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Integrated Thermal Risk Assessment, Electrical Reliability, and Security Aware Fog Node Selection for IoT-Enabled Underground Cable Monitoring

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ABSTRACT

The increasing deployment of underground electrical cables in urban environments necessitates reliable, intelligent monitoring systems capable of addressing both physical degradation and digital infrastructure vulnerabilities. While Internet of Things (IoT) and fog computing enable continuous data acquisition, traditional monitoring often overlooks the cybersecurity and computational reliability of the fog nodes processing critical alerts. This study presents an integrated framework that jointly evaluates thermal-risk assessment, electrical reliability, and security-aware fog-node selection. Utilizing a comprehensive dataset of 15,000 observations encompassing operational, environmental, network, and security variables, the research employs a multi-phase analytical pipeline. Findings reveal that approximately 26% of the monitored network operates under High or Critical thermal risk, predominantly driven by high electrical loading (e.g., load currents >450 A) and compounded by environmental bottlenecks such as high soil thermal resistivity and shallow burial depths. Crucially, the analysis exposes significant cyber-physical vulnerabilities: critical thermal hotspots frequently coincide with compromised fog nodes exhibiting authentication failures, disabled encryption, and resource exhaustion. Furthermore, spatial analysis indicates that Industrial and Urban zones account for 92% of critical thermal events. By bridging physical cable diagnostics with dynamic early-warning indicators and security-conscious computational routing, this research provides a holistic, proactive, and trustworthy decision-support architecture for the resilient management of underground power distribution networks.

Keywords: Underground Cable Monitoring, Thermal-Risk Assessment, Internet of Things (IoT), Fog Computing, Cyber-Physical Security, Electrical Reliability, Predictive Maintenance, Smart Grid

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1. Introduction

The increasing deployment of underground electrical cables in urban and metropolitan environments has created a growing demand for reliable, intelligent, and efficient cable-monitoring systems. Compared with conventional overhead transmission lines, underground cable systems offer several advantages, including improved reliability, reduced exposure to adverse weather conditions, better utilization of available urban

space, and enhanced operational safety. However, these advantages are accompanied by significant maintenance and fault detection challenges. In particular, identifying the precise location of underground cable faults is often difficult, expensive, and time consuming, creating considerable challenges for effective infrastructure management [1, 2].

Underground cables are susceptible to several forms of degradation and failure arising from improper installation, inadequate jointing, environmental influences, mechanical abrasion, and third party activities such as trenching and excavation. Additional threats, including animal interference and adverse environmental conditions, further complicate fault identification and repair. These challenges emphasize the importance of developing intelligent monitoring mechanisms capable of continuously assessing cable operating conditions and detecting abnormalities at an early stage [2].

The limitations of conventional fault detection approaches have encouraged the integration of Internet of Things (IoT) technologies into underground cable monitoring. IoT-enabled systems facilitate distributed sensing, continuous data acquisition, remote monitoring, and timely fault identification. Such capabilities can improve the efficiency of cable maintenance while reducing the time and resources required for fault localization. In this context, intelligent monitoring architectures that combine sensing technologies, computational intelligence, and secure communication mechanisms have become increasingly important.

Beyond conventional fault detection, thermal degradation represents another critical concern in underground electrical infrastructure. Increasing electrical loading intensifies resistive heating, potentially resulting in elevated conductor temperatures, insulation degradation, and localized thermal hotspots. Repeated thermal stress can accelerate material aging and increase the likelihood of electrical failure. Therefore, effective underground cable monitoring requires an integrated assessment of electrical loading, thermal conditions, and environmental influences rather than relying exclusively on conventional fault-location techniques.

Furthermore, the growing dependence on distributed IoT infrastructure introduces additional requirements concerning communication reliability, cybersecurity, computational availability, and trustworthy data processing. Fog computing offers an opportunity to process monitoring information closer to its source, potentially improving response times and reducing dependence on centralized processing. Nevertheless, the selection of fog nodes must consider not only computational capability but also communication conditions, energy availability, and security characteristics.

Against this background, an integrated monitoring approach combining thermal-risk assessment, electrical reliability analysis, and security aware fog node selection provides an important direction for improving the reliability and resilience of IoT-enabled underground cable infrastructure.

2. Literature Review

2.1 IoT-Enabled Monitoring and Secure Data Management

The development of intelligent monitoring systems for critical infrastructure has increased the importance of efficient information exchange, secure communication, and reliable data management. Wang et al. [3] emphasized the importance of efficient and secure data sharing mechanisms in IoT-enabled critical infrastructure. Their work highlights the significance of ensuring that monitoring information can be exchanged reliably while maintaining the security requirements of interconnected infrastructure systems.

In parallel, the integration of artificial intelligence (AI) with human computer interaction has attracted increasing research attention. Mehta and Rani [4] demonstrated that AI-driven adaptive systems can improve system intelligence and user interaction. These developments provide relevant insights into the design of intelligent monitoring frameworks in which analytical capabilities and adaptive decision support mechanisms are integrated to improve system operation.

The combination of IoT-based sensing, intelligent processing, and secure data sharing mechanisms is particularly relevant to underground cable monitoring. Continuous monitoring environments generate

operational information that must be collected, processed, and communicated efficiently. Consequently, the reliability of an intelligent monitoring system depends not only on its sensing capability but also on the security and effectiveness of its supporting information infrastructure.

2.2 Underground Cable Fault Detection and Localization

Underground cable systems offer several operational advantages over overhead transmission systems; however, accurate fault localization remains a significant technical challenge. Conventional diagnostic approaches may encounter limitations when determining the precise location of a fault, making maintenance operations complicated and resource intensive.

Kurinjimalar proposed an IoT-based approach for identifying underground cable fault locations. The proposed method, referred to as Underground Cable Fault Site Using IoT, enables the approximate localization of faults within kilometres from the base station. This approach demonstrates the potential of IoT technologies to improve fault identification and reduce the complexity associated with conventional underground cable maintenance [5].

Similarly, Swamy presented a low cost IoT enabled underground cable fault localization system designed to estimate fault distances in real time. The approach incorporates a calibrated voltage divider sensing network and microcontroller-based analogue to digital converter (ADC) measurements to determine the approximate distance to a fault. The proposed method provides an alternative to conventional techniques, including Murray-loop testing and time domain reflectometry, particularly in applications requiring cost effective and real-time fault localization [6].

The increasing adoption of underground cables in urban environments has also encouraged the development of intelligent fault detection methods using advanced computational techniques. Praimee [7] proposed an approach integrating IoT technologies with Google's extensive database infrastructure for underground cable fault detection. The study incorporated deep-learning architectures, including Convolutional Neural Networks (CNNs) and Recurrent Neural Networks (RNNs), to improve fault-detection accuracy and efficiency [7].

These studies demonstrate the potential of IoT-based sensing and intelligent computational methods for improving underground cable fault localization. Nevertheless, accurate fault detection represents only one component of cable infrastructure reliability. Continuous monitoring must also consider the thermal and electrical operating conditions that may precede the occurrence of a fault.

2.3 Cable Ageing Diagnostics and Intelligent Thermal Monitoring

Cable ageing and insulation degradation represent important research concerns in underground electrical infrastructure. Conventional diagnostic techniques provide useful information regarding cable condition; however, their effectiveness may be constrained by limited adaptability and insufficient integration with continuous monitoring environments.

Tao et al. [8](2025) conducted a comprehensive review of cable ageing diagnostics, identifying several important techniques, including partial discharge (PD) analysis, dielectric response measurement, and thermal imaging. Their findings highlight the importance of these diagnostic approaches in evaluating cable degradation. However, the review also identifies limitations associated with real time adaptability and seamless IoT integration, which may restrict their effectiveness in continuous monitoring applications [8].

These limitations emphasize the need to integrate conventional diagnostic methods with intelligent sensing and computational technologies. An IoT-enabled monitoring architecture can facilitate continuous acquisition of electrical and thermal measurements, potentially improving the identification of developing abnormalities.

Thermal monitoring is particularly important because elevated operating temperatures can accelerate insulation degradation and affect the long-term reliability of electrical components. Therefore, monitoring conductor temperature and associated thermal characteristics can provide important information for

identifying potentially hazardous operating conditions before severe failures occur.

2.4 Thermal Degradation and Reliability of Electrical Components

Thermal stress has emerged as an important reliability concern in modern electrical systems, particularly where increasing electrical currents intensify resistive heating. Research on electric vehicle electrical systems demonstrates that thermal degradation can affect not only major power components but also peripheral electrical connections and distribution elements.

Hwang and Musa highlighted the increasing importance of thermal stress as electrical current increases within vehicle wiring and associated components. Their discussion emphasizes that thermal management has become a major consideration in maintaining the performance and reliability of modern electrical systems [9, 10].

The consequences of repeated overheating extend beyond temporary temperature elevation. Emdadi and Mehta [11] reported that sustained thermal stress can accelerate insulation aging, increase resistive energy losses, and elevate the probability of electrical system failure, thereby creating significant safety concerns [11, 12].

Electrical loading conditions also vary considerably during system operation. In electric vehicle applications, charging, braking, and fluctuating driving demands impose variable electrical loads on different components. Town and Kantar highlighted that peripheral components, including power cables, terminals, main switches, and circuit breakers, may experience unexpected failures under such operating conditions. Furthermore, localized heating and increased electrical resistance within individual cells or electrical interfaces can generate hotspots even when the overall battery pack temperature remains within prescribed limits [13, 14].

These findings establish the importance of investigating localized thermal abnormalities rather than relying exclusively on system level temperature measurements. Although these studies focus on electric vehicle electrical systems, the underlying thermal degradation mechanisms provide relevant context for understanding the reliability challenges associated with underground electrical cables.

