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Review

Multi-Sensor Fusion and Data Analytics for Power Cable Condition Monitoring and Predictive Maintenance

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Abstract: Power cables are critical infrastructure for electric power transmission, and their reliability directly affects supply security. The expansion of cable deployment has increased the difficulty of condition monitoring, while more complex operating environments intensify the challenge of early identification of insulation aging and latent defects. This paper systematically analyzes power-cable condition-monitoring and intelligent operation-and-maintenance (O&M) technologies, comparing electrical monitoring methods—such as partial discharge, sheath current, and dielectric loss—with non-electrical parameter monitoring of temperature, humidity, and strain, thereby clarifying the performance characteristics and applicable scopes of each approach. We also examine O&M methods including intelligent inspection, supervisory control and data acquisition (SCADA) system integration, and data-fusion algorithms. The results show that establishing a multi-parameter collaborative sensing framework, platform-based integration, and an artificial intelligence (AI)-driven O&M system enables accurate condition assessment and predictive maintenance of cables. This study provides a technical pathway for transitioning power-cable O&M from periodic maintenance to predictive maintenance and offers practical value for enhancing grid reliability.

Keywords: power-cable maintenance; condition assessment; aging diagnosis partial; discharge

1. Introduction

Power cables are the key carriers for transmission and distribution in modern power systems, and their operating condition is directly tied to the safety and continuity of supply. As urban undergrounding, cross-regional interconnection, and high-load operation intensify, the coupled multi-stress exposures in long-term service—thermal, electrical, moisture, chemical, and mechanical—make insulation aging and latent-defect identification increasingly difficult, posing challenges for early fault localization and rapid restoration. Meanwhile, industry statistics indicate that underground cable systems still exhibit a non-negligible annual failure-rate band (about 0.7–2 incidents per 100 miles), with significant implications for system operation and asset cost [1]. Against this backdrop, building a data-centric framework for cable condition sensing and health management has become an imperative to enhance grid resilience and reliability.

In existing studies, two main categories of limitations are commonly observed. On the monitoring side, electrical methods are susceptible to electromagnetic interference and coupling conditions, making partial discharge (PD) noise discrimination difficult [2]; very high frequency (VHF)/ultra high frequency (UHF) approaches are constrained by metallic sheaths, propagation attenuation, and deployment sensitivity [3]; acoustic emission is limited by inspection distance and environmental noise [4]. For environmental-parameter monitoring, conventional humidity sensors exhibit weak anti-interference capability, while fiber-optic sensing—despite immunity to electromagnetic interference and long-reach advantages—faces durability and cross-modal consistency issues, and cost still limits long-term online coverage [5]. On the O&M side, intelligent inspection and basic SCADA remain insufficient in fault localization, predictive analytics, and safety/security [6]; workflows and protocols for condition assessment are not unified, data governance and cross-system consistency are inadequate, and factors such as durability and cost continue to constrain large-scale adoption. Therefore, to overcome the existing bottlenecks in cable condition sensing and O&M, advances are urgently needed in both the reliability of monitoring technologies and the intelligence of O&M decision-making.

We review key technologies for power-cable condition monitoring and O&M along two themes: optimizing monitoring methods and improving O&M practices. On the monitoring side, we compare partial discharge, sheath current, dielectric loss, temperature, and other environmental measurements, focusing on accuracy, interference tolerance, and coverage. On the O&M side, we examine intelligent inspection, SCADA integration, data fusion, and algorithm design to shift from reactive to predictive maintenance and improve efficiency. We end by summarizing the main gaps and practical next steps toward more reliable, scalable cable O&M.

The unique value of this review lies in its proposal of a unified taxonomy and side-by-side comparison framework that integrates both electrical monitoring—such as partial discharge, dielectric loss, and sheath current—and non-electrical monitoring, including temperature, humidity, and strain, thereby clarifying the performance boundaries, deployment constraints, and complementary roles of different technologies. It further systematically elaborates on the design patterns and empirical effectiveness of multi-parameter sensor fusion combined with AI algorithms in enhancing detection rates, localization accuracy, and false-alarm control. Finally, the study puts forward a practical reference architecture that incorporates internet of things (IoT), digital twins, and data governance, offering an actionable technical pathway for utilities to shift from periodic maintenance toward predictive, closed-loop maintenance.

