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Review Article

Integrated Assessment of Soil Resistivity and Maintenance Practices in Grounding Systems: A Systematic Review

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Abstract *- Electrical safety relies fundamentally on the ability of grounding systems to dissipate fault currents; however, seasonal variability in soil resistivity and deficiencies in maintenance practices continue to pose significant operational risks. This review proposed a conceptual model of an adaptive life cycle that interrelates three key dimensions: the temporal evolution of resistivity, the progressive degradation of grounding connections, and the diagnostic capability of intelligent technologies. A taxonomy of emerging solutions was also developed and classified according to their Technology Readiness Level (TRL). The methodology was based on a systematic Scopus search of articles published between 2020 and 2025, from which 54 relevant studies were selected. The analysis combined structured thematic extraction, qualitative synthesis, and chronological trend evaluation. The findings reveal that increases in resistivity above 500 Ω·m can raise potential gradients by up to 60%; condition-based maintenance programs reduce unforeseen failures and operational risks by 30% to 70%; distributed sensing technologies offer return on investment in less than three years; and artificial intelligence algorithms such as LSTM and GAT achieve diagnostic accuracy exceeding 90%, although they still require field validation. The study concludes that integrating multi-seasonal measurements, risk-based maintenance, and real-time diagnostics is essential to ensure the operational resilience of grounding systems in future electrical networks. This work provides a technical roadmap for researchers, regulators, and operators aiming to establish grounding systems as intelligent and self-adaptive assets.*

Keywords *- Grounding, Soil resistivity, Earthing systems, Predictive maintenance, Electrical safety, High resistivity, IoT monitoring, Ground faults.*

1. Introduction

Grounding Systems (GS) represent the first line of defense in any electrical installation, enabling the rapid dissipation of fault currents and maintaining step and touch potentials within safe limits for both personnel and equipment. Despite decades of standardization through IEEE Std-80, IEC 60364, and national codes, ground faults remain one of the leading causes of critical incidents in substations, renewable generation facilities, and port infrastructures [1, 2]. This pattern indicates that conventional design and maintenance practices are insufficient to meet the growing safety and operational continuity demands. A key challenge is the seasonal variability of soil resistivity (ρ). Measurements in photovoltaic parks located in desert areas show that a single site can exhibit resistivities as low as 100 Ω·m during wet seasons and exceed 1000 Ω·m during drought, increasing potential gradients by up to 60% [3, 4]. In direct current microgrids, electromagnetic simulations show that maintaining grounding resistance between 3 and 5 Ω minimizes voltage spikes in IGBT switches, whereas values above 10 Ω double the transient overvoltages [5]. These findings question the validity of static design approaches based on a single ρ value, particularly under extreme climatic conditions. A second challenge lies in the limitations of preventive maintenance. Field surveys conducted in 96 poultry farms revealed that only 64% of the systems met the 25 Ω threshold recommended by the National Electrical Code (NEC) at the end of the dry season [6]. In residential environments, hazardous backfeed conditions have been reported due to degraded ground connections in homes using low-quality switched-mode power supplies [7]. Even in 220 kV substations, failures have occurred on the low-voltage side of transformers due to dead zones in protection systems caused by corroded joints [8]. Traditional inspection methods, such as four-point measurements and annual visual checks, leave expansive windows of vulnerability in which corrosion and joint loosening may progress undetected [9]. The technical community has proposed several responses: condition monitoring via shield current in medium-voltage cables [10], risk-based maintenance models that optimize inspection intervals according to the criticality of each segment [11], and intelligent feeder selection algorithms based on steady-state substation data [12]. However, the literature remains fragmented, with most studies focusing either on numerical modeling or artificial intelligence, without holistically integrating the relationship between soil variability and GS degradation. Moreover, existing reviews address these aspects in isolation, leaving the reader without a comprehensive background on the combined challenges of grounding systems. This lack of integration represents the main research gap, as prior works address soil resistivity variability, maintenance practices, and intelligent diagnostics separately rather than within a unified framework.

To address this gap, the present article systematically reviews 54 studies published between 2020 and 2025, covering substations, renewable energy installations, railway systems, LV/MVDC networks, and submarine cables. A conceptual model of an adaptive life cycle was proposed based on critical analysis, linking ρ variability, connection degradation, and intelligent diagnostics. A taxonomy of emerging technologies was also established and positioned according to their TRL. Unlike prior reviews that examined soil resistivity or maintenance practices separately, this work integrates both perspectives and positions emerging technologies according to their maturity level, reflecting this study's novelty.

2. Fundamentals and Regulatory Criteria

The reliability of a GS is based on the interaction of three variables: the electrode geometry, soil resistivity (ρ), and the integrity of the electrical connections. Its purpose is to maintain a sufficiently low fault impedance so that step (E_step) and touch voltages (E_touch) remain below the physiological thresholds established in IEEE Std-80 and IEC 60364 [1].