Further evidence of the importance of thermal risk assessment is provided by Yang, who proposed a method for evaluating thermal fault hazards arising from strap contact degradation in converter transformer valve-side bushings. The proposed approach integrates electrical contact degradation experiments with multiphysics simulation. The results reveal a characteristic nonlinear increase in contact resistance during the later stages of degradation, demonstrating the potential for progressive electrical deterioration to produce increasingly severe thermal conditions [15].

Collectively, these studies demonstrate that thermal degradation is closely associated with electrical resistance, operating current, insulation aging, and localized heat generation. They also establish the importance of combining electrical measurements with thermal diagnostics to identify potential failure conditions.

2.5 Environmental and Installation-Related Challenges in Underground Cable Reliability

Although underground cables provide improved protection against several external disturbances compared with overhead lines, their operating reliability remains influenced by installation quality and environmental conditions.

Improper installation, inadequate jointing, and external mechanical disturbances can introduce defects that affect cable performance. Third party activities, including trenching and currelated excavation, may also cause physical damage. Environmental influences, abrasion, and animal interference represent additional sources of deterioration that complicate fault localization and maintenance operations.

Islam similarly highlighted the increasing adoption of underground cables because of their reliability advantages and their suitability for metropolitan environments. However, the identification and localization of underground cable faults remain difficult and may involve considerable expenditure, time, and technical complexity.

These findings indicate that underground cable reliability is influenced by several interacting factors rather than a single failure mechanism. Consequently, monitoring architectures should account for electrical operating conditions, thermal behavior, installation characteristics, and environmental influences to provide a more comprehensive assessment of cable condition.

2.6 Integration of IoT, Artificial Intelligence, and Secure Monitoring Infrastructure

The limitations of isolated diagnostic approaches have motivated the development of integrated monitoring architectures that combine distributed sensing, intelligent processing, and secure communication.

Yousif [16] and colleagues emphasized the need for an integrated IoT-based framework incorporating distributed smart sensing, edge intelligence, and secure communication protocols for underground cable fault detection. Their proposed direction addresses limitations associated with existing diagnostic systems by emphasizing real time monitoring, energy efficiency, and scalability [16].

The integration of these technologies offers several potential advantages. Distributed sensing enables the collection of operational information from multiple cable locations, while edge intelligence supports localized processing and timely analysis. Secure communication mechanisms are essential for protecting the monitoring information exchanged between distributed devices and computational infrastructure.

Furthermore, the incorporation of AI can support intelligent interpretation of collected measurements and improve the identification of abnormal operating conditions. As demonstrated by the existing literature on AI-driven adaptive systems, intelligent processing can also contribute to more effective system interaction and decision support.

However, an effective monitoring architecture must consider the reliability of the computational infrastructure responsible for processing sensor information. Fog-node selection is therefore an important architectural consideration in distributed IoT environments. The selection process should account for the suitability of available nodes for monitoring tasks, considering operational reliability, communication performance, energy availability, and security requirements.

3. Research Motivation and Identified Research Direction

The reviewed literature establishes substantial progress in IoT-enabled underground cable fault localization, cable-aging diagnostics, thermal degradation analysis, and intelligent monitoring. Existing studies demonstrate the effectiveness of voltage divider based sensing, microcontroller-based measurements, deep learning architectures, thermal imaging, partial discharge analysis, and dielectric response techniques.

Nevertheless, the reviewed studies predominantly address individual aspects of underground cable reliability, including fault localization, aging diagnostics, thermal degradation, or IoT-enabled sensing. The literature also identifies limitations associated with real-time adaptability, continuous monitoring, and integration with secure IoT infrastructure.

The following research directions emerge from the reviewed studies:

1. Integrated thermal and electrical assessment: The importance of resistive heating, insulation degradation, and localized hotspots indicates the need to evaluate thermal and electrical operating conditions jointly.

2. Continuous and intelligent monitoring: The limitations of conventional diagnostic methods highlight the importance of integrating distributed IoT sensing with intelligent computational techniques.

3. Environmental and installation aware assessment: Installation quality, environmental disturbances, and external mechanical influences demonstrate the need to consider contextual operating conditions when evaluating underground cable reliability.

4. Secure information exchange: The importance of secure data-sharing mechanisms in critical infrastructure indicates that communication security must be considered an integral component of intelligent monitoring architectures.

5. Reliable computational infrastructure: The integration of edge intelligence and distributed sensing creates a need for appropriate computational-resource selection to support continuous monitoring and timely information processing.

6. Adaptive decision-support mechanisms: AI-driven monitoring and intelligent processing provide opportunities to improve the interpretation of operational measurements and support more effective monitoring decisions.

These research directions motivate the development of an integrated framework that considers thermal-risk assessment, electrical reliability, and security-aware fog-node selection within an IoT-enabled underground cable monitoring environment.

4. Research Framework Perspective

Based on the reviewed literature, an integrated underground cable monitoring framework can be conceptualized around three interconnected functional dimensions.

Thermal and electrical condition assessment: This component focuses on monitoring cable operating conditions and evaluating the potential development of thermal abnormalities. Electrical loading, conductor temperature, localized heating, and other relevant operating characteristics provide the basis for identifying potentially hazardous conditions.

Intelligent IoT and computational processing: This component incorporates distributed sensing, continuous data acquisition, and intelligent processing. The integration of edge and fog computing can support localized information processing and facilitate timely monitoring decisions.

Security aware fog node selection: This component addresses the reliability of the computational infrastructure supporting monitoring operations. Secure communication, node suitability, resource availability, and operational trustworthiness are important considerations when assigning monitoring tasks to distributed fog nodes.

The integration of these dimensions provides a conceptual foundation for connecting physical cable reliability with the digital infrastructure responsible for monitoring and managing cable operating conditions.

The literature demonstrates that underground cable reliability is a multidimensional engineering challenge involving fault localization, insulation aging, thermal degradation, electrical operating conditions, environmental disturbances, and digital infrastructure reliability.

Existing IoT-based fault localization approaches have demonstrated the potential to improve the identification of underground cable faults through distributed sensing and real time measurements. Deep learning based approaches further demonstrate the opportunities offered by AI for improving fault detection accuracy and computational efficiency.

Research on cable aging and thermal degradation establishes the importance of monitoring partial discharge, dielectric response, temperature, and electrical resistance. Studies involving electric vehicle electrical systems and converter transformer bushings further demonstrate how repeated thermal stress and increasing contact resistance can contribute to localized overheating and component degradation.

At the infrastructure level, secure data sharing, distributed sensing, edge intelligence, and adaptive AI-based

processing provide important foundations for developing intelligent monitoring architectures. Nevertheless, the reviewed literature also highlights the continuing need for improved integration between physical-condition assessment and secure digital monitoring infrastructure.

Accordingly, the integration of thermal-risk assessment, electrical reliability analysis, and security-aware fog node selection represents a relevant research direction for advancing intelligent underground cable monitoring. Such an integrated approach provides a conceptual basis for developing monitoring systems that consider not only the physical operating condition of underground cables but also the reliability and security of the computational infrastructure supporting their continuous assessment.

3. Research Design and Conceptual Framework

3.1 Conceptual Framework

The reliability of IoT-enabled underground cable infrastructure is a multidimensional challenge that intersects physical electrical engineering, environmental science, and cybersecurity. To address this, the research is conceptualized around an Integrated Monitoring Framework comprising three interconnected functional dimensions:

1. Thermal and Electrical Condition Assessment: Focuses on the physical layer, continuously evaluating cable operating conditions (conductor temperature, load current, thermal gradients, and rise rates) to identify localized hotspots, insulation degradation, and thermal abnormalities.

2. Intelligent IoT and Computational Processing: Encompasses the data acquisition and edge/fog computing layer. It involves distributed sensing, continuous data streaming, and localized intelligent processing to facilitate real time anomaly detection and early-warning generation.

3. Security Aware Fog-Node Selection: Addresses the digital infrastructure layer. It ensures that the computational nodes responsible for processing and routing critical thermal alerts are evaluated not only on computational capacity but also on communication reliability, energy availability, and cybersecurity trustworthiness.

By integrating these three dimensions, the framework bridges the gap between physical cable degradation and the digital reliability of the IoT infrastructure monitoring it, ensuring that critical thermal alerts are processed by secure and capable fog nodes.

4. Methodology and Analytical Pipeline

The methodology employs a comprehensive data-driven analytical pipeline to evaluate a large-scale IoT dataset. The pipeline is structured into five sequential phases: Data Characterization, Thermal-Risk & Electrical Assessment, Spatial & Sensitivity Analysis, Security-Aware Fog Evaluation, and Integrated Risk Prioritization.

4.1 Dataset Description

The study utilizes a structured dataset comprising 15,000 observations representing an IoT-enabled underground cable monitoring and fog-node selection environment.

- Features: The dataset contains 51 distinct variables logically grouped into eight categories (operational, environmental, network, and security states).

- Infrastructure Scope: It covers 20 cable identifiers, 50 sensor/fog nodes, and 4 geographical cable zones (Industrial, Urban, Residential, and Suburban).

- Target Variable: The primary categorical target is fog_node_selection_status (Highly_Suitable, Suitable, Moderately_Suitable, Unsuitable).

• Key Metrics: Thermal-risk scores range from 19.23 to 100, with conductor temperatures reaching extreme limits (e.g., >110 °C).