2. Causes of Power-Cable Aging and Corresponding Monitoring Technologies

2.1. Electrical Aging Mechanisms and Monitoring Technologies

Electrical monitoring centers on PD, sheath voltage/current, and dielectric loss/dissipation factor (tan δ), targeting the identification and localization of insulation aging and incipient defects. Because different insulation systems exhibit distinct discharge mechanisms and signal morphologies, a tailored taxonomy of methods and matching data-processing pipelines is required to avoid diagnostic bias from single-channel measurements. As summarized in Table 1, multiple PD detection approaches have been developed to accommodate the diversity of insulation materials, cable designs, and laying environments.

Table 1. Various partial discharge monitoring techniques.

Techniques	Methods	Advantages	Disadvantages	References
Electrical	Indirect measurement circuit with an external capacitor coupling capacitor	Direct measurement of electrical parameters	Requires physical connections which can introduce noise	[2]
Electromagnetic	VHF/UHF antenna-type sensors; transient earth voltage (TEV)	Non-intrusive and can be implemented without direction contact	Susceptible to electromagnetic interference from external sources	[3]
Acoustic Emission	Piezoelectric sensors; accelerometers; microphones	Effective in noisy electrical environments	Limited detection range due to rapid attenuation of acoustic signals	[4]
Optical	Fiber optic sensors; Fabry–Perot interferometry; fiber bragg grating (FBG)	Capable of providing high resolution data	Typically, more expensive due to advanced technology requirements	[7]

Among these, high-frequency current transformer (HFCT), VHF, UHF, and acoustic emission (AE) are the most widely used engineering combinations. HFCT, VHF, UHF, and AE techniques are employed for PD detection, with their principles illustrated in Figure 1. Electrical methods also include capacitive couplers (CC), magnetic couplers (MC), and ultraviolet imaging to improve detectability and localization under varying noise conditions [8–10]. High sensitivity to incipient insulation defects; easy clamping on return paths; wide-band coverage for radiometric methods (VHF/UHF/TEV). Etallic sheaths and strong electromagnetic interference

(EMI) severely attenuate VHF/UHF; long-distance AE suffers from rapid acoustic attenuation and coupling variability; reflectometry detects abrupt impedance changes better than slow aging; optical FBG are EMI-immune but costlier and installation-sensitive. Techniques like HFCT, VHF, UHF and AE are devised for PD detection as depicted in Figure 1.

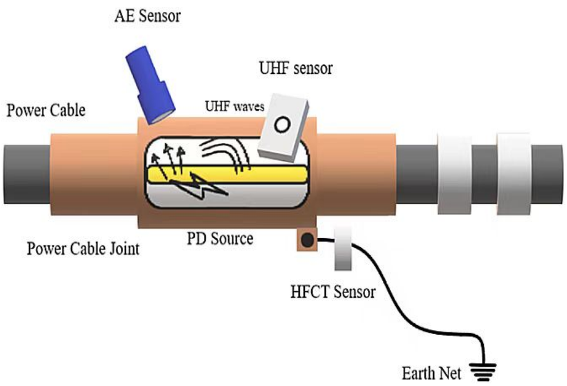

Figure 1. Partial Discharge Detection Technology for Power Cable Joints [8].

For the trade-off between online and offline testing, engineering practice places greater emphasis on the representativeness of online schemes under real load and real noise. Online PD systems are often combined with time-domain/Time-Difference-of-Arrival (TDOA) localization to cover long distances, complex topologies, and joint-dense line sections. As shown in Table 2, the differential method and electromagnetic coupling also offer alternative routes in noisy grounding and complex electromagnetic environments. In practice, fusing the time–frequency features from multiple sensor types and pairing them with pattern-recognition or learning-based classifiers can significantly increase detection rates, reduce false alarms, and improve localization stability [9].

Table 2. Online Partial Discharge (PD) Testing Technologies.