When the grounding grid ceases to be equipotential due to corrosion, loose connections, or seasonal variations in ρ, the ground potential can escalate to hazardous levels, as demonstrated by semi-spatial E_touch simulations in 110-750 kV substations [9]. Soil resistivity is a dynamic parameter governed by moisture content, temperature, electrolyte concentration, and soil granulometry. In arid climates, it can exceed 1,000 Ω·m, whereas in saturated clay soils, it rarely exceeds 20 Ω·m [3]. Such variability requires seasonal design margins and periodic verification of connection prerequisites, as reflected in international standards through fault impedance and safety voltage limits.

The main applicable standards are summarized in Table 1, which compares their scope, typical grid resistance limits, and specific features of each approach. This regulatory compendium will serve later to contrast empirical evidence regarding ρ variability and maintenance strategies. The guidelines converge in their aim to reduce fault impedance and control voltages transferred to the human body, but they differ in how they address soil stratification, DC systems, periodic verification, and online monitoring.

Table 1. Regulatory criteria for grounding systems

Standard	Application Context	Grid Resistance Limit (R_grid)	Distinctive Feature
IEEE Std-80	HV substations	≤ 5 Ω (guide value)	E_touch curves based on I_k and soil stratification
IEC 60364-4-41	LV/MV installations	Function of I^2t	Differentiates TN, TT, IT schemes; mandates RCDs in TT systems
NEC (Art. 250, U.S.)	Civil and agricultural infrastructure	25 Ω per grounding conductor	Practical reference rather than physiological limit
KEC (KEPIC-EAC, Korea)	HV substations in monsoon climates	Differentiated TN/TT values	Adjusts E_touch according to seasonal humidity
IEEE/IEC 80005-1	Shore-to-ship power connections (HVSC)	E_touch calculated for 50/60 Hz	Requires resistive grounding (NGR) and continuous ground-to-ship voltage monitoring

3. Impact of Soil Resistivity on GS

3.1. Variability and Determining Factors

Soil resistivity (ρ) is the most volatile physical variable in the design of grounding systems. Table 2 summarizes resistivity values for different soil types. Multi-seasonal measurement campaigns have reported that a single site can exhibit values ranging from 10 Ω·m in saturated clay to over 1000 Ω·m in dry sand, potentially increasing the grid resistance by a factor of five to thirty [3]. In photovoltaic parks located in desert regions, it has been documented that an increase in ρ from 100 to 1000 Ω·m can raise the potential gradient by up to 60% during 100 kA lightning events, even in dense configurations validated through FDTD/PEEC simulations [4].

Beyond climate, other technical factors influence ρ behavior. A sensitivity study on insulation monitoring in distribution networks revealed that the maximum detectable transition resistance may vary from 2500 Ω to 230 Ω, depending on whether the grounding configuration is isolated, Petersen coil, or resistively grounded [13].

Table 2. Soil resistivity by type

Soil Type	ρ [Ω·m]	Estimated R_grid	Ref.
Saturated clay	5 - 20	baseline	[3]
Moist loam	20 - 100	×2 - ×4	[4]
Rocky or dry soil	100 - 500	×5 - ×15	[1]
Arid sandy soil	500 - 1 000+	×15 - ×30	[6]

In DC microgrids, electromagnetic simulations indicate that maintaining grounding resistance between 3 and 5 Ω helps mitigate voltage spikes in IGBT switches, whereas values above 10 Ω can double transient overvoltages [5]. Environmental parameters, such as temperature and salt leaching, also affect ionic mobility. A 15°C temperature drop can increase resistivity by 20% in clay soils and up to 40% in sandy soils. Controlled experiments using bentonite and zeolite mixtures have demonstrated reductions in the resistance of portable electrodes installed in soils with resistivity above 500 Ω·m [14].

3.2. Measurement and Characterization Methods

Accurate measurement of soil resistivity (ρ) and effective grid resistance is essential for reliable diagnostics of grounding systems without interrupting electrical service. Although the traditional Wenner method remains widely applied, advanced techniques have been developed to achieve high-precision characterization of ρ under real operating conditions [15]. Among these, clamp-on probes assisted by machine learning or neural networks have demonstrated the ability to correct the typical overestimation observed in extensive networks, achieving accuracies of approximately ±7% in grids exceeding 100 meters [16].

Similarly, high-frequency meters (25 kHz) enable early detection of corrosion processes and seasonal ρ fluctuations, with errors below 10% when compared to PEEC models [17]. In critical substations or resonant-neutral environments, methodologies such as impulse testing, touch voltage (E_touch) analysis, and zero-sequence admittance calculations, particularly when processed through FTUs, enhance diagnostic capabilities by providing precise estimations of residual currents and fault localization [18].

Table 3 presents a comparative summary of these diagnostic methods, highlighting their applicability, reported accuracy, and specific contributions documented in the literature.

