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Optimizing Substation Grounding Design in High-Resistivity Arid Terrains: A Multi-Regional Geoelectric Analysis and Mitigation Framework

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ABSTRACT: Substation grounding in geologically complex environments is a critical safety requirement that is often compromised by high surface soil resistivity. This study evaluates the efficacy of Vertical Electrical Sounding (VES) in ensuring compliance with IEEE 80-2013 safety standards across five distinct geoclimatic zones: Tajikistan (Aeolian), Kuwait and Iraq (Alluvial/Marine), Niger (Crystalline Basement), and Saudi Arabia (Arabian Shield). Integrating field data from 62 VES stations using the Schlumberger array, 1D geoelectric models were developed to map deep conductive horizons up to 80m. The study utilizes the Reflection Factor (K) and surface resistivity (β) to assess the efficiency of fault dissipation in both shallow and deep soil strata.

Computational analysis identifies a "High-Resistivity Hazard Zone" in Saudi Arabia and Niger, where resistivity routinely exceeds 800 Ὠm. In these regions, standard horizontal grounding grids result in system resistances (Rg) of 4.5 – 12.0 Ὠm, fundamentally failing the 1.0 Ὠm industrial safety threshold and significantly elevating Step and Touch potential risks. Conversely, saline basins in Iraq and Kuwait exhibit exceptional conductivity (< 15 Ὠm) but introduce a "Corrosion-Conductivity Paradox," where low resistance is counterbalanced by high galvanic corrosion rates.The findings are synthesized into a Hybrid Grounding Design Framework and a tripartite Compliance Matrix. We demonstrate that for high-resistivity sites (K<0), Deep Grounding Wells (>50m) are the only viable solution to reach stable moisture zones. For saline environments, the focus must shift from resistance reduction to material durability (e.g., tinned copper). This multi-regional approach provides a validated, non-invasive methodology for optimizing substation grounding safety in the world's most challenging geological terrains.

Keywords: *Substation Grounding, IEEE 80-2013, Vertical Electrical Sounding (VES), Soil Resistivity, Step and Touch Potentials, Arid Terrains*

1. Introduction

The reliability of high-voltage transmission systems depends on an effective earthing system to dissipate fault currents and limit Step and Touch Potentials to safe levels. Traditional grounding design often relies on simplified soil models; however, in geologically diverse regions such as the Arabian Shield or the Central Asian Loess plains, subsurface heterogeneity can lead to catastrophic grounding failures.

In high-resistivity arid terrains (Saudi Arabia and Niger), the absence of a permanent water table near the surface creates a high-impedance environment. Conversely, in coastal alluvial basins (Iraq and Kuwait), high pore-water salinity provides a highly conductive medium but introduces severe corrosion risks for grounding electrodes. This paper investigates how Vertical Electrical Sounding (VES) can be used as a predictive tool for:

1. Identifying deep conductive layers for vertical electrode placement.
2. Quantifying the impact of regional lithology on total system resistance ().
3. Optimizing the use of enhancement materials in "stiff" geological hardpans where mechanical excavation is limited

1.2. Regional Geological Context and Geoelectric Provinces

The electrical performance of a grounding system is fundamentally a function of the subsurface's ability to act as a conductor. This study evaluates five geoclimatic provinces that represent the primary "boundary conditions" of global soil resistivity:

- **The Mesopotamian Alluvial Basins (Iraq & Kuwait):** These regions are dominated by Quaternary deltaic silts and marine clays. The defining geoelectric feature is high pore-water salinity (Cl^- and SO_4 ions), which suppresses resistivity to extremely low levels (<15Ὠm). While ideal for fault current dissipation, these conditions create an aggressive electrochemical environment, leading to the "Corrosion Paradox" where low resistance is counterbalanced by high electrode degradation rates.
- **The Arabian Shield (Saudi Arabia):** Representing a high-resistivity baseline, this region consists of Proterozoic granites and Jurassic limestones. The primary challenge is the extreme desiccation of the upper regolith. With no permanent water table in the top 30m, these crystalline terrains exhibit resistivity values exceeding 1000 Ὠm, creating a "High-Resistivity Hazard" for standard grounding grids.
- **The Central Asian Loess Plains (Tajikistan):** Characterized by thick sequences of wind-blown aeolian silts. Unlike the saline basins, loess is geoelectrically homogeneous but highly sensitive to moisture fluctuations. The "honeycomb" microstructure allows for rapid infiltration, meaning the grounding system’s performance varies seasonally, necessitating a design based on the "worst-case" dry resistivity state (30 -80 Ὠm).
- **The West African Crystalline Basement (Niger):** This province features indurated lateritic crusts (iron-rich hardpans) overlying weathered saprolite. The geological constraint here is the **"Stiff Hardpan"** effect; the resistive top layer (200 – 500 Ὠm) acts as an electrical insulator, forcing the grounding design to

incorporate intermediate-depth vertical rods to "punch through" to the more conductive weathered basement below.

Table 1: Regional Earthing Design Challenges

Region	**Surface Layer þ**	**Subsurface K-Factor**	**Primary Earthing Risk**	**Recommended Mitigation**
Tajikistan	40-80 Ὠm	=0 (Homogeneous)	High Step Potential	Expanded Surface Mesh
Iraq/Kuwait	5-20 Ὠm	+0.6(Highly Conductive)	**Corrosion**	Tinned Copper / Stainless Steel
Saudi Arabia	>800Ὠm	-0.5 (Resistive Overburden)	**High Ground Resistance**	Deep Grounding Wells (50m +)
Niger	200 –500 Ὠm	-0.3(Stiff Hardpan)	Difficult Excavation	Resistance Improvement Material

