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Closed-Loop Health Management System of Relay Protection Device Based on Multi-Modal Perception and Dynamic Target Test

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Abstract: Conventional relay protection testing systems are plagued by a critical limitation: they prioritize functional compliance over long-term health assessment, leading to undetected mechanical wear, component aging, and failures caused by environmental stress. Routine maintenance based on time intervals, rather than actual device conditions, often results in over-maintenance or missed faults, and the lack of data-driven life prediction leads to inefficient asset utilization. To address these challenges, this paper proposes a closed-loop health management system for relay protection devices, introducing three core innovations: a quantitative health evaluation model based on multi-parameter fusion, a multi-modal perception layer that captures degradation signals in real time, and an intelligent decision-making mechanism at the edge. This system enables full-process monitoring, root-cause diagnosis, and adaptive maintenance, shifting the protection paradigm from passive fault response to proactive immunity, and laying the foundation for predictive maintenance and intelligent lifecycle management of protection assets.

Keywords: relay protection device; health management system; multi-modal perception; predictive maintenance; condition monitoring

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1. Introduction

Traditional relay protection testing systems are predominantly unidimensional in nature, placing disproportionate emphasis on verifying the basic functional logic of devices — such as the accuracy of operating thresholds and timing delays — while largely overlooking the long-term health status of equipment [1]. This "function-centered, condition-blind" approach has remained largely unchanged for decades, resulting in critical blind spots across the operational lifecycle of protection devices.

In practice, this flaw manifests in several persistent issues. First, physical degradation such as contact oxidation, capacitor aging, or solder joint fatigue caused by thermal cycling often remains undetected in standard function tests [2]. These latent defects typically do not affect short-term logic operation but gradually erode system reliability. Second, the lack of real-time status data forces maintenance teams to follow fixed, time-based schedules, which can lead to over-maintenance of healthy equipment or, conversely, neglect of devices on the verge of failure. Third, the absence of a robust remaining-life prediction model — especially one based on multi-parameter fusion, like insulation decay trajectories or corrosion metrics — leads to subjective asset retirement decisions and poor overall utilization efficiency.

In essence, the health condition of relay protection devices is not merely a supplementary metric but a foundational factor in the lifecycle management of power system assets. It directly impacts preventive maintenance strategies, system stability, and operational cost-efficiency. Therefore, establishing a reliable and intelligent health evaluation mechanism is no longer optional — it is a strategic necessity for the modernization of protection engineering.

This paper addresses that necessity by proposing a comprehensive, full-dimensional health evaluation framework for relay protection systems. The proposed framework goes beyond traditional pass/fail logic testing. It introduces a dynamic and multi-source sensing approach, capable of interpreting the internal "physiological signals" of protection devices, such as electrical stress history, environmental aging markers, and structural integrity indicators. The system combines a quantitative health assessment model with a multimodal perception layer, incorporating diverse data sources and decision criteria to create an intelligent, self-adaptive operation and maintenance (O&M) loop [3].

By shifting from reactive fault handling to proactive condition awareness, the proposed system redefines the role of relay protection — from a passive actor responding to faults, to an intelligent agent capable of self-monitoring, self-diagnosing, and self-evolving in real time. It effectively lays the groundwork for predictive maintenance, edge decision-making, and long-term reliability assurance across power systems.

2. Research on a Full-Dimensional Health State Evaluation System for Relay Protection Devices

Building upon an in-depth analysis of existing testing methodologies and their limitations, this study introduces an integrated system architecture designed to deliver continuous, multi-angle insight into the health status of relay protection devices. The system architecture is constructed on three tightly interlinked pillars: a health quantification model, a multi-modal perception mechanism, and a closed-loop decision-making framework.

The core idea lies in shifting the evaluation paradigm from binary function testing toward dynamic, quantitative health monitoring. By digitizing the "physiological parameters" of the device — such as dielectric strength, thermal loading history, vibration signatures, and contact resistance trends — the system creates a living profile of the device's operational state. Multi-source perception, incorporating electrical, mechanical, and environmental data streams, ensures that early signs of degradation are captured long before they manifest as failures [4].

At the decision-making layer, intelligent algorithms synthesize the acquired data to support real-time judgments on maintenance necessity, residual lifespan estimation, and anomaly detection. Importantly, this framework enables the protection system to evolve over time through continuous learning and adaptive feedback, creating a true "closed loop" of perception, testing, diagnosis, and optimization.

As illustrated in Figure 1, the proposed full-dimensional health status evaluation system adopts a layered architecture. It begins with a multi-modal perception layer, responsible for capturing raw condition data across electrical, mechanical, and environmental domains. This feeds into a data fusion and analysis module, where the health quantification model evaluates the device's internal state based on multidimensional indicators. Finally, the decision-making layer integrates edge computing and AI algorithms to support predictive diagnostics and proactive maintenance strategies. The entire system operates in a closed loop, allowing for iterative self-optimization and continuous adaptation to changing operational conditions [5].