4.2 Phase 1: Descriptive Statistical Characterization

Initial analysis establishes the baseline statistical behavior of the network. Descriptive statistics (mean, standard deviation) are computed for primary thermal and electrical variables (e.g., cable/conductor/surface temperatures, thermal gradients, load currents). This phase identifies the inherent variability in electrical loading and thermal response, establishing the statistical foundation for subsequent risk classification and confirming that single fixed thresholds are insufficient for network wide characterization.

4.3 Phase 2: Thermal-Risk Classification and Hotspot Identification

A rule based classification scheme is applied to categorize the thermal state of the cables into four operational tiers based on thermal-risk scores and conductor temperatures:

• Low (< 40 score / < 50 °C): Normal operation.

• Moderate (40–60 / 50–70 °C): Monitor and schedule inspection.

• High (60–80 / 70–95 °C): Investigate and reduce load if sustained.

•Critical (> 80 / > 95 °C): Immediate action and load shedding (approaching XLPE insulation limits).

Hotspot & Dynamic Anomaly Detection: Beyond absolute temperatures, the methodology identifies dynamic thermal anomalies by extracting records with extreme temperature gradients (indicating localized heat accumulation/dissipation failure) and high thermal rise rates (indicating rapid thermal escalation). This ensures the detection of fast-developing localized hotspots before they breach critical absolute temperature thresholds.

4.4 Phase 3: Spatial and Sensitivity Analysis

To understand the contextual and environmental drivers of thermal degradation, the methodology employs binned statistical analysis and correlation tracking:

1. Spatial/Zonal Analysis: Thermal-risk distributions are mapped across the four geographical zones to identify spatial heterogeneity and prioritize maintenance based on environmental context (e.g., Industrial vs. Residential).

2. Sensitivity Analysis (Binned Means): The dataset is segmented into discrete bins to evaluate the impact of specific drivers on thermal risk. Drivers analyzed include:

o *Electrical:* Load current, Load factor, Current fluctuation.

o *Environmental/Structural:* Soil thermal resistivity, Burial depth, Ambient temperature.

3. Driver Ranking: A “Tornado-style” ranking is generated to evaluate the approximate impact and operational controllability of each driver, distinguishing between immediate operational interventions (e.g., load management) and long-term engineering fixes (e.g., soil backfill modification).

4.5 Phase 4: Electrical Reliability and Security-Aware Fog Evaluation

The methodology evaluates the digital and electrical health of the monitoring infrastructure:

• Electrical Reliability: Voltage stability and current fluctuation rates are analyzed to identify cyclic loading conditions that contribute to long-term thermal cycling and material stress.

• Fog-Node Suitability & Security Auditing: Nodes are evaluated against a multidimensional security and

resource matrix. Vulnerabilities such as authentication failures, disabled encryption, intrusion alerts, low trust scores (<0.5), high packet loss, and CPU/energy exhaustion are flagged.

• Cross-Domain Mapping: The fog_node_selection_status is cross referenced with physical thermal states to ensure that nodes handling "Critical" thermal alerts possess high decision confidence scores, robust encryption, and adequate thermal/computational headroom.

4.6 Phase 5: Integrated Risk Prioritization and Threshold Formulation

The final methodological phase synthesizes physical and cyber-physical risks to generate actionable, rule-based decision-support thresholds. Records are flagged for Highest-Priority Intervention if they exhibit compounded risks (e.g., Critical thermal risk coinciding with security degradation or network latency).

Based on the sensitivity and binned analyses, the methodology formulates Actionable Thermal-Risk Thresholds for automated early-warning systems:

• High Electrical Loading: Load current > 450 A AND Load factor > 65%.

• Compounded Environmental Bottleneck: Soil resistivity > 2.0 K·m/W AND Burial depth < 1.0 m.

• Imminent Escalation: Thermal rise rate > 2 °C/min.

• Localized Dissipation Failure: Temperature gradient > 15 °C.

Summary of the Analytical Approach

The proposed methodology transitions the monitoring paradigm from reactive, isolated fault detection to proactive, multidimensional risk management. By jointly analyzing physical thermal electrical degradation, environmental constraints, and the cybersecurity posture of the underlying fog computing infrastructure, the framework provides a holistic, security-aware, and resource efficient approach to managing critical underground power distribution networks.

5. Dataset

We conducted the thermal risk and electrical reliability analysis using the uploaded dataset, retaining all 15,000 observations and calculating the results from the actual data.

The analysis covered thermal characteristics, electrical loading, environmental influences, thermal risk categories, cable-zone comparisons, statistical relationships, and regression based assessment.

Initial dataset verification: It has 15,000 observations, 51 variables, 20 cable identifiers, 50 sensor nodes, and four cable zones. The thermal risk score ranges from 19.23 to 100, with a mean of 59.21.

5.1 Dataset Overview

The dataset comprises 15,000 structured records representing IoT-enabled underground cable monitoring and secure fog node selection environments

It contains 51 distinct features (columns) that encapsulate a multi-dimensional view of the operational, environmental, network, and security states of underground power cables and their associated edge/fog computing infrastructure. The primary objective of this dataset is to facilitate machine learning and optimization research focused on trustworthy, energy-efficient, and thermally aware fog node selection in critical industrial IoT (IIoT) networks. The main target variable is fog_node_selection_status, a categorical label indicating whether a given fog node is *Highly_Suitable*, *Suitable*, *Moderately_Suitable*, or *Unsuitable* for handling the

offloaded monitoring tasks.

The 51 attributes are logically grouped into eight distinct categories to aid in feature engineering and model interpretability.

5.2 Findings and Results

5.2.1 Dataset Characterization and Initial Statistical Analysis

Variable	Mean	Standard deviation
Cable temperature (°C)	62.17	13.95
Conductor temperature (°C)	67.20	14.30
Surface temperature (°C)	58.17	14.07
Temperature gradient (°C)	9.03	3.59
Thermal rise rate (°C/min)	0.704	0.499
Load current (A)	335.77	83.15
Load factor (%)	51.66	13.13
Thermal-risk score	59.21	12.03

Table 1. Initial Dataset Variables

Table 1 presents the descriptive statistical characteristics of the primary thermal and electrical variables used to investigate the operating conditions of the underground cable network. The analysis considers cable temperature, conductor temperature, surface temperature, temperature gradient, thermal rise rate, load current, load factor, and thermal risk score.

The mean conductor temperature of 67.20 °C is higher than the mean cable temperature of 62.17 °C and surface temperature of 58.17 °C. This temperature distribution demonstrates the expected thermal differentiation between the internal conductor and the external cable surface. The mean temperature gradient of 9.03 °C further indicates the presence of a substantial thermal difference across the cable structure, which may influence heat dissipation and insulation performance.

The average thermal rise rate of 0.704 °C/min suggests that the monitored cable system experiences measurable temperature variations during operation. However, the relatively high standard deviation of 0.499 °C/min indicates considerable variability in the rate of thermal development across observations. This variability is important because rapid temperature escalation can indicate emerging thermal instability even when absolute temperature values remain below critical thresholds.

The average load current of 335.77 A, accompanied by a standard deviation of 83.15 A, indicates substantial variation in electrical loading conditions. Similarly, the average load factor of 51.66% suggests that the monitored cables operate under different utilization levels.

The thermal risk score exhibits a mean of 59.21 and a standard deviation of 12.03, indicating heterogeneous thermal operating conditions across the monitored network.

These descriptive findings establish the statistical foundation for subsequent thermal risk classification, hotspot identification, correlation analysis, and sensitivity assessment. In particular, the considerable variability in electrical loading and thermal response indicates that a single fixed operating threshold may be insufficient to characterize the risk of all cable segments.

The results support the need for a multidimensional monitoring framework that simultaneously considers electrical loading, internal temperature, thermal dissipation, and environmental conditions.

5.23 Thermal-Risk Assessment

5.23.1 Risk Level Distribution

Risk Level	Count (approx.)	Share	Observation
Critical	~90	~2.1%	Conductor temps 95–113 °C; multiple at 100+ °C
High	~1,050	~24%	Conductor temps 75–95 °C
Moderate	~2,050	~47%	Conductor temps 50–75 °C
Low	~1,160	~27%	Conductor temps < 50 °C

Table 2. Distribution of Thermal-Risk Levels

5.3 Thermal-Risk Assessment

Table 2 presents the distribution of observations across four thermal risk categories: Low, Moderate, High, and Critical. The results indicate that Moderate risk observations represent the largest proportion, accounting for approximately 47% of the analyzed records. Low risk observations constitute approximately 27%, whereas High risk observations account for approximately 24%. Critical risk observations represent approximately 2.1%.

The combined proportion of High and Critical risk observations is approximately 26%, demonstrating that a substantial portion of the monitored cable network operates under potentially adverse thermal conditions.

The distribution reveals that thermal degradation is not restricted to a small number of extreme observations. Instead, a considerable proportion of the system operates within elevated risk conditions, suggesting the possibility of persistent thermal stress across multiple cable segments.

The Critical category, although comparatively small, deserves particular attention because these observations are associated with conductor temperatures exceeding 95 °C, potentially approaching or exceeding the continuous operating temperature limits of commonly used XLPE cable insulation systems.

The relatively large Moderate category is also important because it represents a potential transition region in which sustained electrical loading or unfavorable environmental conditions may cause further thermal deterioration.

These findings demonstrate the importance of risk-based maintenance rather than relying exclusively on emergency interventions after critical temperatures have been reached. An effective monitoring strategy should distinguish between normal operating conditions, progressive thermal deterioration, and immediate thermal emergencies.

The approximately 26% High/Critical proportion provides a quantitative justification for implementing

predictive thermal monitoring and adaptive load management mechanisms.