Techniques	Frequency	Detected Feature	Disadvantages	References
HFCT	0.3 MHz to 30 MHZ	Impulse current	Applicable only to cables with a grounded outer shield	[10]
VHF	30 MHz–300 MHz	Electromagnetic waves	The attenuated partial discharge pulse closely resembles radio noise signals	[11]
Electromagnetic (EM) Coupling	3 MHz–60 MHz	Electromagnetic field changes	Attenuation of high-frequency signals affects sensi tivity over distance	[12]
Capacitive Coupling	10 MHz–500 MHz	Voltage changes	Capacitive couplers may not capture the full spectrum of PD signals, sensitivity to external noise, calibration challenges	[13]
UHF	0.3 GHz–3 GHz	Electromagnetic wave	Detection over long distances is challenging, making it more suitable for detecting partial discharges in small power cable accessories.	[14]
Difference method	30 MHz	Change in electrical parameters (Voltage and current)	Experiences high-frequency signal attenuation, reducing detection sensitivity and precision over long cable.	[15]
Directional Coupling	~600 MHz	Directional electromagnetic wave propagation	Limited band width, more expensive than simpler coupling	[16]

Electrical-parameter approaches that use DF/leakage current as indicators are more accurate for estimating insulation aging: a low-frequency open-delta injection scheme combined with interpolation and windowed fast fourier transform (FFT) enables online evaluation but is sensitive to environmental and power-frequency components. Using very-low-frequency (VLF) injection together with cross-correlation denoising can markedly enhance measurement robustness, supporting a sustainable online dielectric-loss evaluation chain [17,18].

2.2. Non-Electrical Aging Mechanisms and Monitoring Technologies

Non-electrical monitoring focuses on the long-term effects of exogenous thermal, moisture, and mechanical stressors. Cable ampacity and failure probability are highly sensitive to temperature: in urban settings, heavy loading and poor ventilation raise temperatures, making joint/connector overheating a frequent trigger. Online temperature monitoring can both detect hotspots early and prevent thermal mismatch, while also informing life-cycle management and operational optimization [19].

Fiber-optic temperature/strain monitoring has become foundational for tunnels, submarine cables, and long-haul backbones: FBG offers high sensitivity and electromagnetic immunity, well suited for near-field placement at hotspots/joints; distributed temperature sensing (DTS) provides long-distance, continuous temperature profiles for corridor- or line-level coverage; optical time-domain reflectometry (OTDR) combines long reach with fault localization for fast troubleshooting; integrated multi-sensor modules enable coordinated monitoring of temperature–strain–PD, improving reliability and safety margins (shown in Table 3) [17]. Further studies show that combining machine learning with brillouin optical time-domain analysis (BOTDA) can robustly detect temperature/strain variations in complex marine environments, while FBG is highly suitable for axial-strain and deformation monitoring in submarine cables—pushing fiber sensing from temperature measurement toward state-driven predictive maintenance scenarios [20].

Table 3 Comparison of optical fiber temperature sensing technologies.

Technology	Cost	Real-Time Monitoring Capability	Description	Advantages	References
Fiber Bragg Grating	Low	Periodic	Reflects specific wavelengths that change with temperature, providing accurate monitoring	High sensitivity, anti-electromagnetic interference, accurate positioning	[16]
Distributed Temperature Sensing	High	Continuous	Uses Raman scattering to achieve continuous temperature measurement along the cable length	Continuous monitoring, no blind zone, high precision	[9]
Optical Time—Domain Reflectometer	Low	On-Demand	Measures backscattered light to detect temperature changes and locate faults	Long-distance monitoring, accurate positioning, reliable	[21]
Integrated Optical Fiber Module	Medium	Continuous to Periodic	Combines multiple sensors to achieve comprehensive monitoring of temperature, strain and partial discharge	Comprehensive monitoring, multi—parameter data, improved reliability and safety	[22]

Conventional capacitive/resistive humidity sensors still lack strong anti-interference performance and remote controllability. By contrast, fiber-optic relative-humidity (RH) and FBG sensors offer miniaturization, EM immunity, and corrosion resistance, making them suitable for tunnels and other harsh EM/corrosive environments. For ultra-long-distance remote humidity monitoring, nonadiabatic tapered optical fiber (NATOF) can achieve high sensitivity near the dispersion-turning point with transmission distances > 10 km; a humidity–temperature sensitivity matrix suppresses cross-sensitivity, improving the reliability and maintainability of tunnel humidity measurements [23].