Table 3. Measurement and diagnostic methods in GS

Method	Operating Principle	Reported Accuracy / Scope	Limitations	Ref.
Clamp-on + ANN	I-V relationship without disconnection	±7% error in grids > 100 m	Requires inductive calibration	[16]
HF meter (25 kHz)	Electrode harmonic impedance	<10% error vs. PEEC	Conversion to 50/60 Hz	[17]
10/350 µs impulse	Z_hf and R measurement	Characterization against lightning	Expensive instrumentation	[20]
Experimental touch voltage	Test the current + semi-spatial model	Detection of non-equipotential zones	Current is limited to 600 A	[9]
Zero-sequence signal (FTU)	Transient admittance	High accuracy in resonant systems	Requires FTU/PMU	[18]
ρ sensitivity curve	V_0 variation vs. R_trans	The threshold is between 230 and 2500 Ω	Applicable up to 35 kV	[13]
DC optimization	EMC simulation in converters	Optimal R of 3-5 Ω, peak control	Design-dependent	[5]

Each method addresses a specific context: clamp-on devices and HF meters are helpful for audits without disconnection; impulse testing is suitable for lightning resistance evaluation; E_touch analysis detects potential imbalances; and transient admittance techniques are ideal for resonant systems.

The sensitivity curve described in [13] demonstrates the influence of grounding configuration on detection thresholds, while [5] validates how poor R_ground design in DC systems can double internal overvoltage.

3.3. Design Implications

The presented data support an adaptive design approach that integrates multi-seasonal measurements, advanced simulations (FDTD/PEEC), and safety margins against corrosion. When soil resistivity exceeds 200 Ω·m, it becomes cost-effective to incorporate conductive additives, deepen the electrodes, or combine horizontal and vertical configurations. The sensitivity curve in [13] warns that detection thresholds vary significantly with the neutral-to-ground scheme, and the study [5] shows that improper selection of R_ground can double internal overvoltages in DC systems. Integrating sensors such as clamp-on probes and HF meters into the grounding grid allows the implementation of digital twins and predictive maintenance strategies, thereby closing the gap between design values and actual performance throughout the operational life cycle of the GS.

4. Preventive Maintenance Techniques

Recent literature confirms that even a properly designed grounding system will lose performance if its resistance is not systematically monitored and corrected. Three contemporary approaches have emerged: Condition-Based Maintenance (CBM), Risk-Based Maintenance (RBM), and IoT-supported monitoring. These modern strategies have evolved toward condition- and risk-driven models. For instance, CBM uses sheath current in medium-voltage cables to anticipate failures caused by corrosion or loose connections [10]. On the other hand, RBM relies on the IFC model to adjust inspection frequency according to the criticality of each segment, potentially reducing operational risk by up to 70% [11]. In parallel, IoT-based solutions, such as Earthing Monitoring platforms, enable the real-time mapping of grounding grids, identification of return paths, and detection of hotspots across the network [19]. Table 4 summarizes the indicators, benefits, and limitations of the main approaches developed in recent years; the following subsections detail each strategy.

Table 4. Contemporary strategies for predictive and risk-based maintenance

Method	Operating Principle	Reported Accuracy / Scope	Limitations	Ref.
Calendar-based inspection	Annual 4-point resistance test	Operational simplicity	Extended risk windows	[9]
CBM (RMS trend of Isheath)	Temporal evolution of the sheath current	≈ 30% fault reduction	Requires continuous sensing	[10]
CBM phase-amplitude	Phase-magnitude comparison at both ends	Early detection of degraded joints	Requires a fine-tuned phase reference	[24]
CBM FAFO	Spectral attenuation of the transient	Diagnosis of incipient carbonization	Sensitive to impulsive noise	[25]
CBM Isheath/Iearth ratio	Sheath-to-earth current ratio	Internal fault classification	Requires validation on more topologies	[26]
CBM μ-σ analysis of Isheath	Longitudinal sheath current statistics	> 90% derivation detection	Requires complete profiles	[27]
RBM IFC-risk	Probability × consequence product	≈ 70% risk reduction	Requires detailed failure history	[11]
RBM with stationary data	Zero-sequence V and I	98%-line selection accuracy	Applicable to LR systems only	[12]
IoT-based mesh monitoring	Node voltage and current	Three outages avoided per year	Cybersecurity demands	[19]
Goertzel-ESP32 meter	12th-order harmonic impedance	< 0.5 s neutral loss detection	Cloud bandwidth requirements	[28]
LV-side diagnosis	Negative sequence in LV	90% single-phase fault location	Requires instrumented transformers	[29]
Phase-differential protection	I0-V phase shift in active LR	Selectivity with connected DG	Requires precise synchronization	[30]

4.1. Condition-Based Maintenance (CBM)

CBM is based on the premise that current flowing through the cable's metallic sheath reflects the integrity of its grounding connections. Study [10] demonstrated that the RMS trend of this current can predict joint corrosion weeks in advance, resulting in a reduction of approximately 30% in unplanned interruptions. To improve sensitivity, [24] introduced a method that compares current amplitude and phase at both ends of a high-voltage cable, successfully detecting defective splices under variable load conditions.

The work in [25] added a spectral indicator, the waveform attenuation factor (FAFO), which correlates the dilution of high-frequency components with the internal carbonization length, generating alerts nearly 48 hours before irreversible failure. Where topology complicates interpretation, [26] established quantitative thresholds for the defective/reference sheath current ratio. At the same time, [27] demonstrated that the mean and standard deviation of current throughout the circuit can identify faults in tunnels with multiple cables.