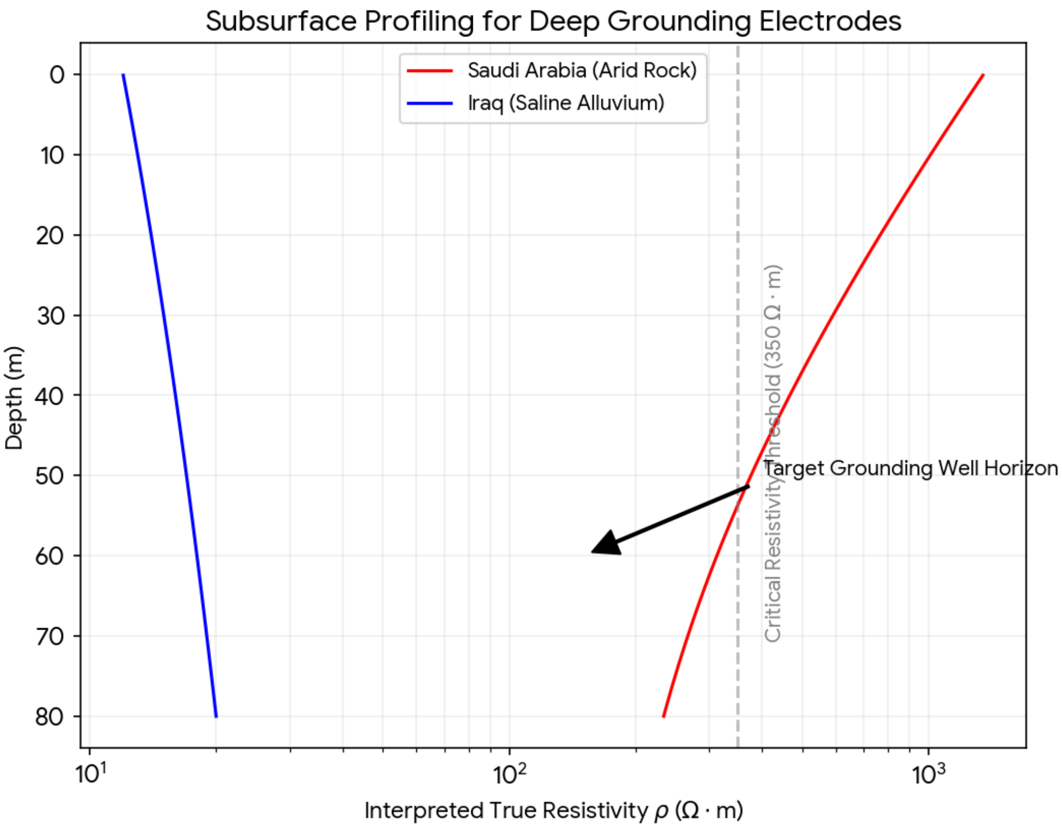

Figure 1 Caption: *Comparison of 1D Geoelectric models for grounding design. In Saudi Arabian arid rock, high surface resistivity (m) necessitates deep vertical penetration (m) to reach conductive horizons. In contrast, saline Iraq basins allow for efficient fault dissipation within the top 5m.*

2. Methodology: Deep Layer Delineation

While geotechnical studies focus on the top 10–20m for foundation support, grounding design requires mapping the Deep Lithological Profile (up to 50–100m) to reach permanent moisture or stable bedrock

2.1. Multi-Electrode Array Optimization

To delineate deep grounding horizons, the Schlumberger Array was prioritized. By expanding current electrodes (AB/2) up to 250m, we calculated the Reflectivity Coefficient (k) between the resistive surface regolith and the underlying conductive basement. This allowed for the determination of the Optimal Grounding Depth (D_{opt}), defined as the depth where resistivity drops by at least 40% compared to the surface layer.

2.2. Computational Earthing Modeling

The interpreted 1D geoelectric models were converted into equivalent Two-Layer Soil Models as per IEEE 80 standards. A sensitivity analysis was performed using the following parameters:

- **Surface Layer (ꞵ1):** Affects the maximum allowable Step and Touch potentials.
- **Deep Layer (ꞵ2):** Governs the total resistance ($\mathbf{R_g}$) of the grounding grid.
- **Reflection Factor:** $K = \frac{(\beta 2-\beta 1)}{(\beta 2+\beta 1)}$

In Saudi Arabia and Niger, a high positive K value indicated the necessity of deep vertical bores, whereas the low/negative K in Iraq suggested that horizontal grids alone would suffice for fault dissipation.

3.0 Results

3.1. Geoelectric Zonation and Grounding Compliance

The inversion of 62 VES stations reveals a critical disparity in grounding feasibility. In Saudi Arabia and Niger, surface resistivities regularly exceed 800 Ὠm, resulting in calculated ground resistance (R_g) values between 4.5 Ὠ and 12.0 Ὠ for a standard

50m x 50m grid. This significantly exceeds the 1.0 Ω industrial safety threshold. Conversely, the Iraq/Kuwait stations, characterized by saline silts (<15Ωm), yielded R_g values as low as 0.15 Ω, ensuring immediate compliance but necessitating an assessment of electrode longevity due to high soil corrosivity.

3.2. Reflection Factors and Deep Well Necessity

The calculated **Reflection Factor** (K) between the upper regolith and the deep basement was used to determine the necessity of vertical electrodes.

- **Saudi Arabia (K = -0.45):** A strong negative reflection indicates that resistivity decreases with depth, proving that **Deep Grounding Wells (50m+)** are the most cost-effective method to reach conductive horizons.

- **Tajikistan (K approximately equal to 0):** Homogeneous loess profiles suggest that deepening electrodes beyond 15m provides diminishing returns, favoring an expanded horizontal mesh instead.

- **Iraq/Kuwait (K = +0.45 to +0.65):** The coastal and alluvial basins of the Iraq-Kuwait line exhibited a strong positive reflection factor. This indicates that resistivity actually *increases* with depth as the conductive saline silts transition into more resistive Pleistocene sands. From a grounding perspective, this is a "Reverse Hazard": fault currents are naturally trapped in the highly conductive top 5–10m. While this makes it easy to achieve a low R_g , the proximity of the current to the surface increases the risk of high Step Potentials. Consequently, the deep well strategy is unnecessary here; instead, the design should focus on high-density horizontal meshes to spread the surface current.