In comprehensive use of non-electrical parameters, temperature–humidity (moisture content)–stress/vibration–environmental disturbances form a synergistic observation framework together with electrical indicators (PD/dielectric loss/sheath current). Long-term temperature trends provide early indications of ampacity and thermal degradation; humidity and moisture content act as latent-risk amplifiers; strain/vibration reflects mechanical perturbations and external damage risks. When this thermo–hydro–mechanical–electrical framework is combined with intelligent platforms and unified data standards, single-indicator misclassification rates are significantly reduced and trend-prediction stability and interpretability are improved. Evidence from online-monitoring platforms and case studies indicates that building multi-parameter databases and a cross-scenario feature space is essential for a smooth transition from monitoring to assessment–prediction. DTS provides continuous along-route coverage at higher cost; FBG offers high-resolution point/segment sensing near hot spots, joints, and terminations. Conventional RH sensors have weak EMI immunity; fiber RH/FBG resist EMI/corrosion but need protection and cross-sensitivity handling. The embedding of optical fiber into the power cable is shown in Figure 2. This has given rise to optical fiber composite cable, a sophisticated blend of optical fibers and cables. Optical fiber composite cable boasts a compact design and superior mechanical strength, enabling DTS to monitor cable temperatures with greater accuracy and efficiency.

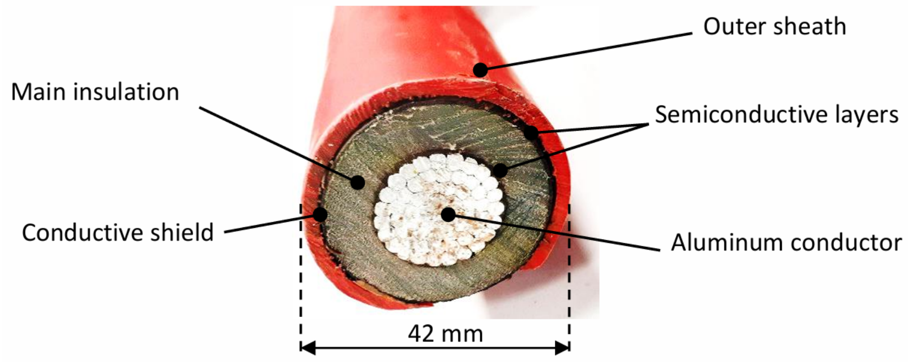

Figure 2. Cross-sectional image of a 20 kV underground cable [24].

2.3. Modern Intelligent Monitoring Technologies

Modern intelligent approaches emphasize the synergy of "multi-source sensing—platformization—algorithmization". At the device layer, intelligent inspection systems take video/infrared/fiber-optic/electrical signals as inputs and employ machine learning to enable early identification of latent defects and risk warning, markedly outperforming the occasional and subjective nature of manual inspection. For example, a CatBoost Aquila–optimized multi-feature assessment framework that integrates load, electrochemical corrosion, and PD features attains high accuracy, and a multimodal online system combining Rogowski coils, fiber-interferometric temperature monitoring, and support vector machine (SVM) achieves high-sensitivity, low-false-alarm online condition evaluation for both cross-linked polyethylene (XLPE) and oil-impregnated paper insulation, providing reliable inputs for subsequent predictive maintenance [25,26].

At the platform layer, SCADA serves as the hub for sensing–acquisition–supervision, supporting remote condition awareness and autonomous management. However, basic SCADA still falls short in precise fault localization, predictive analytics, and cybersecurity. It needs to be coupled with more open data buses, unified semantics, and AI inference services to deliver an end-to-end upgrade for multi-source data—online diagnosis—closed-loop O&M [27].

Concurrently, the latest online-monitoring research embeds AI directly into the sensing-to-diagnosis chain: 3D convolutional neural network (CNN) are used for PD localization in complex electrical environments; phase-portrait–based IoT signal processing reveals how temperature modulates PD excitation/detection; and self-powered triboelectric nanogenerator (TENG) and AI integrated sensing schemes reduce long-term energy consumption and maintenance costs, opening the door to maintenance-free, long-lifetime edge intelligence [28].

