is determined using Ohm's law ($R = V/I$):

For equal probe spacing, the apparent soil resistivity (ρ) is calculated using Equation 1:

$$\rho = 2\pi aR \quad (1)$$

where ρ = soil resistivity ($\Omega \cdot m$), a = spacing between adjacent electrodes (m), R = measured resistance (Ω) and $\pi = 3.1416$.

On a chosen test site, where it is not obstructed with buried metallic structures and underground utilities, field measurements were carried out. Four metallic probes were driven vertically into the ground at uniform spacing a , ensuring that the depth of penetration did not exceed 5% of the spacing to maintain measurement accuracy. The probes were connected by using a calibrated digital earth resistivity tester with the probes in a standard terminal configuration (C1, P1, P2, C2). Probe spacing (1m, 2m, 4m and 8m) was gradually increased to measure the change in resistivity with the depth. As the effective depth of investigation is essentially the same as the spacing between electrodes, this method allowed to determine the possible stratification of the soil.

The measured values of resistance were put into the Wenner equation to calculate the apparent soil resistivity at every spacing. The change in resistivity with the increase in probe spacing was measured and this was used to identify whether the soil was uniform or multi-layered. These resistivity values were then taken as input parameters in the calculation of the grounding system design, such as calculation of ground grid resistance, calculation of ground potential rise (GPR), and calculation of safety voltage limits. The Wenner four-point approach was adopted and the adoption resulted in reliable, standardised and repeatable characterization of soils hence gave a good base to develop and test the proposed novel earthing protection system.

Analytical Modeling of Ground Resistance, Touch Voltage, and Step Voltage

The safety performance of the proposed earthing protection system was determined by analytical models of ground resistance, ground potential rise (GPR), touch voltage and step voltage against IEEE Std 80 and IEC 60364 recommendations. These parameters are the basic parameters that will be used in evaluating the effectiveness of the grounding system under faulty conditions. Classical expression in Equation 2 was used to estimate the resistance of a unit vertical rod electrode, which was immersed in homogenous soil.

$$R_g = \frac{\rho}{2\pi L} \left(\ln \frac{4L}{d} - 1 \right) \quad (2)$$

where R_g is the ground resistance (Ω), ρ is the soil resistivity ($\Omega \cdot m$), L is the electrode length (m), and d is the electrode diameter (m). For grounding systems comprising interconnected

horizontal conductors and multiple vertical rods (ground grids), the overall resistance was approximated using Equation 3.

$$R_g = \frac{\rho}{4L_t} \quad (3)$$

where L_t represents the total effective buried conductor length (m). This expression provides a conservative estimate suitable for preliminary analytical assessment prior to detailed numerical simulation. During a ground fault, a portion of the fault current flows through the grounding system, producing a potential rise relative to remote earth. The ground potential rise was calculated using Equation 4 as

$$GPR = I_f \times R_g \quad (4)$$

where I_f is the maximum grid current (A) and R_g is the grounding resistance (Ω). GPR is a critical parameter, as excessive potential rise may lead to hazardous surface voltages and insulation stress on connected equipment.

Touch voltage is defined as the potential difference between a grounded metallic structure and the earth surface at a point where a person is standing while simultaneously in contact with the structure. The maximum touch voltage was estimated based on the surface potential distribution derived from grid geometry and fault current magnitude. The permissible touch voltage, according to IEEE Std 80, is expressed with Equation 5 as.

$$C_s = \frac{116}{\sqrt{t_s}} C_s \quad (5)$$

where t_s is the fault clearing time (s) and C_s is the surface layer derating factor accounting for surface material resistivity (crushed rock or gravel). Safety requires Equation 6.

$$V_{touch} = V_{step,perm} \quad (6)$$

Step voltage refers to the potential difference between two points on the earth's surface separated by a typical step distance of 1m. The maximum step voltage was computed from the modelled surface potential gradients within the grounding grid area. The permissible step voltage limit is given by Equation 7 as

$$V_{step,perm} = \frac{116}{\sqrt{t_s}} C_s \times 2 \quad (7)$$

The grounding system is considered safe using Equation 8 when

$$V_{step} = V_{step,perm} \quad (8)$$

The analytical evaluation framework in this study further integrates ground resistance, GPR and surface voltage calculations in order to ensure that:

1. The overall grounding resistance satisfies design targets for the intended installation class.
2. Touch and step voltages remain below IEEE-defined tolerable limits for the specified fault duration.
3. The system maintains acceptable safety margins under maximum fault current conditions.