4.2. Risk-Based Maintenance (RBM)

When assets span hundreds of kilometres, inspecting all segments at the same frequency becomes impractical. The IFC-risk model proposed in [11] weighs failure probability and service criticality for each segment; when applied to a 220 kV cable, this approach reduces annual risk by 70% and operational expenditure by 25%. In networks with low neutral resistance and limited historical data, [12] showed that steady-state zero-sequence voltage and current are sufficient to identify the affected feeder with 98% accuracy.

4.3. IoT and Distributed Analytics

Connecting sensors to the cloud complements and enhances the two previous strategies. In a pilot with 52 nodes, the platform described in [19] mapped grid voltages and currents, identified altered return paths following civil works, and prevented three outages valued at USD 150000. In residential environments, [28] developed a device that injects a 12th-order harmonic and uses an ESP32 microcontroller to estimate impedance in under 0.5 seconds, detecting ground conductor loss and electricity theft events. Study [29] showed that the harmful sequence component captured at the secondary of a distribution transformer can locate a single-phase ground fault in the MV section with 90% accuracy, eliminating the need to instrument the MV feeder. Even in active networks with distributed generation, a phase-differential algorithm proposed in [30] maintains protection selectivity, distinguishing internal and external faults even under bidirectional current injection.

4.4. Synthesis and Challenges

The convergence of CBM, RBM, and IoT is transforming grounding maintenance from an annual corrective task into a continuous, prescriptive process. Sheath-current-based indicators function like an electrocardiogram for the cable, while risk analytics optimize the allocation of maintenance resources. IoT deployments provide traceability and a strong economic justification for the transition, but also introduce challenges in data governance, interoperability, and cybersecurity: unencrypted MQTT protocols may be exploited to falsify readings, prompting pilot projects to adopt IEC 61850/GOOSE messaging with IEC 62351 authentication [31, 32]. Additionally, economies of scale remain a barrier in short networks, and long-term validation in marine environments or LV/MVDC systems is still in its early stages of development.

5. Emerging Technologies for Monitoring and Diagnostics

The convergence of advanced sensing technologies, digital communications, and artificial intelligence algorithms is driving significant progress in the intelligent management of grounding systems. These innovations are transforming a traditionally passive component into an active system capable of real-time condition diagnosis and adaptive response. Table 5 provides a structured classification of reported solutions according to their operational principle, documented performance, and declared or inferred Technology Readiness Level (TRL) to contextualise these developments. In addition, Figure 1 offers a comparative analysis of the relative performance of the most representative approaches, highlighting their strengths and limitations within practical implementation scenarios.

Table 5. Emerging diagnostic technologies (2020-2025) and estimated maturity

Technology / Article	Principle and Application	Accuracy / Error	Latency	TRL
Clamp-on with neural network [16]	I-V measurement without disconnection; substations, wind farms	±7% (grids > 100 m)	<1 s	7
HF impedance meter 25 kHz [17]	Harmonic R_ground evaluation; transmission towers	<10% (vs. PEEC)	<5 s	6
FTU with transient admittance [33]	HIF fault location in resonant systems	Real-time accuracy (RTDS)	60-100 ms	6
LV-side sensors [34, 29]	Negative sequence in LV to detect MV faults	90% location accuracy	20-50 ms	5
Goertzel-ESP32 device [28]	12th-order harmonic impedance detection	Neutral loss <0.5 s	200-500 ms	6
Multiclass logistic classifier [35]	Rapid HV mesh classification (27 topologies)	>95%	50-100 ms	5
LSTM network for sheath [36]	Diagnosis of 18 failure modes	100% (lab)	70-150 ms	4
Graph Attention Network [37]	Explicit topology-based analysis	+14% vs. dense NN	150-250 ms	4
CART-MRN multidomain [38]	Single-phase fault classification	>92%	30-60 ms	4
Entropy-kurtosis + MVMD [39]	Single-end fault location in LR systems	<2% (20 dB noise)	40-80 ms	4
Discrete Fréchet [40]	HIF detection in resonant systems with DG	100% (simulation)	100-200 ms	3-4

Zonal scheme with PSDs [32]	Sectionalizing in offshore DC wind parks	Tripping <0.5 ms	5 ms (ID signals)	4
Smart safety meters [41]	Correlation of consumption and trip events	12% fire reduction	1-5 s	5
Equivalent shielding model [42]	Reduction factor estimation	<5% error	Offline	5
FEM model for submarine cable [43]	Thermal gradient in splices	Gradient reproduction	Offline	3