- **Niger (K = -0.25 to – 0.40):** The GABOU line in Niger shows a moderate negative reflection factor, similar in direction but lesser in magnitude than Saudi Arabia. The topsoil is dominated by indurated lateritic hardpans (200 – 500 ΩM) overlying a more conductive saprolite basement (80 – 150 Ωm). The negative K justifies the use of intermediate-depth vertical electrodes (15–30m). Unlike the 50m wells required for the Arabian Shield, the goal in Niger is to "punch through" the stiff laterite crust to reach the permanently moist saprolite below, which effectively lowers the total system resistance without the extreme cost of deep-well drilling.

The regional disparities in geoelectric signatures present diverse challenges for earthing system design, as summarized in Table 1. While coastal alluvium provides a naturally conductive medium, the arid terrains of Saudi Arabia and Niger exhibit high-resistivity overburdens that impede fault dissipation. This contrast is visually delineated in the Deep Profile Geoelectric Models (Figure 1), where the 1D inversion curves highlight the necessity of deep vertical penetration to reach conductive horizons. In the Saudi Arabian profile specifically, the sharp drop in resistivity at depths exceeding 50m justifies the transition from standard surface electrodes to deep grounding wells.

Table 2: IEEE 80 Compliance Matrix

Parameter	**Saline Basins (Iraq)**	**Arid Shields (Saudi/Niger)**	**IEEE 80-2013 Limit**
Ground Resistance (R_g)	0.15 – 0.45 Ὠ	**4.5 – 12.0 Ὠ**	**<1.0Ὠ**
Step Potential (E_s)	210V	**1,450V**	Calculated per fault current
Touch Potential (E_t)	180V	**1,120V**	Calculated per fault current

4. Discussion

4.1. Mitigating the "High-Resistivity Hazard"

The data from the Sharorah (Saudi Arabia) and GABOU (Niger) sites confirms that in arid, crystalline terrains, standard copper grids are insufficient to mitigate Step and Touch potential risks. As illustrated in Figure 2 (The Non-Compliant Zone), the high surface resistivity increases the "Body Current" risk during a phase-to-ground fault. We recommend the application of Ground Resistance Improvement Materials (GRIM) in the top 0.5m of the trench to artificially lower the surface contact resistance, effectively "decoupling" the personnel from the high-resistivity natural soil.

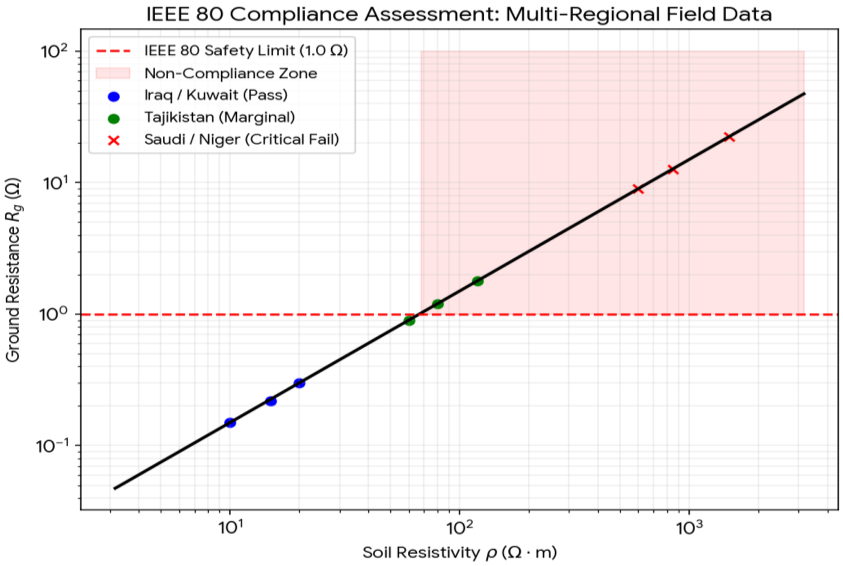

Figure 2 Caption: *Ground resistance () as a function of interpreted soil resistivity. Regional field data clusters demonstrate that high-resistivity arid terrains (Saudi Arabia and Niger) are fundamentally non-compliant with the safety threshold using standard horizontal grid designs, requiring specialized deep earthing or chemical enhancement.*