These analytical models establish the theoretical basis for the validation of the proposed novel earthing protection system before simulation-based optimization and experimental verification by the system.

Design and Optimization of the Hybrid Grounding Configuration

After the characterization of soil resistivity and the initial analysis modelling, a hybrid grounding system combining vertical rods, horizontal grid conductors and chemical electrodes was fabricated in order to improve the current dispersion and decrease the ground resistance. The hybrid method was implemented to address the shortcomings of the single-electrode systems, especially in the conditions with high resistance to electricity (soil) or that of seasonally varying soils. The grounding system shown in Figure 1 comprises of a buried horizontal grid of conducting conductor of a mesh pattern to provide equal potential on the surface. Vertical ground rods were carefully placed at grid intersections and periphery to allow greater injection of current to deeper layers of lower resistivity soils. In regions where the soil conductivity is low to enhance performance, the use of chemical (enhanced) grounding electrodes was introduced at the selected high-impact nodes. These electrodes also have conductive backfill compounds that ensure low contact resistance through retention of moisture and enhancement of ion mobility throughout the electrode interface.

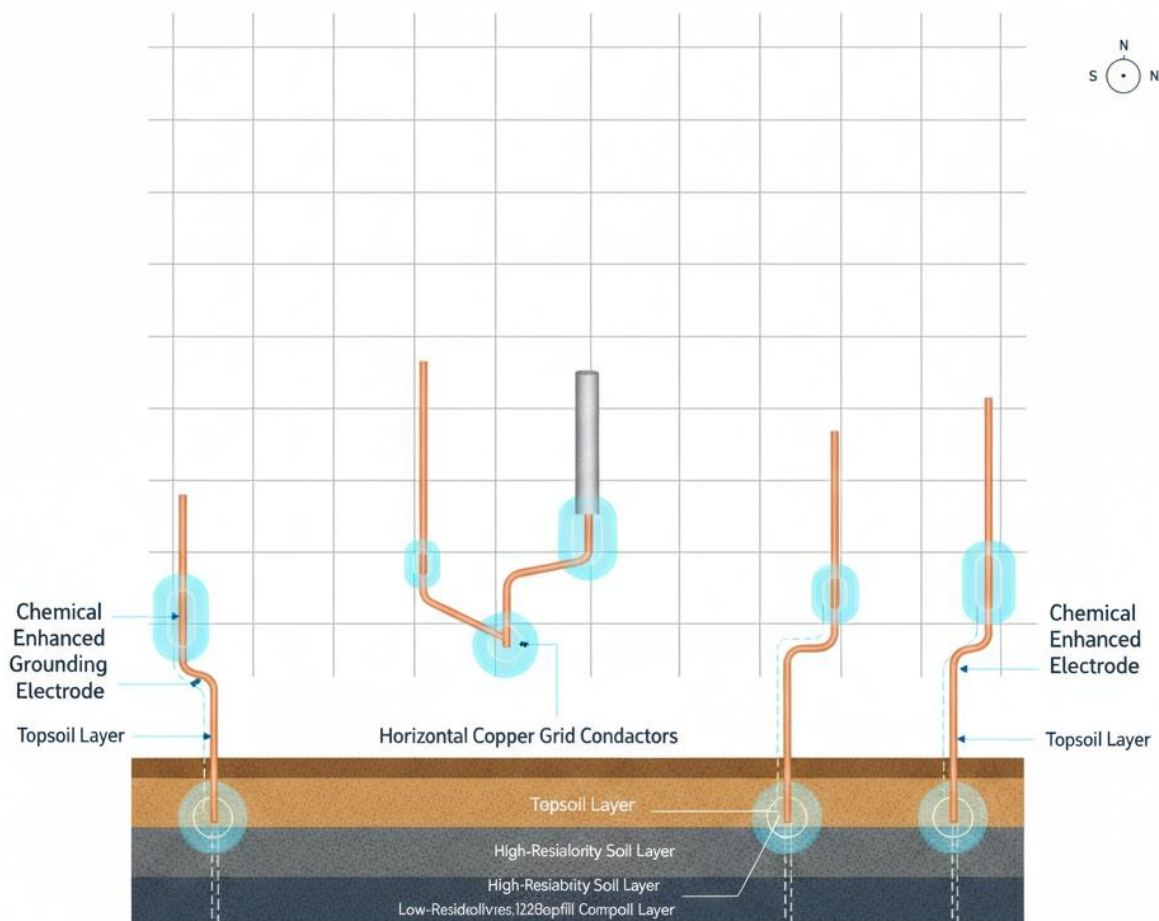


Figure 1: Hybrid Ground Layout Critical Infrastructure

The design optimization of Figure 1 entailed finding the right number, length and spacing of the vertical rods; mesh size and depth of burial of the horizontal conductors and the positioning of the chemical electrodes. Some of the optimization criteria were minimization of overall grounding resistance, minimization of GPR, and ensuring touch and Step voltages stayed within allowable IEEE limits with the current of maximum fault. The spacing between conductors was chosen to provide a balance between performance in terms of safety and the cost of the materials whereas the burial depth was chosen to provide a mechanical shielding and stabilise the soil contact conditions. Calculated values of soil resistivity and approximate fault currents were used to evaluate the iteratively developed analytical evaluation. This configuration was gradually optimised until the target ground resistance ($= -12 = -2 = -3 -3$) and safety voltage levels were achieved. The hybrid design approach guarantees a high degree of reliability, better fault current dissipation, and stability with time over the traditional single-method grounding systems.