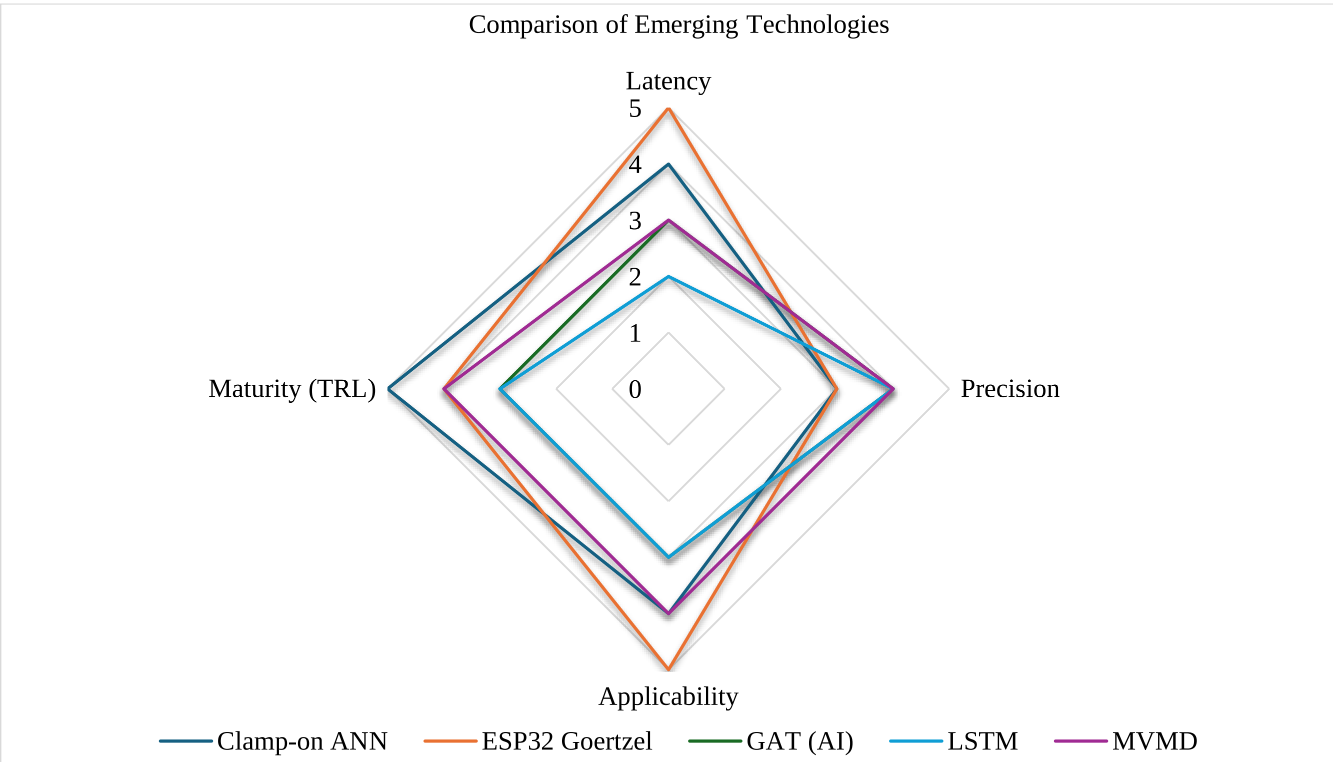

Fig. 1 Comparison of emerging technologies based on accuracy, latency, TRL, and applicability

5.1. High-Maturity Technologies (TRL 6-7)

TRL 6 and 7 technologies are either pre-commercial or already operating in the field. Clamp-on sensors with embedded neural networks [16] and high-frequency harmonic impedance meters [17] stand out in this category, with proven application in substations and transmission lines.

These tools enable non-intrusive measurements, allowing for the monitoring of seasonal corrosion. However, they face challenges such as calibration under mutual inductance when the grid perimeter exceeds 200 meters.

5.2 LV-Side Applicable Technologies (TRL 5)

Intermediate TRL 5 technologies enable fault inference from the low-voltage side, thereby avoiding the need for direct instrumentation of the medium-voltage network. Sensors leveraging harmful sequence components from the secondary transformer [34, 29] achieve 90% accuracy with 20-50 ms latency, which is highly valuable for rural operators with limited budgets. Devices like the Goertzel-ESP32 [28] allow fast detection of lost neutrals through harmonic injection and embedded spectral algorithms.

5.3 AI-Based Solutions (TRL 4-5)

Artificial intelligence-based approaches comprise a significant portion of the TRL 4-5 range. Multiclass logistic regression algorithms [35] can distinguish up to 27 HV mesh configurations with greater than 95% accuracy and low computational cost, making them ideal for edge deployment.

For time-dependent pattern applications, LSTM networks have achieved 100% lab accuracy [36]; however, field validation and the use of large datasets are still required.

Meanwhile, Graph Attention Networks [37] explicitly integrate grid topology into the diagnostic process, increasing accuracy by 14% compared to dense networks and showing promise in urban environments with shared infrastructure.

5.4. Experimental Technologies for Extreme Conditions (TRL 3-4)

At the experimental end, algorithms tailored for extreme conditions are still undergoing validation. The discrete Fréchet distance [40] amplifies zero-sequence current patterns, enhancing detection of high-impedance faults that elude conventional protection. Similarly, entropy-kurtosis, combined with MVMD [39], optimizes computation time compared to VMD-TEO methods, favoring implementation in smart poles; however, robustness under harmonic distortion and distributed generation remains to be assessed.