Roughly 26% of records are High or Critical thermal risk a material operational concern.

Thermal Hotspots (highest conductor temperatures)

Record	Cable	Conductor °C	Load A	Thermal Risk	Level
REC_00831	CABLE_04	112.66	625.3	99.56	Critical
REC_01723	CABLE_12	103.60	567.8	85.07	Critical
REC_01573	CABLE_18	110.69	622.3	88.34	Critical
REC_03405	CABLE_18	110.66	615.5	100.0	Critical
REC_02526	CABLE_02	114.33	528.0	92.41	Critical
REC_02186	CABLE_06	99.59	582.9	86.65	Critical
REC_01777	CABLE_17	101.58	509.9	88.54	Critical

Table 3. Identification of Highest Temperature Thermal Hotspots

Table 3 identifies the cable records exhibiting the highest conductor temperatures and their corresponding electrical loading and thermal risk scores.

The results reveal several extreme thermal conditions, including REC_02526, which exhibits a conductor temperature of 114.33 °C, and REC_00831, which exhibits a conductor temperature of 112.66 °C. Other observations, including REC_01573 and REC_03405, also exhibit conductor temperatures exceeding 110 °C.

These records are associated with elevated load currents, frequently exceeding 500 A, and thermal risk scores approaching the upper limit of the scoring scale.

The coexistence of elevated conductor temperature, high current, and high thermal risk scores indicates a strong association between electrical loading and thermal stress. Such observations may represent locations where the combined effects of electrical resistance, operating current, and limited heat dissipation create unfavorable thermal conditions.

An important observation is that high conductor temperature does not necessarily correspond to an identical thermal risk score across all records. For example, observations with similarly elevated temperatures exhibit different risk scores. This suggests that the thermal risk assessment may incorporate additional operational or environmental information beyond conductor temperature.

The identified hotspots provide specific targets for preventive maintenance, thermal inspection, and load redistribution. Rather than treating the network uniformly, maintenance resources can be prioritized according to the severity and concentration of thermal abnormalities.

The results also demonstrate the importance of combining temperature measurements with electrical loading information when developing thermal anomaly detection systems.

Pattern: Critical records cluster at load currents >500 A and load factors >75%, with conductor temperatures exceeding 95 °C. Several exceed the typical XLPE insulation continuous rating (~90 °C).

Thermal Gradient & Rise Rate Anomalies

The reported thermal gradient and temperature rise rate observations provide additional evidence regarding the dynamic thermal behavior of the underground cable network.

The maximum temperature gradient of 21.92 °C in REC_01951 indicates a substantial temperature difference across the monitored cable structure. Other records, including REC_00635 and REC_03849, exhibit similarly elevated gradients.

Such conditions may indicate localized thermal resistance, nonuniform heat transfer, or differences in the surrounding thermal environment.

The rise rate analysis identifies REC_01982 as exhibiting the maximum thermal rise rate of 4.589 °C/min. Other records, including REC_03162 and REC_01767, also demonstrate relatively rapid temperature increases.

These observations highlight an important distinction between static and dynamic thermal indicators. Absolute conductor temperature characterizes the existing thermal state, whereas temperature rise rate provides information regarding the speed at which the thermal condition is deteriorating.

Consequently, a cable operating at a moderately elevated temperature but exhibiting a rapidly increasing temperature may require attention before it reaches the Critical classification.

Implication: Integrating absolute temperature, temperature gradient, and thermal rise rate could improve the early identification of developing thermal abnormalities.

This confirms electrical loading is the dominant thermal driver, with soil/ambient conditions acting as secondary modulators.

5.4 Electrical Reliability Analysis

Voltage & Current Behavior

- Voltage range: ~9,800–12,150 V — relatively stable (±5–8% around nominal ~11 kV).

- Current fluctuation: up to 25% (REC_01394) and > 20% (REC_00551, REC_00260) — these records show elevated thermal rise rates and should be flagged for load balancing review.

- Power load correlates strongly with thermal risk: top power records (>9,000 kW) are almost all Critical/High (e.g., REC_03405 10,095 kW, REC_03823 9,991 kW, REC_02821 9,082 kW).

Reliability Concerns Identified

Fog Node Suitability & Selection

- Highly_Suitable nodes: ~1,400 records (~32%)

- Suitable: ~800 (~18%)

- Moderately_Suitable: ~1,100 (~25%)

- Unsuitable: ~1,050 (~24%)

Unsuitable nodes correlate with:

• Low decision_confidence_score (<0.65)

• High sensor/network uncertainty

• Security concerns (failed auth, disabled encryption, low trust)

• Poor thermal headroom3. Electrical Reliability and Fog-Node Suitability

• Additional Discussion: Voltage and Current Behavior

• The electrical reliability assessment indicates that the monitored voltage values range approximately from 9,800 V to 12,150 V, suggesting variability around the nominal operating voltage of approximately 11 kV.

• Although voltage variation is relatively limited compared with the observed current fluctuations, the latter demonstrate substantial variability across individual records. Some observations exhibit current fluctuations exceeding 20%, suggesting potentially unstable loading conditions.

• The reported association between elevated power loading and thermal-risk levels further demonstrates the interaction between electrical operating conditions and cable temperature.

• For example, several high-power observations exceed 9,000 kW and are classified as High or Critical thermal-risk records.

• These findings indicate that current variation and power loading should be considered alongside absolute current values when assessing electrical reliability. Persistent or cyclic loading variations may contribute to repeated thermal expansion and contraction, potentially increasing long-term insulation and conductor stress.

• Research significance: Electrical reliability assessment should extend beyond voltage and current limits to include the dynamic behavior of loading conditions and their influence on thermal degradation.

5.4 Fog-Node Suitability and Selection

• The fog-node suitability assessment identifies four categories: Highly Suitable, Suitable, Moderately Suitable, and Unsuitable.

• The reported distribution indicates that approximately 32% of observations are classified as Highly Suitable, 18% as Suitable, 25% as Moderately Suitable, and 24% as Unsuitable.

• The findings suggest that fog-node selection is influenced by multiple operational dimensions, including computational capacity, network conditions, security status, and thermal headroom.

• Unsuitable nodes are associated with lower decision-confidence scores, elevated sensor and network uncertainty, authentication failures, disabled encryption, reduced trust scores, and inadequate thermal headroom.

• This observation is particularly important in industrial IoT environments because fog nodes serve as intermediate computational infrastructure between distributed sensors and higher level processing systems.

• Selecting a computationally capable node without considering its security and reliability characteristics may introduce additional vulnerabilities into the monitoring architecture.

• Similarly, selecting a secure node with insufficient computational resources or energy availability may compromise the timely delivery of critical thermal alerts.

• Research significance

• These findings support a multidimensional fog-node selection strategy in which computational capability, communication reliability, security trustworthiness, and operational availability are considered jointly.

• The suitability classification can therefore serve as an additional decision-support mechanism for reliable thermal monitoring.

5.5 Combined Risk Prioritization

Issue	Evidence	Count
Authentication failures	authentication_status = Failed	~100+ records
Encryption disabled	encryption_status = Disabled	~80+ records
Elevated failed logins	>3 failed attempts	~40 records
Intrusion alerts	intrusion_alert_count > 0	~150 records
Low trust score (<0.5)	e.g., REC_01063 (0.302), REC_02883 (0.305), REC_01150 (0.333)	~30 records
High packet loss (>10%)	REC_00776 (14.4%), REC_01712 (15.52%), REC_00374 (13.44%)	~25 records
High network latency (>40 ms)	REC_01850 (39.27), REC_00670 (37.69), REC_00374 (39.31)	~20 records
Low remaining energy (<20%)	REC_02784 (25.03), REC_01228 (16.99), REC_01025 (14.86), REC_00334 (10.29)	~15 records
High CPU utilization (>90%)	REC_01923 (93.81), REC_02884 (91.83), REC_03323 (94.41)	~10 records

Table 5. Combined Risk Prioritization

Table 5 summarizes the major security, communication, and computational reliability concerns identified in the monitored fog-enabled cable network.

The results reveal multiple categories of operational vulnerability, including authentication failures, disabled encryption, elevated failed login attempts, intrusion alerts, low trust scores, high packet loss, network latency, reduced remaining energy, and excessive CPU utilization.

Authentication failures and encryption-disabled conditions indicate potential weaknesses in access control and communication confidentiality. Similarly, observations involving repeated failed login attempts and intrusion alerts suggest the presence of security-related events that could compromise the reliability of the monitoring infrastructure.

Network-related abnormalities, particularly packet loss and elevated latency, may affect the transmission of time-sensitive sensor measurements and thermal alerts.

Computational constraints also emerge as an important concern. Fog nodes exhibiting CPU utilization above 90% or remaining energy below 20% may experience reduced processing availability, potentially affecting the timely execution of monitoring and decision making tasks.

An important finding is that these vulnerabilities represent different but interconnected dimensions of system reliability. Security weaknesses may compromise data integrity and trust, communication degradation may interrupt information delivery, and resource limitations may affect computational responsiveness.

The results demonstrate that thermal reliability cannot be evaluated independently of the supporting communication and computational infrastructure.

A cable monitoring architecture may accurately detect a thermal abnormality but still fail operationally if the selected fog node cannot securely and reliably transmit the associated alert.

Therefore, thermal risk management should incorporate security aware and resource aware fog node selection.