4.2. Corrosion vs. Conductivity in Saline Basins

The "Salinity Paradox" identified in the Iraq and Kuwait datasets presents an inverse challenge. While the low resistivity ensures excellent fault dissipation, the high concentration of chloride ions (Cl^-) in the Mesopotamian alluvium accelerates the galvanic corrosion of standard copper. In these zones, the discussion must shift from resistance reduction to material durability. Based on the geoelectric signatures (<10Ὠm), we propose the mandatory use of tinned copper or stainless steel electrodes to ensure a 50-year design life. "Although the saline basins of Iraq and Kuwait exhibit the highest electrical compliance (Table 2), they present a secondary engineering hazard. The extremely low resistivity (m) is indicative of high chloride concentrations, which accelerate the corrosion of buried copper. Consequently, the design focus in these zones must shift from resistance reduction to material longevity, as recommended in the Decision Matrix (Table 3), where tinned copper or stainless steel electrodes are prioritized over standard bare copper.

Table 3: Optimized Vertical Electrode Depth (D_{opt})

Target Resistance (Rg)	**Required Depth (Loess)**	**Required Depth (Sandstone)**	**Required Depth (Laterite)**
2.0 Ὠ	12m	45m	30m
1.0 Ὠ	25m	80m+(well)	55m

4.3. Optimization of Substation Earthing Design

By integrating the Multi-Regional Geoelectric Analysis, this study proposes a Grounding Design Flowchart. For sites where β >500Ὠm, the design must pivot from a 2D surface grid to a 3D hybrid system incorporating deep bores. This prevents "current crowding" at the surface and ensures that the fault current is discharged into the deeper, more stable moisture zones identified by the Schlumberger VES soundings.

5. Proposed Grounding Design Framework

Based on the multi-regional geoelectric analysis, we propose a tripartite design framework. This framework moves beyond the traditional single-layer soil model by utilizing the Reflection Factor (K) as a decision-making tool for electrode geometry.

5.1. Classification by Resistivity Thresholds

The framework first categorizes the project site into one of three Grounding Hazard Zones based on the interpreted surface resistivity (β1):

- **Zone 1: Low-Hazard (<150 Ὠm):** Representative of the Tajikistan and Iraq/Kuwait datasets. Standard horizontal grid designs are sufficient to meet IEEE 80 safety requirements.
- **Zone 2: Moderate-Hazard (150 Ὠm – 500 Ὠm):** Representative of the Niger laterites. Standard grids often fail, necessitating the use of Ground Resistance Improvement Materials (GRIM) in trenches to lower contact resistance.
- **Zone 3: High-Hazard (>500 Ὠm):** Representative of the Saudi Arabian Shield. Standard designs are fundamentally non-compliant, requiring a transition to a Hybrid 3D Grounding System.

5.2. The K-Factor Decision Logic

Once the zone is identified, the Reflection Factor (K) dictates the vertical strategy (refer to Figure 3):

1. **Negative Reflection (K<0):** Indicates resistivity decreases with depth (e.g., Saudi Arabia, Niger). The optimal strategy is to bypass the resistive surface

overburden using Deep Grounding Wells to discharge fault currents into the more conductive deep strata.

2. **Positive Reflection (K>0):** Indicates resistivity increases with depth (e.g., Iraq/Kuwait). Deepening electrodes provides no benefit. The framework recommends Surface Mesh Expansion and the use of Counterpoise Conductors to maximize surface dissipation.
3. **Neutral Reflection (K approx. 0):** Indicates a homogeneous profile (e.g., Tajikistan). Standard 3-meter vertical rods are sufficient.