5.5. DC and Port Environment Applications

The push for electrification and decarbonization has accelerated the development of specific solutions for DC environments. One example is the zonal scheme using polarity-sensitive PSDs in offshore DC wind parks, which discriminates faulty zones in under 0.5 ms using average voltage polarity and current, integrated with IEC 61850 GOOSE signaling for automatic tripping [32]. Studies on high-voltage shore connections in port environments confirm the benefits of resistive grounding (NGR) in limiting touch voltages; however, the lack of sensors adapted to saline conditions remains a technological barrier.

5.6. Technological Convergence and Future Outlook

Shortly, a convergence of mature and intelligent technologies is anticipated. Clamp-on sensor manufacturers are embedding classification algorithms in their firmware to compensate for the influence of adjacent conductors. Simultaneously, network operators are integrating HF impedance meters with IoT platforms and digital twins to simulate dynamic grounding grid behavior under events such as storms detected by weather radar. With real-time data on sheath currents, soil resistivity, and environmental conditions, grounding systems are evolving from passive components to active units with prescriptive capabilities.

6. Chronological Analysis of Research

Research on grounding systems conducted between 2020 and 2025 reveals a progressive transition from conventional approaches centered on geometric redesign and traditional measurement techniques toward intelligent, self-monitoring solutions integrated with network automation platforms. Figure 2 illustrates the annual evolution of scientific outputs during this period, providing a visual overview of the increasing emphasis on digitalization and intelligent monitoring strategies.

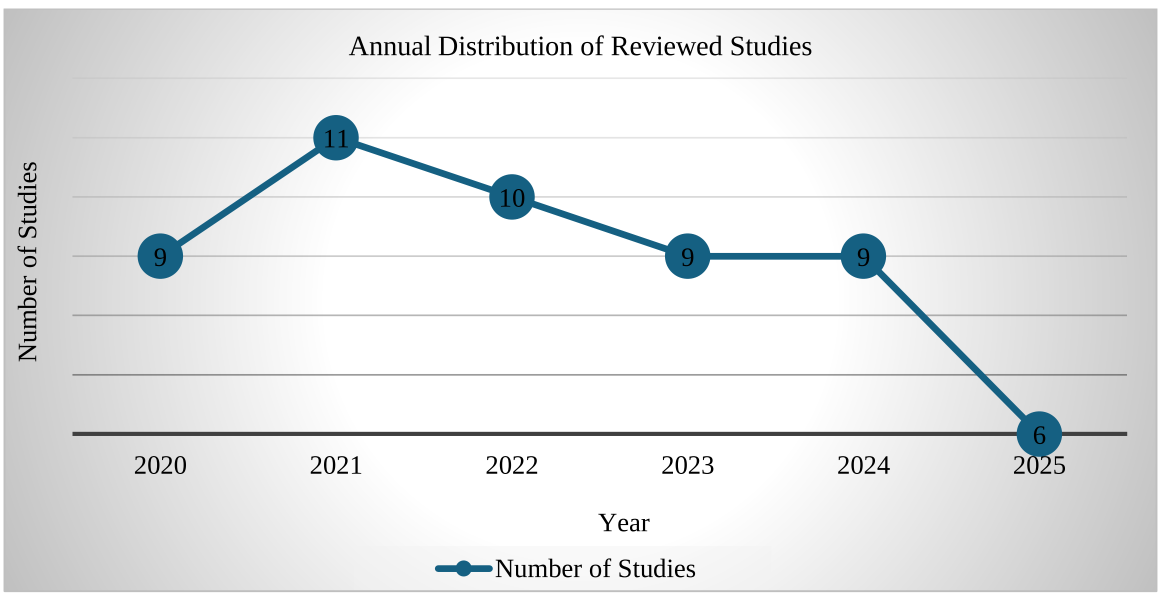

Fig. 2 Annual distribution of the 54 reviewed studies during the 2020-2025 period

This progression reflects a paradigm shift prioritizing continuous diagnostics, predictive maintenance, and integration with digital platforms. Table 6 summarizes the yearly distribution of the 54 reviewed studies, identifying dominant thematic axes and representative articles for each year. Figure 3 summarizes the frequency of key subtopics across the reviewed literature.

Table 6. Distribution of reviewed studies by year of publication (2020-2025)

Year	No. of Studies	Dominant Topics
2020	9	Impulse methods, early CBM, initial PV analysis
2021	11	Conductive compounds, overvoltages, IFC-risk
2022	10	Transient location, FLISR, auto-disconnection, FTU in resonant systems

2023	9	Advanced algorithms, LVDC safety, and stray currents
2024	9	IoT-cloud, HVSC protection in ports, FDTD simulations
2025	6	Deep AI (GAT, LSTM), HF measurements, structural line solutions