Highest	**Priority**	**Records**	**(Critical thermal + security/ network degradation)**
Record	Thermal Risk	Conductor °C	Security/Network Flag
REC_03405	Critical (100.0)	110.66	auth OK, but intrusion=1
REC_00831	Critical (99.56)	112.66	low trust (0.33), intrusion=3
REC_00691	Critical (93.91)	102.29	intrusion=2, low trust
REC_02883	Critical	105.44	Failed auth, disabled encryption, 5 failed logins, trust 0.305
REC_01723	Critical (85.07)	103.60	encryption disabled
REC_01075	Critical (92.26)	113.87	5 failed logins, low trust 0.533

Table 6. Highest-Priority Records with Combined Thermal and Security Risks

Table 6 identifies records exhibiting simultaneous thermal abnormalities and security related weaknesses.

The results demonstrate that several observations classified as Critical thermal risk also contain security concerns, including intrusion alerts, failed authentication, disabled encryption, repeated failed login attempts, and low trust scores.

For example, REC_03405 exhibits a thermal-risk score of 100.0 and a conductor temperature of 110.66 °C, together with an intrusion alert.

Similarly, REC_02883 exhibits a conductor temperature of 105.44 °C and a thermal-risk score within the Critical category, while also exhibiting failed authentication, disabled encryption, repeated failed logins, and a low trust score.

These observations indicate the presence of compounded operational risks, where physical infrastructure degradation coincides with weaknesses in the digital infrastructure responsible for monitoring and responding to those conditions.

The significance of this combination is greater than considering thermal or security vulnerabilities independently. A critical thermal event requires timely detection, secure communication, and reliable

computational processing. Weaknesses in any of these components may compromise the effectiveness of the overall response.

The identified records support the development of integrated risk prioritization mechanisms that evaluate physical and cyber related vulnerabilities simultaneously.

A suitable risk management framework should assign higher intervention priority to observations involving critical thermal conditions and compromised fog-node security.

The results also provide justification for excluding unsuitable or compromised fog nodes from critical thermal-alert pathways.

5.6 Recommended Actions

5.6.1 Thermal-risk mitigation

The proposed load shedding strategy for cables exceeding 95 °C aims to reduce excessive conductor heating. Investigation of high soil thermal resistivity and insufficient burial depth addresses the environmental and structural factors that may restrict heat dissipation.

Monitoring temperature rise rates above 2 °C/min provides an additional early-warning mechanism for identifying developing thermal abnormalities.

5.6.2 Electrical reliability improvement

Load redistribution is recommended for cables exhibiting current fluctuations above 15%. Such interventions can potentially reduce uneven loading and cyclic thermal stress.

Voltage regulation should also be investigated where low voltage coincides with high electrical loading.

5.6.3 Security and computational reliability

Fog nodes exhibiting failed authentication or disabled encryption should be excluded from critical monitoring operations until the identified weaknesses are addressed.

Nodes with repeated failed login attempts or low trust scores require security remediation. Similarly, computational nodes exhibiting insufficient remaining energy or excessive CPU utilization may require replacement, additional capacity, or workload redistribution.

These interventions demonstrate that reliable underground cable monitoring requires coordinated management of the physical cable infrastructure and the digital infrastructure supporting its monitoring and control.

5.7 Summary Metrics

Metric	**Value**
Records analyzed	4,355
Critical thermal records	~90 (~2.1%)
High thermal records	~1,050 (~24%)
Combined High+Critical	~26%
Max conductor temperature	114.33 °C (REC_02526)

Max thermal rise rate	4.589 °C/min (REC_01982)
Max temperature gradient	21.92 °C (REC_01951)
Failed authentication records	~100+
Encryption-disabled records	~80+
Unsuitable fog-node records	~1,050 (~24%)
Records with intrusion alerts	~150

Table 7. Summary of Thermal and Reliability Metrics

Table 7 consolidates the principal thermal and reliability indicators identified during the analysis.

The maximum conductor temperature of 114.33 °C represents one of the most important thermal abnormalities in the monitored network. Similarly, the maximum thermal rise rate of 4.589 °C/min and maximum temperature gradient of 21.92 °C indicate the presence of localized thermal conditions requiring further investigation.

The reported approximately 90 Critical thermal records and 1,050 High thermal records collectively demonstrate that a substantial proportion of the analyzed observations exhibit elevated thermal stress.

The security related metrics further indicate that authentication failures, disabled encryption, and intrusion alerts are present within the monitored system.

The approximately 1,050 Unsuitable fog-node observations also indicate that a significant proportion of the evaluated records may not satisfy the operational requirements for reliable monitoring.

Taken together, these findings demonstrate that the reliability of the underground cable monitoring environment depends on the interaction between electrical loading, thermal conditions, communication performance, security configuration, and fog-node resource availability.

Table 7 provides an integrated overview of the system's principal vulnerabilities and establishes the quantitative basis for developing a risk-aware monitoring and maintenance framework.

However, the table should be interpreted as a summary of descriptive indicators rather than as evidence of experimentally established causal relationships.

5.8 Thermal-Risk Distribution Across Cable Zones

5.81 Zone-Level Summary

Cable Zone	Records	Mean Thermal Risk	Mean Condu -ctor °C	Critical	High	Moderate	Low
Industrial	~1,530	~63.5	~68.2	~55	~520	~640	~315

Urban	~1,560	~58.9	~65.1	~28	~330	~735	~465
Residential	~880	~52.4	~61.3	~6	~140	~430	~305
Suburban	~385	~50.1	~59.8	~2	~55	~200	~128

Table 8. Thermal-Risk Distribution Across Cable Zones

5.8.2 Spatial and Cable-Zone-Based Thermal-Risk Analysis

Table 8 presents a comparative assessment of thermal-risk conditions across Industrial, Urban, Residential, and Suburban cable zones.

The Industrial zone exhibits the highest mean thermal-risk score of approximately 63.5 and the highest mean conductor temperature of approximately 68.2 °C.

The Urban zone follows with a mean thermal-risk score of approximately 58.9 and a mean conductor temperature of approximately 65.1 °C.

In contrast, Residential and Suburban zones demonstrate comparatively lower mean thermal-risk scores and conductor temperatures.

The Industrial zone also contains the largest concentration of Critical observations, accounting for approximately 61% of the reported Critical records. The Urban zone contributes approximately 31%.

This distribution indicates that thermal-risk exposure is spatially heterogeneous and that industrial and urban operating environments are associated with a greater concentration of adverse thermal conditions.

The differences may reflect variations in electrical demand, cable utilization, surrounding soil conditions, infrastructure characteristics, and operating environments. However, the present descriptive analysis does not independently establish the contribution of each factor.

The findings demonstrate that uniform maintenance policies may not be equally effective across all geographical zones.

Industrial and Urban zones should receive greater attention during thermal inspection, load management, and preventive maintenance planning.

Zone-specific monitoring thresholds and risk-prioritization mechanisms may improve maintenance efficiency.

5.83 Zone Risk Proportions (%)

Zone	% Critical	% High	% Moderate	% Low
Industrial	3.6	34.0	41.8	20.6
Urban	1.8	21.2	47.1	29.8
Residential	0.7	15.9	48.9	34.7
Suburban	0.5	14.3	51.9	33.2

Table 9. Zone-Wise Thermal-Risk Proportions

Table 9 presents the percentage distribution of thermal risk categories within each cable zone.

The Industrial zone exhibits the highest Critical risk proportion of approximately 3.6%, followed by the Urban zone at 1.8%. Residential and Suburban zones demonstrate considerably lower Critical risk proportions of approximately 0.7% and 0.5%, respectively.

A similar pattern is observed in the High-risk category, where Industrial and Urban zones demonstrate higher proportions than Residential and Suburban zones.

The results indicate that the elevated thermal-risk burden in Industrial and Urban environments is not simply attributable to the number of observations collected from these zones. The within-zone percentages also demonstrate greater relative exposure to Critical thermal conditions.

This distinction is important because absolute counts and relative risk proportions provide different perspectives on infrastructure vulnerability.

For example, a zone with a larger number of observations may contain more critical records simply because it has a larger monitoring population. The percentage distribution provides additional information about the relative risk within each zone.

The findings support spatially differentiated thermal risk management, with Industrial zones receiving the highest preventive maintenance priority, followed by Urban zones.

The results also justify further investigation of geographical and environmental variables through multivariable statistical models.

5.84 Thermal Hotspot Identification

5.841 Top Thermal Hotspots (by Conductor Temperature)

Rank	Record	Cable	Zone	Cond -uctor °C	Load A	Thermal Risk	Level
1	REC_02526	CABLE_02	Urban	114.33	528.0	92.41	Critical
2	REC_01075	CABLE_04	Residential	113.87	557.1	92.26	Critical
3	REC_00831	CABLE_04	Industrial	112.66	625.3	99.56	Critical
4	REC_01573	CABLE_18	Industrial	110.69	622.3	88.34	Critical
5	REC_03405	CABLE_18	Industrial	110.66	615.5	100.0	Critical
6	REC_00842	CABLE_02	Urban	108.79	547.7	93.23	Critical
7	REC_03024	CABLE_19	Urban	107.23	547.9	90.57	Critical
8	REC_02821	CABLE_17	Urban	107.18	535.7	90.89	Critical
9	REC_02186	CABLE_06	Suburban	99.59	582.9	86.65	Critical

10	REC_01777	CABLE_17	Industrial	101.58	509.9	88.54	Critical

Table 10. Top Thermal Hotspots by Conductor Temperature

6. Thermal Hotspot Identification and Cable-Level Analysis

Table 10 ranks the ten highest temperature observations according to their conductor temperatures and provides their corresponding cable identifiers, operating zones, load currents, thermal risk scores, and risk classifications.

The maximum conductor temperature of 114.33 °C is observed in REC_02526, located in the Urban zone and associated with CABLE_02.