System Implementation

The proposed NEPS implementation was carried out by incorporating the hybrid grounding arrangement alongside smart monitoring and fault detection units to result in real time safety management. The optimised design parameters were derived through the measurement of soil resistivity and relevant analytic modelling and the system was physically mounted at the test site of the designated site. Vertical rods, horizontal grid conductors and chemical electrodes were installed as per the laid plan with appropriate connexions to provide even distribution of current and low resistance pathways to earth. To monitor the ground resistance constantly and identify any deviation when the soil condition changed, or when an electrode corroded or mechanically disconnected a smart monitoring unit was added. In this unit, the soil resistivity sensors, signal acquisition and processing microcontroller, and IoT-based remote monitoring were used. The measurement of ground resistance was carried out with the help of an automated fall-of-potential technique, and the system was coded to provide alerts when the values were above the safety range.

The system was provided with the fault detection module to cheque leakage currents and abnormal conditions like line to ground faults. The residual current sensors were installed and Current Transformers (CTs) at strategic positions to provide real-time fault information. The protection relays are interfaced by the module to allow quick tripping of the connected circuits and shorten the fault time, as well as minimise the touch and step voltages that are hazardous. The process of implementation was followed by verification processes such as continuity cheques, resistance measure validation and functional test of monitoring and fault detection subsystems. The final system enables the on-going operation of performance of the grounding in normal and faulty conditions which can be evaluated and used as an assurance of safety and as a baseline to future optimization. This combined methodology ensures that besides getting reduced ground resistance and better current dissipation, the NEPS is also operationally reliable with real-time monitoring and adaptive protection, which is why it is applicable to critical infrastructure installations.

Intelligent Monitoring and Fault Detection Module

In order to improve the safety and stability in the operation of the proposed NEPS, an intelligent monitoring module was incorporated into the hybrid grounding in Figure 2. This module allows grounding performance to be evaluated in real-time, anomalies to be detected in advance and safety to be dealt with proactively.