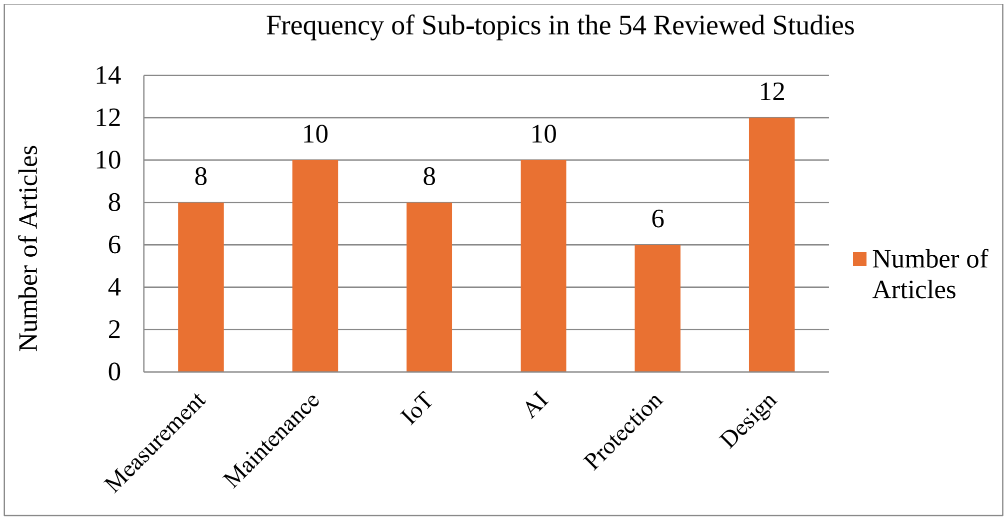

Fig. 3 Relative frequency of key subtopics (measurement, maintenance, IoT, AI, protection, and design) in the 54 reviewed studies

6.1 Period 2020-2021: Technical Fundamentals and Early CBM Strategies

In 2020, efforts focused on strengthening geometric calculations and developing measurement methods that do not require de-energization of the system. The 10/350 µs impulse method proposed in [20] enabled direct field estimation of high-frequency impedance, while [13] introduced an adaptive sensitivity curve for insulation monitoring based on the grounding configuration. In parallel, [3] assessed the economic impact of high resistivity in photovoltaic systems, and [10] validated sheath current as a reliable indicator of grounding system condition.

In 2021, attention shifted toward improvement compounds and maintenance strategies. Bentonite-zeolite mixtures reduced the resistance of portable electrodes by over 50% [14]. On the regulatory side, the comparative analysis in [44] revealed that Russian lightning protection standards are more stringent than those of IEEE or IEC. Finally, the IFC-risk model developed in [11] formalized the evaluation of segment criticality and inspection frequency, introducing the concept of risk-based maintenance for HV cables. The comparative analysis of transient overvoltage curves in [45] provided design guidelines for optimizing electrode configurations in high-resistivity soils.

6.2. Period 2022-2023: Digitalization, Fast Fault Location, and DC Safety

In 2022, research pivoted toward operational digitalization and automation. The expert system proposed in [46] combined sheath transient and zero-sequence currents to locate fleeting faults within a single network cycle. The FLISR architecture in [31] validated the use of the IEC 61850 GOOSE protocol in urban networks, while [47] designed an assisted PST switch that maintained power supply continuity without increasing transition current. In parallel, the ICE Hamburg-Eidelstedt rail workshop implemented an auto-disconnection system with integrated grounding [48, 33] demonstrated that FTUs using transient admittance can localize high-impedance faults at the pole level in resonant systems. In 2023, the focus shifted to DC networks and classification algorithms. The analysis in [7] reported backfeed risks in homes with low-quality UPS under IT schemes, recommending migration to TT configurations. The CART-MRN algorithm in [38] combined Fourier and EMD transforms to identify single-phase faults with an accuracy of over 92%. Simultaneously, [49] examined stray currents in metro networks, showing that metallic mesh interconnections can increase parasitic current by up to nine times in the power grid. In the LVDC domain, the mid-point RCS architecture, as applied in [50], detected and cleared faults in under 80 ms using a low-cost DC-RCD differential breaker.

6.3. Period 2024-2025: IoT, Artificial Intelligence, and Digital Twins

The year 2024 marked a significant leap forward in cloud-connected platforms. As described in [19], the IoT-Earthing solution instrumented over 50 grid nodes, modeled real-time behavior, and prevented three outages valued at USD 150000. Meanwhile, the Goertzel-ESP32 meter [28] identified grounding loss and electricity fraud events in under 0.5 seconds, and enhanced FDTD simulations with variable cell models reduced the average error versus lab tests to only 5% [4]. The HVSC implementation in port environments [2] confirmed that Neutral grounding Resistor (NGR) effectively limits touch voltage in marine installations, though sensor adaptation to saline conditions remains a challenge. In 2025, research focused on integrating AI with specialized hardware. The use of Graph Attention Networks enabled explicit incorporation of grid topology into the diagnostic process, improving accuracy by 14% over dense networks [37]. An LSTM classifier achieved 100% accuracy in detecting 18 sheath fault conditions under lab conditions [36]. HF meters validated in [17] provided harmonic impedance estimates in transmission towers with <10% error, while the structural proposal of V-shaped rods [51] cost-effectively extended the protection radius against lightning strikes. Finally, the PSO-OMP algorithm, combined with the Wigner-Ville distribution in [52], successfully located microcracks in down conductors with less than 10% error margins.