The second highest temperature is 113.87 °C in REC_01075, associated with CABLE_04 in the Residential zone.

Several additional observations in Industrial and Urban zones demonstrate conductor temperatures above 105 °C.

The results reveal that the highest thermal hotspots are distributed across multiple geographical zones rather than being confined exclusively to Industrial environments.

The simultaneous presence of elevated load current and Critical thermal-risk classification indicates that excessive electrical loading is an important characteristic of the identified hotspots.

An important observation is that the top hotspot records are associated with different cable identifiers and operating environments. This suggests that thermal degradation should be investigated at both individual feeder and geographical zone levels.

Table 10 provides a practical ranking mechanism for identifying the most thermally stressed cable sections.

It supports targeted inspection, prioritized load redistribution, and the development of hotspot based maintenance schedules.

Hotspot Clustering by Cable

Cable ID	**Critical Records**	**Max Conductor °C**	**Dominant Zone**
CABLE_02	~12	114.33	Urban/Suburban
CABLE_04	~11	113.87	Industrial/Residential
CABLE_18	~10	110.69	Industrial
CABLE_12	~9	103.60	Urban/Industrial
CABLE_17	~8	107.18	Urban/Industrial
CABLE_06	~7	99.59	Suburban/Industrial
CABLE_19	~6	107.23	Urban/Industrial

Table 11. Hotspot Clustering by Cable

Table 11 summarizes the concentration of Critical thermal observations across individual cable identifiers.

The results suggest that CABLE_02, CABLE_04, and CABLE_18 are among the most critical feeders, with reported maximum conductor temperatures exceeding 110 °C.

The concentration of multiple Critical observations within selected cable identifiers indicates that thermal abnormalities may be associated with particular feeders rather than being uniformly distributed across the network.

This finding has important implications for maintenance planning. A cable exhibiting repeated Critical observations may require more comprehensive investigation than a cable associated with an isolated thermal event.

Potential contributing factors include sustained electrical loading, localized installation conditions, soil thermal resistivity, insufficient heat dissipation, and variations in cable operating environments.

However, repeated Critical observations alone do not establish the underlying physical cause. Additional longitudinal measurements and cable-specific engineering inspections would be necessary to confirm persistent degradation.

The cable-level concentration analysis provides a basis for feeder-specific maintenance prioritization.

Rather than allocating inspection resources equally across all cables, utilities can prioritize feeders exhibiting repeated high-risk observations and extreme conductor temperatures.

Gradient & Rise-Rate Hotspots

Type	Record	Value	Zone
Max gradient	REC_01951	21.92 °C	Industrial
Max gradient	REC_03849	19.74 °C	Suburban
Max gradient	REC_00635	19.48 °C	Urban
Max rise rate	REC_01982	4.589 °C/min	Suburban
Max rise rate	REC_03162	4.011 °C/min	Urban
Max rise rate	REC_01582	3.384 °C/min	Industrial
Max rise rate	REC_01636	3.100 °C/min	Suburban
Max rise rate	REC_01767	3.298 °C/min	Industrial

Table 12. Thermal Gradient and Rise-Rate Hotspots

Note: High gradient + high rise-rate combos (e.g., REC_01636, REC_01637, REC_01982) indicate fast-developing localized hotspots even when absolute temperatures are moderate early warning signals.

Table 12 identifies records exhibiting the highest temperature gradients and thermal rise rates across different geographical zones.

The maximum gradient of 21.92 °C occurs in REC_01951 in the Industrial zone, while REC_03849 in the Suburban zone and REC_00635 in the Urban zone also exhibit elevated temperature gradients.

Regarding thermal rise rate, REC_01982 exhibits the highest value of 4.589 °C/min, followed by REC_03162 at 4.011 °C/min.

These findings indicate that thermal abnormalities can emerge through different mechanisms.

A high temperature gradient may indicate localized heat accumulation or inadequate heat transfer, whereas a high rise rate indicates rapid thermal escalation.

The occurrence of these abnormalities across Industrial, Urban, and Suburban environments demonstrates that early thermal-warning indicators are relevant to all cable zones.

Importantly, dynamic indicators may identify developing thermal problems before absolute temperature thresholds are exceeded.

Research significance

The results support the inclusion of temperature gradient and rise rate in predictive maintenance systems.

An integrated anomaly-detection mechanism combining temperature magnitude, gradient, and temporal rate of change could provide earlier warnings than temperature-threshold monitoring alone.

Thermal-Risk Classification

Classification Scheme (as encoded in dataset)
The dataset classifies thermal_risk_level using thermal_risk_score thresholds:

Level	**Score Range**	**Conductor Temp Range**	**Operational Meaning**
Low	< 40	< 50 °C	Normal operation; no action
Moderate	40–60	50–70 °C	Monitor; schedule inspection
High	60–80	70–95 °C	Investigate; reduce load if sustained
Critical	> 80	> 95 °C	Immediate action; load shedding

Table 13. Thermal-Risk Classification Scheme

7. Thermal-Risk Classification Analysis

Table 13 defines the thermal risk classification scheme according to the thermal-risk score and corresponding conductor temperature ranges.

The classification includes four operational categories: Low, Moderate, High, and Critical.

The Low category represents normal operating conditions, while Moderate conditions indicate the need for monitoring and scheduled inspection.

High-risk conditions indicate elevated thermal stress requiring investigation and potential load reduction. Critical conditions represent severe thermal abnormalities requiring immediate intervention.

The classification framework provides an operational interpretation of the thermal-risk score by translating numerical values into actionable maintenance categories.

The inclusion of both thermal-risk scores and conductor temperatures is particularly useful because it enables the monitoring system to communicate the severity of a thermal condition in terms that are meaningful to engineering operators.

The classification framework establishes a foundation for rule-based thermal monitoring and risk-informed maintenance decisions.

However, the threshold definitions should be made mutually exclusive and should be validated against the applicable cable manufacturer specifications and relevant engineering standards before operational deployment.

Level	Count	Share
Low	~1,160	26.6%
Moderate	~2,050	47.1%
High	~1,050	24.1%
Critical	~90	2.1%

Table 14. Distribution of Thermal-Risk Classification

Table 14 presents the numerical distribution and percentage share of each thermal risk category.

Moderate risk observations account for approximately 47.1%, representing the largest proportion of the dataset.

Low risk observations constitute approximately 26.6%, whereas High risk observations account for approximately 24.1%. Critical risk observations represent approximately 2.1%.

The results indicate that the majority of observations are classified as Low or Moderate risk. Nevertheless, approximately one-quarter of the observations fall within the High or Critical categories.

This distribution suggests that although widespread catastrophic thermal conditions are not evident across all observations, elevated thermal stress represents a significant operational concern.

The relatively large Moderate category also indicates that a substantial proportion of observations may require continued monitoring to identify transitions into higher risk conditions.

The findings support a tiered maintenance strategy:

- Low-risk observations can be managed through routine monitoring.
- Moderate-risk observations require periodic inspection.
- High-risk observations require engineering investigation and load-management consideration.

• Critical-risk observations require immediate operational intervention.

The classification therefore provides a practical mechanism for translating analytical findings into maintenance priorities.

Thermal-Risk Classification Drivers

Additional Discussion: Feature Importance and Classification Drivers

The document identifies conductor temperature as the strongest observed discriminator of thermal-risk classification, with a reported correlation of approximately 0.95 with the thermal risk score.

Load current exhibits a correlation of approximately 0.85, followed by power load at approximately 0.80 and load factor at approximately 0.75.

These findings suggest that the thermal risk score is strongly associated with electrical operating conditions and the resulting conductor temperature.

Thermal rise rate, soil thermal resistivity, temperature gradient, and burial depth provide additional information regarding the development and amplification of thermal stress.

The results reveal two broad categories of thermal risk drivers.

Electrical operating drivers: Conductor temperature, load current, power load, and load factor.

Environmental and structural drivers: Soil thermal resistivity, burial depth, ambient temperature, and temperature gradient.

The distinction is important because electrical loading can potentially be managed through operational interventions, whereas environmental and structural factors may require engineering modifications.

The reported correlation between conductor temperature and thermal risk score is particularly high. However, if conductor temperature is directly incorporated into the formula used to calculate the thermal risk score, this relationship would partly reflect mathematical construction rather than an independently discovered predictive relationship.

Consequently, the reported feature importance should be interpreted as an association-based ranking rather than definitive evidence of independent predictive contribution.

Thermal-Risk Sensitivity Analysis

Method
Sensitivity was assessed by binned mean thermal risk and correlation coefficients against each thermal/electrical driver.

Sensitivity to Load Current

Sensitivity Analysis of Thermal-Risk Drivers

Table 15. Sensitivity of Thermal Risk to Load Current

Table 15 examines the variation in thermal-risk scores, conductor temperatures, and High/Critical risk proportions across different load-current intervals.

Current Bin (A)	Mean Thermal Risk	Mean Condu -ctor °C	% High +Critical
< 200	~35	~45 °C	~5%
200–300	~48	~55 °C	~12%
300–400	~58	~63 °C	~28%
400–500	~68	~72 °C	~48%
500–625	~78	~85 °C	~70%

Table 15. Sensitivity of Thermal Risk to Load Current

The results demonstrate a progressive increase in thermal risk as electrical loading increases.

For currents below 200 A, the mean thermal-risk score is approximately 35, with a mean conductor temperature of approximately 45 °C and only 5% of observations classified as High or Critical.

As current increases to the 400–500 A interval, the mean thermal-risk score increases to approximately 68, while the proportion of High/Critical observations rises to approximately 48%.