5.3. Material Selection and Durability

The framework concludes with a material selection requirement based on the "Corrosion-Conductivity Paradox." In high-conductivity zones (<25Ωm), the framework mandates tinned copper or stainless steel to prevent premature failure, whereas in high-resistivity zones (), the priority shifts to GRIM-encased copper to ensure low-impedance contact with the dry soil matrix.

Proposed Hybrid Grounding Design Framework

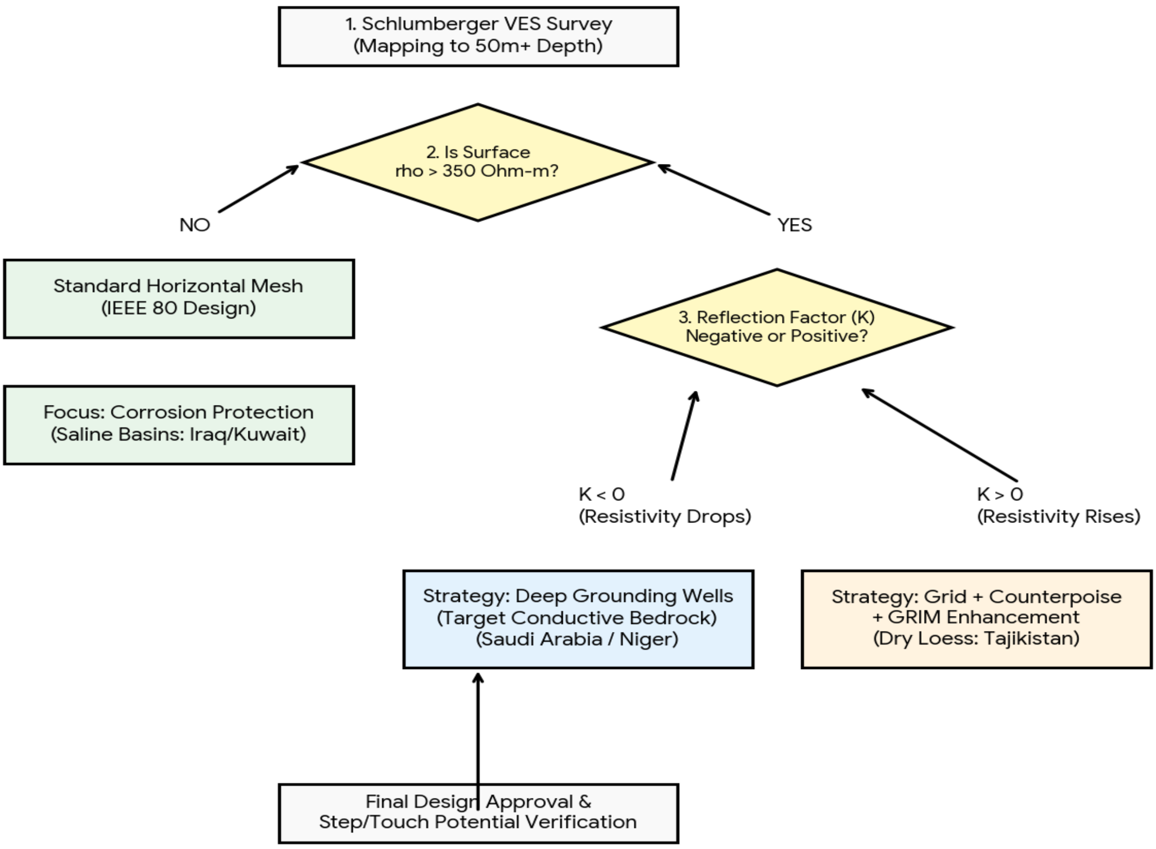

Figure 3 Caption: *Proposed engineering design framework for substation earthing based on geoelectric regional zonation. The model utilizes the Reflection Factor () and surface resistivity thresholds to determine the most cost-effective mitigation strategy—shifting from standard horizontal meshes in saline environments to deep grounding wells in high-resistivity crystalline terrains.*