At the system layer, given nonlinear couplings among electrical/thermal/mechanical factors and fragmentation across vendors/protocols, future systems should adopt modular, interoperable architectures. Using standardized data formats and middleware to aggregate HFCT/DTS/sheath-current/AE and other streams, supporting common protocols such as message queuing telemetry transport (MQTT) /REST, and drawing on IEC 61,850 experience from substation automation to build open interfaces are essential steps. Within this framework, the digital twin acts as the core hub for sensor-data fusion and predictive diagnostics, enabling cross-validation of alarms, reducing false positives, and improving localization accuracy. Meanwhile, to meet growing demands for ruggedized and self-powered sensors, research emphasizes materials and structural design to enhance weatherability, corrosion resistance, and EMI immunity, ensuring long-term stable operation of fiber-optic/AE/electromagnetic sensing in submarine cables, tunnels, and dense urban corridors.In addition, O&M economics and environmental objectives directly influence technology choices. Figure 2 illustrates that incorporating ISO 14067 [29] and life cycle assessment (LCA) to quantify the carbon footprint across inspection, maintenance, and end-of-life enables a tri-objective trade-off among reliability, economics, and low-carbon goals.

This aligns with the trajectory toward platformization and algorithmization: by leveraging data availability and model-based evaluation, cost–risk–carbon can be optimized in tandem.

In summary, the electrical track centers on an "early-defect—localization—assessment" chain built around PD/dielectric loss/sheath current; the non-electrical track focuses on monitoring the background and trigger factors of temperature—humidity/strain—environment; and modern intelligent methods stress standardized ingestion of multi-source sensing on IoT/SCADA/digital-twin platforms, heterogeneous-data fusion analytics, and AI-driven online diagnosis. Together, these three threads form a closed loop from micro-defect sensing to macro-system assessment and from data acquisition to intelligent decision-making, laying a solid technical foundation for next-generation intelligent O&M of power cables [30,31].

3. Methods and Results for Power-Cable Maintenance

3.1. Intelligent Inspection Systems

Inspection systems based on intelligent sensing and machine-learning algorithms are gradually replacing manual inspections, markedly improving O&M efficiency and condition-recognition accuracy through automation. For instance, a practical implementation in an urban power grid demonstrated that an intelligent inspection system utilizing infrared thermography and deep learning you only look once version five (YOLOv5) for cable joint inspection achieved a defect detection rate of 98.5% and reduced inspection time by approximately 70% compared to manual methods, providing quantifiable evidence of its efficiency and accuracy gains. In cable-defect identification, Evangeline et al. proposed a CatBoost and Aquila-optimized evaluation model (shown in Figure 3) that integrates multi-dimensional features such as load, electrochemical corrosion, and PD to achieve precise identification of sheath and insulation defects, with overall accuracy exceeding 99%, significantly outperforming threshold-based methods [32]. This model was validated on a dataset from over 200 km of in-service 110 kV XLPE cables, where it successfully reduced false alarms by 25% in field trials, demonstrating robust performance under real-world noise conditions. In addition, a multimodal online diagnostic system that fuses Rogowski-coil current sensing, fiber-interferometric temperature monitoring, and SVM can capture subtle condition anomalies in XLPE and oil-impregnated paper cables in real time, demonstrating high sensitivity and low false-alarm rates in online condition assessment. Compared with manual inspection, such intelligent systems enable early detection of latent defects and rapid warning [33], provide reliable inputs for predictive maintenance, and effectively reduce the risk of unplanned outages.

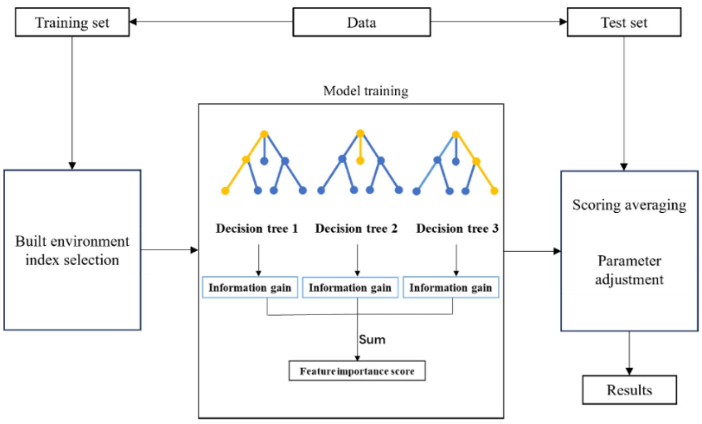

Figure 3. Complete workflow of CatBoost model for defect stage detection of XLPE power [34].