The highest current interval, between 500 and 625 A, exhibits a mean thermal-risk score of approximately 78 and a mean conductor temperature of approximately 85 °C. Approximately 70% of observations in this interval fall within the High or Critical categories.

These findings demonstrate a strong positive relationship between electrical loading and thermal stress.

The increasing proportion of High/Critical observations at elevated currents also suggests that thermal risk may increase more rapidly at higher loading conditions.

Load current emerges as a major operational parameter for thermal-risk management.

The findings support the use of current dependent alert thresholds, particularly when operating current exceeds approximately 450 A.

However, the exact threshold should be validated using observation-level data and appropriate statistical uncertainty estimates.

Sensitivity to Load Factor

Table 16 evaluates the relationship between load factor and thermal-risk scores.

The results indicate a progressive increase in mean thermal risk as the load factor increases.

Observations with load factors below 30% exhibit a mean thermal-risk score of approximately 38, whereas observations exceeding 80% exhibit a mean score of approximately 80.

The proportion of Critical observations also increases from approximately 0% in the lowest loading category

Load Factor Bin (%)	Mean Thermal Risk	% Critical
< 30	~38	0%
30–50	~52	~1%
50–65	~62	~3%
65–80	~72	~7%
> 80	~80	~15%

Table 16. Sensitivity of Thermal Risk to Load Factor

to approximately 15% in the highest category.

The increase becomes particularly important beyond the 65% load-factor interval, where mean thermal-risk scores rise to approximately 72.

This pattern indicates that the utilization level of the cable system is an important indicator of thermal exposure.

The relationship also demonstrates why load factor should be considered alongside instantaneous current measurements. Two cable sections carrying different absolute currents may experience different thermal conditions depending on their rated capacity and utilization.

The findings support load-factor-based thermal alert mechanisms.

An operating load factor above approximately 65% may be considered a candidate threshold for enhanced monitoring, although it should not be treated as a universal safety limit without engineering validation.

Sensitivity to Soil Thermal Resistivity

Resistivity (K·m/W)	Mean Conductor °C	Mean Thermal Risk
< 1.2	~60 °C	~52
1.2–1.6	~64 °C	~56
1.6–2.0	~68 °C	~60
2.0–2.4	~72 °C	~66
> 2.4	~76 °C	~70

Table 17. Sensitivity of Thermal Risk to Soil Thermal Resistivity

Table 17 evaluates the influence of soil thermal resistivity on conductor temperature and thermal-risk scores.

The results indicate that increasing soil thermal resistivity is associated with progressively higher conductor temperatures and thermal-risk scores.

At resistivity values below 1.2 K·m/W, the mean conductor temperature is approximately 60 °C and the mean thermal-risk score is approximately 52.

At resistivity values exceeding 2.4 K·m/W, the mean conductor temperature increases to approximately 76 °C, while the mean thermal-risk score reaches approximately 70.

This pattern is consistent with the thermal behavior of buried electrical cables. Higher soil thermal resistivity restricts heat transfer from the cable to the surrounding environment, potentially increasing conductor temperature under otherwise comparable loading conditions.

The findings indicate that soil characteristics can amplify thermal stress, particularly when electrical loading is already elevated.

The results highlight the importance of incorporating soil thermal properties into underground cable monitoring and maintenance strategies.

Sections exhibiting high soil thermal resistivity should receive particular attention during engineering inspections, especially when combined with elevated load current and shallow burial depth.

The reported temperature differences represent observational associations across resistivity groups; establishing the effect at constant loading would require controlled or adjusted statistical analysis.

Sensitivity to Burial Depth

Depth (m)	Mean Conduc - tor °C	Mean Thermal Risk
< 0.8	~74 °C	~68
0.8–1.2	~67 °C	~61
1.2–1.6	~64 °C	~58
1.6–2.0	~62 °C	~55
> 2.0	~60 °C	~53

Table 18. Sensitivity of Thermal Risk to Cable Burial Depth

Table 18 examines the relationship between cable burial depth, conductor temperature, and thermal-risk scores.

The results indicate that shallower cable installations are associated with higher thermal-risk scores and conductor temperatures.

Observations with burial depths below 0.8 m exhibit a mean conductor temperature of approximately 74 °C

and a thermal-risk score of approximately 68.

In contrast, observations with burial depths exceeding 2.0 m exhibit a mean conductor temperature of approximately 60 °C and a thermal-risk score of approximately 53.

This pattern suggests that burial depth is an important structural and environmental factor influencing cable thermal conditions.

Shallow installations may experience greater exposure to surface temperature fluctuations and potentially unfavorable heat transfer conditions. However, the precise thermal effect also depends on soil properties, installation configuration, surrounding infrastructure, and local environmental conditions.

The findings suggest that cable sections with shallow burial depths should be included in targeted inspection and thermal risk assessment.

Engineering interventions involving installation depth and surrounding backfill conditions may provide opportunities for improving thermal performance, subject to applicable installation standards and site constraints.

Sensitivity to Ambient / Soil Temperature

Ambient Temp Bin (°C)	**Mean Condu -ctor °C**	**Mean Ther -mal Risk**
< 20	~58 °C	~51
20–30	~63 °C	~56
30–40	~67 °C	~60
> 40	~72 °C	~64

Table 19. Sensitivity of Thermal Risk to Ambient Temperature

Table 19 evaluates the relationship between ambient temperature and cable thermal behavior.

The results indicate a progressive increase in mean conductor temperature as ambient temperature increases. For ambient temperatures below 20 °C, the mean conductor temperature is approximately 58 °C and the thermal-risk score is approximately 51.

At ambient temperatures exceeding 40 °C, the mean conductor temperature increases to approximately 72 °C, while the thermal-risk score reaches approximately 64.

This observation demonstrates that ambient temperature contributes to the overall thermal operating environment of underground cable systems.

Higher surrounding temperatures may reduce the temperature difference available for heat dissipation, thereby contributing to elevated conductor temperatures.

The findings also suggest that environmental conditions can amplify the effect of electrical loading, potentially producing more severe thermal conditions during periods of high ambient temperature.

Ambient temperature should be incorporated into adaptive thermal monitoring strategies.

Seasonal and environmental adjustments may improve the interpretation of conductor temperature measurements and enable more context sensitive thermal risk assessment.

The reported sensitivity should be interpreted as an observational relationship rather than an independently established temperature coefficient.

Sensitivity to Current Fluctuation

Fluctuation Bin (%)	**Mean Thermal Risk**	**Mean Rise Rate**
< 2	~57	~0.45 °C/min
2–5	~59	~0.55 °C/min
5–10	~61	~0.75 °C/min
> 10	~64	~1.10 °C/min

Table 20. Sensitivity of Thermal Risk to Current Fluctuation

Table 20 investigates the relationship between current fluctuation and thermal-risk indicators.

The results demonstrate that the mean thermal-risk score increases from approximately 57 for current fluctuations below 2% to approximately 64 for fluctuations exceeding 10%.

More importantly, the mean thermal rise rate increases from approximately 0.45 °C/min to approximately 1.10 °C/min across these categories.

This represents an approximately 2.4-fold increase in mean thermal rise rate, indicating a substantial association between current instability and dynamic thermal behavior.

The findings suggest that electrical instability may be associated with faster temperature escalation, even when the absolute current does not reach the highest observed levels.

Such behavior is particularly important for long-term cable reliability because repeated loading fluctuations may contribute to thermal cycling and associated material stress.

Research Significance

The results demonstrate that current fluctuation should be treated as a complementary early-warning indicator rather than relying exclusively on average or instantaneous current.

Monitoring the magnitude and frequency of current variations may improve the identification of cables experiencing unstable operating conditions.

Tornado-Style Ranking of Drivers

Rank	Driver	Approx. Impact on Thermal Risk	Controllability
1	Load current	+10–12 pts / +100 A	Operationally controllable (load management)
2	Load factor	+15 pts above 65%	threshold Controllable
3	Soil thermal resistivity	+20 pts across 1.0→ 2.5 range	Engineering (backfill)
4	Burial depth	+10 pts below 1.0 m	Engineering
5	Ambient temperature	+13 pts across 20–40 °C	Environmental (seasonal)
6	Current fluctuation	+7 pts and 2.5× rise rate	Load balancing
7	Temperature gradient	Diagnostic/early-warning	Monitoring

Table 21. Tornado-Style Ranking of Thermal-Risk Drivers

Table 21 ranks the major thermal-risk drivers according to their approximate reported influence and operational controllability.

Load current is identified as the most influential operational parameter, with an estimated increase of 10–12 thermal-risk points for every 100 A increment.

Load factor is ranked second, with an approximately 15-point increase above the 65% threshold.

Soil thermal resistivity is ranked third, demonstrating an approximate 20-point increase across the reported resistivity range.

Burial depth, ambient temperature, and current fluctuation are identified as additional contributors to thermal-risk variation.

Temperature gradient is included as a diagnostic indicator rather than a directly quantified risk contribution. The ranking reveals an important distinction between operational and environmental drivers.

Electrical loading variables are comparatively controllable through load redistribution and operating policies. Soil thermal resistivity and burial depth require engineering interventions, while ambient temperature represents an environmental influence that cannot be directly controlled.

The results therefore suggest that thermal-risk mitigation should prioritize factors according to both their reported influence and practical controllability.

Table 21 provides a useful decision-support structure for translating statistical findings into operational and engineering interventions.

It suggests that immediate load-management measures may offer a practical first response, while soil and installation improvements may provide longer-term thermal benefits.

However, the reported impacts should not be interpreted as standardized causal effects because the document

does not specify a common reference model, confidence intervals, or adjusted effect-estimation procedure.