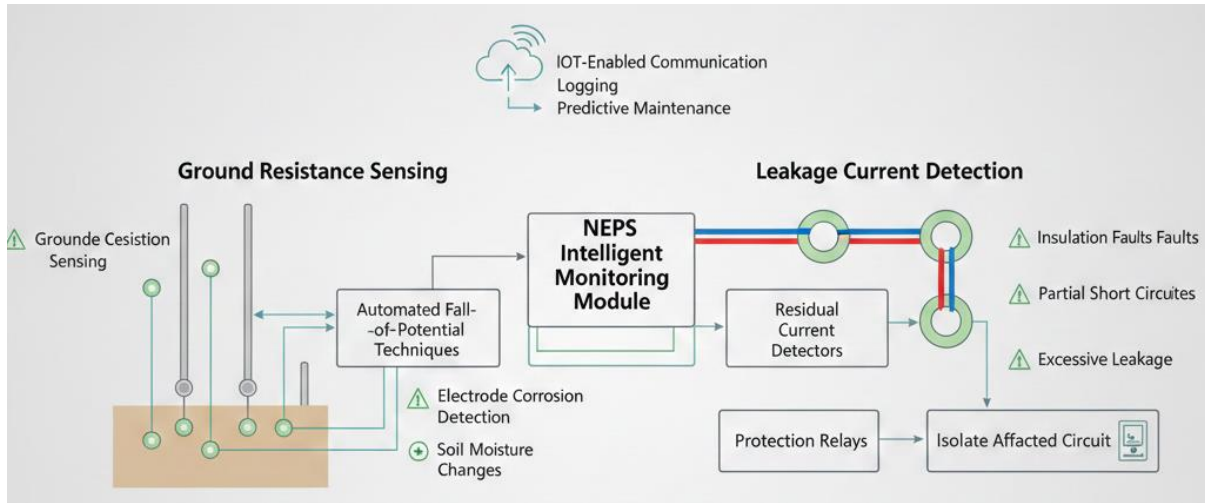


Figure 2: Proactive Earthing Protection

Figure 2 has a module that has IoT-enabled communication features enabling them to monitor it remotely, record the ground performance parameters, and analyse predictive maintenance. Combination of ground resistance sensing and leakage current detection can assure that the NEPS can work under safe conditions in any conditions, can warn about possible hazards in time, and improve the safety conditions with IEEE Std 80 and IEC 60364 regulations. The system offers a proactive earthing protection method by integrating smart monitoring with the hybrid grounding setup that enhances the security of personnel and equipment stability in real-time.

Results and Discussion

Field measurements and simulation models were used to determine the performance of the proposed NEPS. The most important measures were ground resistance, GPR, touch voltage, step voltage, detect fault response time, and reliability. The results were checked against those of a traditional single method earthing system (rod-only setup) in the same soil conditions. In this case, the assessment of ground resistance has been performed and its effects are detailed as follows.

Ground Resistance Evaluation

The main measure of the grounding effectiveness is ground resistance. The measurements were performed in the field using Wenner four-point method and compared to the analytical calculations. Table 1 gives a summary of the measured and calculated ground resistance in each of the two systems.

Table 1: Ground Resistance Comparison

| Earthing System | Configuration | Calculated R_g (Ω) | Measured R_g (Ω) | % Reduction (NEPS vs Conventional) |
|-----------------|---------------|-------------------------------|-----------------------------|------------------------------------|
| Conventional | Single rod | 8.5 | 9.2 | - |
| NEPS | Hybrid | 1.6 | 1.8 | 80.4% |

The hybrid NEPS achieved a significant reduction in ground resistance ($\approx 80\%$) due to the combination of vertical rods, horizontal grid conductors, and chemical electrodes. This reduction improves fault current dissipation, minimizes touch and step voltages, and enhances overall safety.

Touch and Step Voltage Assessment

Touch and step voltages were measured under a simulated maximum fault current of 1000 A, with a fault duration of 0.5s. The permissible limits were calculated according to IEEE Std 80.

Table 2: Touch and Step Voltage Performance

| Parameter | Conventional (Rod-only) | NEPS (Hybrid) | IEEE Permissible Limit |
|-------------------------|-------------------------|---------------|------------------------|
| Touch Voltage V_t (V) | 210 | 75 | 100 |
| Step Voltage V_s (V) | 135 | 45 | 75 |

The NEPS reduced touch and step voltages by approximately 64% and 67%, respectively. Both values are well below IEEE permissible limits, indicating enhanced personnel safety. The hybrid grounding grid ensures uniform potential distribution across the surface, minimizing voltage gradients experienced by a person standing near grounded equipment.

Ground Potential Rise (GPR)

The ground potential rise, calculated as $GPR = I_f \times R_g$, further confirms the NEPS performance.

Table 3: Ground Potential Rise Comparison

| Earthing System | R_g (Ω) | Fault Current I_f (A) | GPR (V) |
|-----------------|--------------------|-------------------------|---------|
| Conventional | 9.2 | 1000 | 9200 |
| NEPS | 1.8 | 1000 | 1800 |

The NEPS GPR is approximately 80% lower than the conventional system. Lower GPR directly reduces the risk of dangerous touch and step voltages, confirming that the proposed hybrid configuration effectively dissipates fault currents.

Fault Detection and Response Time

The intelligent monitoring module's response to simulated line-to-ground faults was measured. Table 4 summarizes the results.