3.2. SCADA System Integration

Supervisory Control and Data Acquisition (SCADA) systems [35] play a central role in intelligent O&M of modern distribution networks. By integrating IoT sensing, data acquisition, and real-time supervision, SCADA enables remote condition awareness and autonomous management of cable operation. However, basic SCADA still shows clear shortcomings in precise fault localization, predictive analytics, and cybersecurity [36].

To address these gaps, Islam et al. [6] proposed a next-generation intelligent SCADA system that integrates IoT technologies, multi-agent systems (MAS), and predictive-maintenance models to achieve automated data collection, real-time analytics, and decision support. Using machine-learning algorithms, the system detects multiple fault types (including open circuit, single-phase-to-ground, line-to-line short circuit, and three-phase short circuit) and enhances cybersecurity. Simulation and hardware testing show that the system outperforms conventional SCADA in fault-detection accuracy, alert timeliness, and scalability, achieving unified management and efficient maintenance of distribution-network cable systems. A field deployment in a regional distribution network reported that this intelligent SCADA system improved fault detection accuracy to 99.2%, reduced the mean time to identify fault types by 65%, and enhanced cybersecurity threat detection by blocking 99% of simulated intrusion attempts, providing concrete performance benchmarks for its advanced capabilities.

3.3. Data Fusion and Optimization Algorithms

Intelligent O&M for cable systems relies not only on single-point monitoring and diagnostic techniques but also on building a platform for multi-source information fusion and decision optimization, enabling comprehensive situational awareness and dynamic management under complex operating conditions. The fusion of multi-dimensional data—sensor measurements, historical fault records, and operating-environment information—is a prerequisite for predictive maintenance and optimal resource scheduling [37].

At the algorithmic level, Yue et al. [38] proposed a multimodal fusion detection framework incorporating attention mechanisms, transfer learning, and reinforcement-learning strategies. Under dynamic operating conditions, it increased equipment-detection accuracy by 15.3% and computational efficiency by 28.7%, while Double Q-learning optimized resource scheduling to adapt maintenance strategies across different scenarios. Meanwhile, Kim et al. [22], using Monte Carlo simulation and life-cycle cost analysis, proposed optimal replacement and maintenance cycles for underground cables. Compared with fixed-interval inspections, the maintenance frequency is reduced by about one-third, and the total cost reaches a minimum. Collectively, these methods drive the shift from reactive repair to proactive prediction, balancing both economic efficiency and system reliability.

Proposing a carbon-footprint accounting method based on the ISO 14067 standard, applying LCA to evaluate carbon emissions across the operation, inspection, maintenance/repair, and end-of-life phases of power cables, thereby providing a quantitative basis for utilities to formulate low-carbon O&M strategies. By combining intelligent algorithms with green environmental metrics, the intelligent O&M framework for cables is expected to achieve a better balance among reliability, economic efficiency, and environmental sustainability.

For long-term operation and multi-mechanism degradation, the monitoring priority is coordinated and standardized multi-source sensing. Heterogeneous data—PD, distributed temperature (DTS/FBG), sheath current, and acoustic emission—should be unified at the platform level in terms of interfaces, protocols, and data models to improve detection rates, localization accuracy, and false-alarm control [39]. At the device layer, attention should be paid to sensor durability and self-calibration under high humidity, strong EMI, and vibration/temperature fluctuations, while materials/packaging and shielding design are used to reduce drift and mismatch. In energy autonomy, TENG and inductive energy harvesting can reduce dependence on external power/batteries, enhancing the sustainability of long-cycle online monitoring. Low-power wide-area wireless (e.g., LoRa-WSN) has demonstrated reliability and energy advantages in harsh conditions, making it suitable for remote or hard-to-reach node access. At the algorithmic layer, multimodal learning must maintain generalization and interpretability under real noise, domain shift, and installation variability; we recommend incorporating weak supervision, transfer learning, and uncertainty estimation within unified platforms and digital twin frameworks to strengthen model robustness and enforce physical priors.