Threshold Analysis (actionable)

Threshold	**Meaning**
Load current > 450 A AND load factor > 65%	High probability of High/Critical risk
Soil resistivity > 2.0 K·m/W AND depth < 1.0 m	Compounded thermal bottleneck
Rise rate > 2 °C/min	Imminent escalation risk alert
Gradient > 15 °C	Localized dissipation failure inspect

Actionable Thermal-Risk Thresholds

The threshold analysis identifies four combinations of operational conditions that can support early-warning and maintenance decisions.

1. High electrical loading
The combination of load current above 450 A and load factor above 65% is associated with a higher probability of High or Critical thermal conditions.

This combination is important because it captures both the absolute electrical loading and the relative utilization of the cable.

2. Combined environmental constraints
Soil thermal resistivity above 2.0 K·m/W, combined with burial depth below 1.0 m, represents a potentially unfavorable thermal environment.

These conditions may restrict heat dissipation and increase the temperature response under elevated electrical loading.

3. Rapid thermal escalation
A thermal rise rate above 2 °C/min is identified as an early-warning indicator of rapid thermal deterioration.

Such conditions warrant immediate investigation because the rate of temperature increase may provide an indication of developing abnormalities before critical absolute temperatures are reached.

4. Elevated temperature gradient
A temperature gradient exceeding 15 °C is identified as a potential indication of localized heat accumulation or inadequate thermal dissipation.

These records should be investigated to identify possible localized installation or thermal-resistance problems.
Overall interpretation

The threshold analysis provides a basis for developing a rule-based early-warning framework.

An effective implementation should combine multiple indicators rather than rely on a single variable. For example, a cable exhibiting high current, elevated soil thermal resistivity, shallow burial depth, and a rapidly increasing temperature should receive a higher monitoring priority than a cable exhibiting only one isolated abnormality.

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Integrated Discussion of the Research Findings

The following section synthesizes the principal results into a coherent scientific discussion suitable for a high-level journal manuscript.

11.1 Interaction Between Electrical Loading and Thermal Degradation
The findings demonstrate that electrical loading represents a major factor associated with thermal-risk variation in underground cable systems.

The observed increase in thermal-risk scores across current and load-factor categories indicates that higher electrical utilization is associated with elevated conductor temperatures.

The relationship is particularly evident in the highest current interval, where mean conductor temperature reaches approximately 85 °C and approximately 70% of observations fall within the High or Critical categories.

This pattern indicates that electrical loading should be incorporated as a central component of intelligent thermal-risk assessment.

However, the relationship is not exclusively determined by current. Environmental and structural factors influence the extent to which electrical energy is dissipated into the surrounding environment.

Consequently, thermal-risk assessment should consider the interaction between electrical loading and heat-transfer conditions rather than relying on isolated current thresholds.

Environmental and Structural Influences on Cable Thermal Performance
The soil thermal resistivity and burial-depth analyses demonstrate that installation and environmental conditions are important factors associated with cable thermal behavior.

Higher soil thermal resistivity is associated with higher conductor temperatures, while shallow burial conditions are associated with increased thermal-risk scores.

Ambient temperature also exhibits a positive association with conductor temperature.

These results suggest that underground cable thermal performance depends on the combined influence of operating conditions and the surrounding thermal environment.

From an engineering perspective, these findings highlight the importance of considering soil properties and installation conditions when evaluating the thermal capacity and reliability of underground electrical infrastructure.

The results further suggest that environmental and structural information should be integrated into predictive thermal monitoring systems.

Spatial Heterogeneity and Geographical Risk Concentration
The cable zone analysis reveals substantial differences in thermal risk exposure across geographical environments.

Industrial zones exhibit the highest mean thermal risk score and the highest proportion of Critical observations. Urban zones represent the second major concentration of elevated thermal risk.

The Industrial and Urban zones together account for approximately 92% of the reported Critical records.

This finding suggests that thermal-risk exposure is spatially heterogeneous and that geographical context should be incorporated into maintenance planning.

The relatively lower risk proportions in Residential and Suburban zones do not imply the absence of localized thermal abnormalities. The identification of high temperature hotspots in these zones demonstrates that individual cable segments may still experience severe thermal stress.

Therefore, an effective monitoring framework should combine geographical prioritization with individual cable-level hotspot identification.

Importance of Dynamic Thermal Indicators for Early Warning
The analysis of thermal gradients and rise rates provides evidence that thermal-risk assessment should extend beyond absolute temperature measurements.

While conductor temperature describes the existing thermal state, temperature rise rate indicates the speed of thermal escalation.

Similarly, temperature gradient provides information regarding differences in thermal conditions across the cable structure.

These indicators may provide complementary information for identifying emerging thermal abnormalities.

The observation of rise rates exceeding 4 °C/min demonstrates that some records exhibit rapid temperature changes that could be overlooked by conventional threshold-based monitoring if only periodic temperature measurements are considered.

Integrating dynamic indicators into intelligent monitoring systems could therefore improve early identification of potentially hazardous thermal conditions.

Coupling of Physical Infrastructure Reliability and Cybersecurity
One of the important contributions of the analysis is its consideration of thermal reliability alongside fog-node security and computational suitability.

The findings demonstrate that some thermally critical observations also exhibit security related abnormalities, including authentication failures, disabled encryption, intrusion alerts, and low trust scores.

This highlights a potential weakness in conventional monitoring architectures that evaluate physical infrastructure and digital infrastructure independently.

In an IoT-enabled monitoring environment, the effectiveness of thermal-risk detection depends not only on the accuracy of sensors but also on secure communication, reliable fog-node processing, and the availability of computational resources.

Consequently, thermal-critical observations should be associated with fog nodes that satisfy appropriate security and resource-availability requirements.

The combined assessment of physical and digital reliability provides a foundation for developing trustworthy and resilient industrial IoT monitoring systems.

Sensitivity-Based Operational Decision-Making
The sensitivity analysis demonstrates that different thermal-risk drivers exhibit different levels of operational influence and controllability.

Load current and load factor emerge as important operational indicators, whereas soil thermal resistivity and burial depth represent environmental and engineering related influences.
Current fluctuation and thermal rise rate provide additional information about the dynamic behavior of the system.

These findings suggest that maintenance planning should distinguish between immediate operational interventions and longer term engineering improvements.

Load redistribution and current stabilization may provide relatively immediate responses to excessive thermal loading. In contrast, soil improvement and installation modifications may require more extensive engineering interventions.

The resulting sensitivity-based prioritization can support the allocation of maintenance resources according to the severity, controllability, and potential consequences of identified abnormalities.

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Overall Research Implications
The findings have several important implications for the design and implementation of intelligent underground cable monitoring systems.

First, thermal-risk monitoring should be multidimensional. Conductor temperature alone may not provide sufficient information to characterize developing thermal abnormalities. Electrical loading, thermal gradient, temperature rise rate, soil thermal resistivity, burial depth, and ambient temperature should be evaluated jointly.

Second, geographical risk differentiation is important. Industrial and Urban cable zones exhibit greater concentrations of thermal abnormalities and should receive higher inspection priority.

Third, early warning mechanisms should incorporate dynamic indicators. Temperature rise rate and temperature gradient may provide information about developing thermal problems before absolute temperature thresholds are reached.

Fourth, fog-node selection should be reliability aware. Nodes with poor trust scores, failed authentication, disabled encryption, or inadequate computational resources should not be assigned to critical monitoring operations.

Fifth, maintenance strategies should be sensitivity-driven. Operationally controllable factors, particularly current and load factor, should be prioritized for immediate intervention, while environmental and structural factors should be addressed through longer-term engineering measures.

Collectively, these implications support the development of an integrated monitoring architecture that connects thermal sensing, electrical reliability assessment, environmental analysis, cybersecurity, and fog-node selection.

13. Conclusion

The present investigation provides an integrated assessment of thermal-risk conditions, electrical reliability, environmental influences, and fog node suitability in IoT-enabled underground cable monitoring environments. The findings reveal substantial variability in thermal operating conditions, with approximately 26% of the reported observations classified within the High and Critical thermal-risk categories. Conductor temperature, load current, and load factor emerge as the principal indicators associated with thermal-risk variation, while soil thermal resistivity, burial depth, ambient temperature, and current fluctuation provide additional

information regarding thermal stress and its development.

The geographical analysis demonstrates that Industrial and Urban zones exhibit comparatively higher thermal-risk exposure, accounting for approximately 92% of the reported Critical observations. The identification of individual cable hotspots further highlights the nonuniform distribution of thermal abnormalities across the monitored infrastructure. In addition, the analysis of temperature gradients and thermal rise rates demonstrates the importance of dynamic thermal indicators for identifying potentially developing abnormalities before critical temperature thresholds are reached.

An important finding is the coexistence of thermal abnormalities and digital infrastructure vulnerabilities. Authentication failures, disabled encryption, intrusion alerts, low trust scores, communication degradation, and limited fog node resources represent additional concerns that may compromise the reliability of monitoring and response operations. These findings emphasize that trustworthy underground cable monitoring requires coordinated consideration of physical infrastructure conditions and the reliability of the supporting IoT and fog computing architecture.

The sensitivity assessment further indicates that electrical loading represents an important operational risk driver, whereas soil thermal resistivity and burial depth constitute significant environmental and structural influences. These relationships provide a basis for developing adaptive monitoring thresholds, targeted maintenance strategies, and engineering interventions. Overall, the findings support the development of an integrated, thermal aware, security conscious, and resource efficient monitoring framework capable of improving operational reliability and supporting proactive maintenance in underground electrical distribution infrastructure.

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