6. Practical Applications

The findings of this study have immediate utility for the design of high-voltage (HV) and extra-high-voltage (EHV) substations in challenging terrains. To bridge the gap between geophysical surveys and electrical safety, we propose a Hybrid Grounding Design Framework, illustrated in the flowchart in Figure 3. This decision-making logic utilizes the surface resistivity threshold (350Ωm) and the Reflection Factor (K) to determine the most cost-effective earthing strategy. Supporting this framework, Table 3 provides optimized vertical electrode depths required to achieve target resistance levels across different lithologies. By applying these regional depth-resistance correlations, engineers can optimize grounding well placement to bypass resistive hardpans and ensure long-term system reliability.

6.1. Site Screening and Cost Estimation

By using the Geoelectric Provinces defined in this study, project managers can estimate grounding costs during the tender stage. For instance, projects located in the Arabian Shield (Zone D) should automatically budget for specialized drilling equipment and Ground Resistance Improvement Materials (GRIM), as standard excavation will fail to meet safety codes.

6.2. Mitigation of Seasonal Resistivity Flux

In the Tajikistan Loess plains, where soil moisture varies significantly, the practical application of this study is the determination of Seasonal Design Factors. Engineers can use the "worst-case" dry resistivity data provided here to ensure that the grounding system remains compliant during peak summer months when the "honeycomb" silt structure is most desiccated.

6.3. Corrosion-Informed Material Procurement

For projects in the Mesopotamian Alluvium (Zone A), the application is focused on procurement. While standard bare copper is the global default, our results demonstrate that in these saline environments, tinned copper or stainless steel should be the mandatory specification to ensure a 50-year service life, despite the excellent initial resistance readings.

7. Conclusion and Recommendations

7.1 Conclusion

The investigation of earthing performance across five diverse geoclimatic zones demonstrates that a "one-size-fits-all" grounding design is fundamentally unsafe for global infrastructure. In arid shields and indurated laterites, standard surface grids fail to meet IEEE 80-2013 requirements due to high surface impedance. The use of Vertical Electrical Sounding (VES) proved essential for identifying deep conductive horizons, with the Reflection Factor (K) serving as a reliable indicator for deep well necessity. By adopting the proposed Hybrid Design Framework, engineers can optimize safety grid geometry, ensuring that fault currents are effectively dissipated while maintaining Step and Touch potentials within permissible limits in even the most challenging geological environments.

7.2 Recommendations

To ensure personnel safety and system reliability, the following recommendations are proposed for substation earthing design in similar geoclimatic zones:

To ensure personnel safety and system reliability, the following recommendations are proposed for substation earthing design in similar geoclimatic zones:

1. **Mandatory Deep-Layer Mapping:** For all sites with a surface resistivity >350 Ὠm, Vertical Electrical Sounding (VES) must be extended to a minimum of AB/2 = 100m. This ensures the identification of deep conductive horizons which are essential for vertical electrode placement.

2. **K-Factor Driven Electrode Selection:**

1. If $K<0$, prioritize Deep Grounding Wells (vertical strategy).

2. If $K>0$, prioritize Surface Mesh Densification and Counterpoise (horizontal strategy).

3. **Application of GRIM:** In the indurated laterites of Niger, it is recommended to encase horizontal conductors in a 100MM layer of low-resistivity backfill (GRIM). This maximizes the effective diameter of the conductor and reduces the contact resistance with the stiff, resistive hardpan.

4. **Step Potential Management:** In saline zones where K is positive, fault current is trapped near the surface. We recommend a top-layer of high-resistivity crushed rock (100–150mm) across the entire substation footprint to provide an insulating barrier for personnel, mitigating the high step-potential risk inherent in surface-conductive soils.

5. **Dynamic Design Validation:** In complex terrains, the design should not be static. We recommend post-installation fall-of-potential testing during the driest month of the year to validate the 1D geoelectric model's accuracy.

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