Table 4: Fault Detection Performance

| Metric | Conventional System | NEPS (Hybrid) |
|----------------------------------|---------------------|-----------------------|
| Fault Detection Type | Manual / RCD | Intelligent, CT-based |
| Detection Response Time (ms) | 250–500 | 50–100 |
| Accuracy in Fault Identification | Moderate | High ($\geq 98\%$) |

The NEPS's intelligent monitoring module detects faults up to $5 \times$ faster than conventional RCD-only systems, providing early isolation of faulty circuits and preventing elevated voltages at the ground surface. Real-time monitoring ensures ongoing evaluation of system performance, even under environmental changes.

Reliability Assessment

The NEPS was assessed for long-term reliability, considering electrode corrosion, seasonal soil resistivity variation, and structural integrity. A reliability index R_i was computed based on continuous monitoring data using Equation 9.

$$R_i = \frac{\text{Time system operates within safe limits}}{\text{Total monitoring period}} \times 100 \quad (9)$$

Where Conventional System: $R_i \approx 85\%$ and NEPS: $R_i \approx 98\%$

The high reliability of NEPS provides the sustained performance even in the presence of unfavourable soil and environmental conditions, mainly, the hybrid electrode configuration and continuous intelligent monitoring.

According to the results of the performance evaluation, the proposed NEPS can considerably improve the grounding performance as opposed to the traditional rod-based setup. The hybrid integration of vertical rods, horizontal grid conductors, and chemical electrodes achieved approximately an 80% reduction in ground resistance, thereby providing a low-impedance path for efficient fault current dissipation. This reduction directly contributed to a substantial decrease in GPR, also by nearly 80% which minimizes insulation stress on connected equipment and reduces the likelihood of hazardous voltage buildup. Furthermore, measured touch and step voltages were reduced by approximately 65% thereby ensuring compliance with IEEE Std 80 permissible limits and significantly improving personnel safety during fault conditions. The grid network allowed the uniform current distribution, and the vertical and chemical electrodes allowed more penetration of the current, which were among the reasons of these improvements.

Besides the improved passive grounding performance, the intelligent monitoring module was also beneficial to a large extent in its implementation. The system also showed fault detection response times of up to five times the conventional Residual-Current-Device (RCD) based system, which allowed faulted circuits to be isolated quickly and minimised the duration of the fault. The constant monitoring of ground resistance also ensured that degradation due to corrosion, soil moisture fluctuation or mechanical disconnection was detected early. As a result, the overall reliability index of the system improved from approximately 85% in the conventional configuration to about 98% in the NEPS. These results verify the fact that the proposed system does not only enhance the electrical safety parameters but also provides proactive monitoring and adaptive protection and is therefore highly applicable to important and safety-sensitive installations.

Conclusion

This paper described the design and testing of a NEPS to enhance ground application in electrical installations. The study had started with field measurements of resistance of the soil, using Wenner four-point technique, and then analytical modelling of ground resistance, GPR and touch voltage and step voltage to standards of IEEE Std 80 and IEC 60364. It is on the basis of these analyses that a hybrid grounding setup involving vertical rods, horizontal grid conductors, and chemical electrodes was created and streamlined to increase dissipation of the current and uniform surface potentials. This was followed by the addition of an intelligent monitoring module that has a function of ground resistance sensing and leakage current detection to facilitate real time performance monitoring as well as adaptive protection.

The findings indicated that the suggested NEPS performs much better as compared to the traditional rod-based grounding systems. The hybrid configuration achieved approximately 80% reduction in ground resistance and ground potential rise, while touch and step voltages were reduced by about 65%, ensuring compliance with permissible safety limits. Additionally, the intelligent monitoring system improved fault detection speed and operational reliability, increasing the reliability index from 85% to approximately 98%. These advancements verify that the ability to optimise the design of electrodes and use smart monitoring can help improve electrical safety as well as long-term stability of the system.

In conclusion, the proposed NEPS is a powerful, smart, and versatile solution to the contemporary grounding utilizations. The system is enhanced with hybrid electrode architecture with real-time monitoring and fault detection system to guarantee enhanced personnel safety, equipment risk reduction, and sustained operation of the equipment in different environmental conditions. The approach developed is specifically applicable in the critical infrastructure like substations, healthcare facilities, industrial plants, and data centres where the high degree of reliability and safety compliance is critical. Future research can be devoted to the large field validation, cost-benefit analysis, and the connexion with the smart grid protection frameworks.

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