7. Discussion

The systematic review reveals that grounding system reliability is a dynamic phenomenon shaped by the natural variability of soil resistivity and the gradual degradation of electrical connections. Both field studies and simulations consistently indicate that seasonal increases in ρ above 500 Ω·m can raise potential gradients by up to 60%, compromising safety even in dense grounding meshes [3, 4]. This vulnerability is partially mitigated by the use of bentonite-zeolite compounds, which reduce electrode resistance in arid soils by over 50% [14]. By adapting the neutral-to-grounding scheme to match monitoring sensitivity, the curve proposed in [13] shows that the maximum detectable transition resistance can decrease from 2,500 Ω to 230 Ω when transitioning from an ungrounded system to one with low-resistance grounding. However, DC microgrid optimization studies warn that setting grounding resistance outside the 3-5 Ω range can double transient overvoltages in converters [5], confirming the need for adaptive design throughout the system's lifecycle.

On the operational front, evidence is conclusive: annual inspections leave vast risk windows. Condition-based maintenance methods leveraging sheath current have reduced unplanned failures by approximately 30% [10], while phase-amplitude criteria and spectral metrics have enabled detection of defective joints up to 48 hours before failure [24, 25]. The ratio between defective and reference sheath current for complex grounding grids has proven effective in differentiating between internal and ground faults [26]. In parallel, risk-based maintenance enables the classification and prioritization of resources. The IFC-risk model, for instance, reduced annual costs by 25% in a 220 kV circuit [11], and steady-state data logic improved faulted line selection to 98% in LR networks [12]. Nevertheless, these algorithms rely on historical failure data that many utilities have yet to systematize, thus emerging as the weakest link. Emerging technologies are accelerating the shift from reactive to prescriptive maintenance. Intelligent clamp-on sensors and harmonic impedance meters monitor grounding resistance without service interruption, achieving errors below 10% [16], [17]. IoT devices equipped with ESP32 microcontrollers inject controlled harmonics and detect lost neutrals or energy fraud events in under 0.5 seconds [28]. Integrated into cloud platforms, these data flows enabled [19] to map a 500 km² network in real time and prevent three outages valued at USD 150000. However, penetration testing revealed that unencrypted protocols allow for falsified readings; pilot programs are transitioning to IEC 62351-secured messaging over IEC 61850/GOOSE [31, 32].

Deep learning adds diagnostic accuracy but depends heavily on labeled datasets and validation in heterogeneous environments. The Graph Attention Network increased accuracy by 14% by incorporating explicit topology [37]; the LSTM classifier reached 100% accuracy under lab conditions using 14 feature vectors [36]; and the entropy-kurtosis + MVMD combination localized single-end faults with errors <2% even under 20 dB SNR [39].

Large-scale deployment will require digital twins that integrate historical data, FDTD/PEEC simulations, and IoT measurements, reducing the need for labeling and adapting to local conditions. Limitations observed in the literature include high methodological heterogeneity hindering quantitative meta-analysis the short duration of marine pilots (e.g., thermal ablation in submarine cables [43], sheath current diagnostics in underwater lines [53]), and the scarcity of lifecycle studies in LV/MVDC systems, where standards and protection coordination are still maturing [50, 54]. Furthermore, fewer than 20% of studies report detailed return-on-investment analyses, despite economies of scale remaining a barrier in small networks.

Looking ahead, the most promising research directions include the development of multifunctional sensors capable of simultaneously measuring voltage, current, and moisture; the implementation of self-supervised learning to reduce dependence on labeled data; the consolidation of digital twins integrating electromagnetic models and online data; and the expansion of field testing in saline, arid, or harmonically rich environments where the correlation between ρ, corrosion, and degradation remains poorly documented. Finally, the standardization of harmonic impedance-derived metrics and explainable AI will be essential for regulators to accept digital evidence on par with traditional physical testing, thereby closing the design-operation-maintenance cycle under a truly adaptive framework.

8. Conclusion

This study presented a conceptual model of an adaptive life cycle that links the seasonal variability of soil resistivity, the cumulative degradation of grounding connections, and the diagnostic capabilities of intelligent sensing technologies. Based on 54 recent studies, a technology taxonomy classified by TRL was also developed, enabling the integration of design, operation, and monitoring into a unified analytical framework for cost-effectively comparing solutions and planning interventions. The analyzed evidence demonstrates that increases in soil resistivity above 500 Ω·m significantly raise potential gradients, compromising safety even in dense grounding meshes. Condition-based maintenance has reduced unforeseen failures by approximately 30%, while risk-based approaches have lowered annual operational risk by up to 70% and cut operating costs by 25%. IoT platforms demonstrated return-on-investment periods of under three years, and deep learning algorithms achieved diagnostic accuracies above 90% by incorporating mesh topology. This work also acknowledges essential limitations: the review was restricted to a single database (Scopus) and the 2020-2025 period; methodological heterogeneity prevented a quantitative meta-analysis; and several algorithms remain in early validation stages. Moreover, aspects such as cybersecurity and data governance are only marginally addressed in the analyzed literature. Looking forward, it is recommended to validate algorithms in extreme environments and real networks; develop digital twins that integrate electromagnetic models with real-time IoT data streams; apply self-supervised learning techniques to reduce dependence on labeled datasets; and establish standardized, auditable, and explainable metrics that regulators can adopt.

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