Platforms should realize standardized ingestion of multi-source data, spatiotemporal alignment, and quality control, while exposing open interfaces to host algorithmic services—thus enabling routine, comparable assessments across assets, voltage levels, and insulation types. A digital twin should serve as the O&M middle platform to support state replay, strategy simulation, and risk quantification, and to embed predictive maintenance into daily workflows and resource scheduling [32]. In terms of governance, norms for data lineage, threshold/version management, and model auditing are needed to ensure traceability, reproducibility, and auditability. For economics and sustainability, a joint framework of life-cycle cost (LCC) and carbon footprint (ISO 14067/LCA) is recommended to balance reliability, cost, and environmental objectives and to form a transferable decision baseline. As wireless and self-powered monitoring become widespread, capabilities for link-health monitoring, packet-loss self-healing, and energy-budget assessment should be established, and integrated communications-and-sensing should be treated as an O&M object to ensure end-to-end availability and long-term operational stability [40]. *N* dense urban tunnels with strong EMI and metallic sheaths, far-field UHF alone is insufficient; near-joint placement with multi-point TDOA or hybrid HFCT+AE is required for coverage and localization.

4. Discussion

To support long-term operation under multi-mechanism degradation, priorities should shift from adding sensors to standardizing multi-source sensing and platform-centric integration [41]. At the device layer, sensors must be durable and self-calibrating in high-humidity/strong-EMI/vibration environments to control drift and mismatch. Energy autonomy is needed for long-cycle monitoring, using TENG or inductive harvesting with explicit energy budgets [42]. Low-power wide-area wireless (e.g., LoRa-WSN) has demonstrated reliability and energy advantages in harsh conditions, making it suitable for remote or hard-to-reach node access [43].

On the algorithm side, multimodal learning must remain generalizable and interpretable under real noise, domain shift, and installation variability; weak supervision, transfer learning, and uncertainty estimation within digital-twin frameworks help enforce physics priors. Platforms should provide standardized ingestion, spatiotemporal alignment, quality control, and open interfaces for algorithm services to enable routine, comparable assessments across assets, voltage levels, and insulation types [44]. A digital twin should serve as the O&M middle platform to support state replay, strategy simulation, and risk quantification, and to embed predictive maintenance into daily workflows and resource scheduling. In terms of governance, norms for data lineage, threshold/version management, and model auditing are needed to ensure traceability, reproducibility, and auditability [45]. For economics and sustainability, a joint framework of life-cycle cost (LCC) and carbon footprint (ISO 14067/LCA) is recommended to balance reliability, cost, and environmental objectives and to form a transferable decision baseline [46]. Treat integrated communications-and-sensing as an O&M object, establishing end-to-end availability through continuous link diagnostics, proactive recovery, and energy-budget assessment.

5. Conclusions

Addressing the condition-sensing and O&M needs of power cables, this paper presents a system-level analysis centered on detection and O&M technologies. On the detection side, it reviews the principles, application scenarios, and key limitations of online PD (HFCT/VHF/UHF/AE), dielectric-loss and sheath-current measurements, as well as distributed fiber-optic temperature/strain and environmental-parameter monitoring. Emphasis is placed on standardized interfaces and unified data models to enable multi-source information synergy, thereby improving early defect identification and localization accuracy. On the O&M side, intelligent inspection systems driven by smart sensing and machine learning are displacing manual methods; digital twins support state replay, alarm validation, and strategy simulation. Through data and model governance, comparable assessments and closed-loop maintenance can be achieved across assets, voltage classes, and insulation types. The work provides a structured reference for building scalable and reusable cable-monitoring and O&M systems, and offers guidance for alignment between future research and engineering practice.

Author Contributions

Conceptualization, X.Z., Y.L. and L.H.; methodology, Y.L. and F.Z.; investigation, X.Z., Y.L., F.Z., W.H., Y.H. and Y.C.; resources, X.Z. and W.H.; data curation, Y.L. and Y.C.; writing–original draft preparation, Y.L. and Y.C.; writing—review and editing, X.Z., Y.L., F.Z., W.H., Y.H., Y.C. and L.H.; visualization, Y.H. and Y.C.; supervision, X.Z. and L.H.; project administration, X.Z. and L.H.; funding acquisition, X.Z. and L.H. All authors have read and agreed to the published version of the manuscript.

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Informed Consent Statement

Not applicable.

Data Availability Statement

The original contributions presented in this study are included in the article. Further inquiries can be directed to the corresponding authors.

Conflicts of Interest

The authors declare no conflicts of interest. Given the role as the Editorial Board Member, Lvwen Huang had no involvement in the peer review of this paper and had no access to information regarding its peer-review process. Full responsibility for the editorial process of this paper was delegated to another editor of the journal.

Use of AI and AI-Assisted Technologies

No AI tools were utilized for this paper.

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