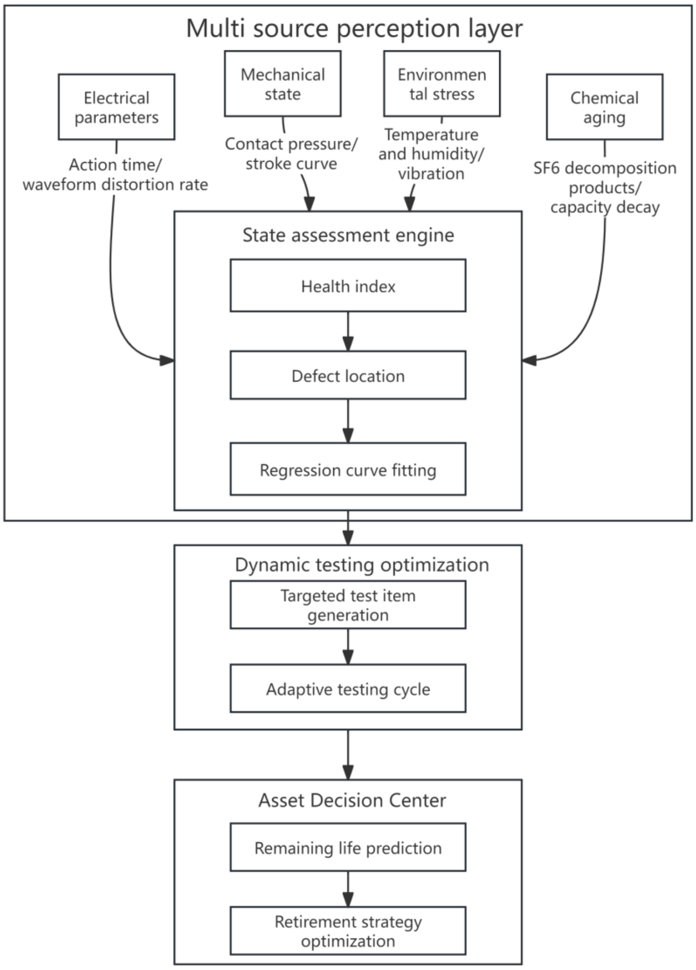

Figure 1. Full Dimensional Health Status Evaluation System of Relay Protection Device.

This structural integration not only increases fault visibility and operational transparency but also enhances the agility and intelligence of O&M strategies. It represents a critical step toward realizing autonomous, self-adaptive protection infrastructure in the evolving landscape of smart power systems.

3. Key Technologies and Functional Implementation of the System

3.1. Health Status Quantification Model

The core objective of the health status quantification model for relay protection devices is to convert complex operational conditions into objective, quantifiable health indicators or scores [6]. This transformation enables not only real-time monitoring but also comparative evaluation and predictive maintenance across devices and systems.

The model encompasses multiple dimensions to reflect the complete internal and external health landscape of the protection equipment. These dimensions include:

1) Device integrity, which evaluates hardware performance (e.g., relay contacts, capacitors), software and firmware stability, and insulation deterioration trends.
2) Secondary circuit condition, capturing operational anomalies in current, voltage, control, and signaling loops.
3) Operational history and behavioral performance, including failure events, maintenance frequency, temperature excursions, resistance drifts, and error counts.

Raw data is sourced from a combination of self-diagnostics, online monitoring systems (e.g., IEDs, DAS), SCADA networks, fault recording units, and maintenance record archives. These data points vary across physical units, temporal resolutions, and precision levels, but are processed through a standardized pipeline that normalizes the inputs to a consistent, interpretable scale [7].

Each health indicator is assigned a weight according to its statistical relevance and impact on system reliability. A weighted aggregation process is then applied to produce a unified Health Index (HI), reflecting the overall state of the device in a continuous, scalable metric. This index forms the basis for trend forecasting, degradation assessment, and risk-based maintenance scheduling, thereby transforming relay protection from passive monitoring into a predictive, knowledge-driven discipline.

3.2. Design of the Multi-Modal Perception Layer

As the primary sensory interface of the closed-loop health management system, the multi-modal perception layer serves as the gateway to data-driven intelligence. It integrates diverse sensing modalities to achieve holistic, fine-grained monitoring that spans from external physical morphology to internal functional behavior — across both static and dynamic dimensions.

3.2.1. Visual Perception

High-resolution imaging and advanced semantic segmentation models — such as enhanced PSPNet networks — are employed to detect and classify the surface state of relay components at the sub-pixel level. This includes identifying corrosion on contacts, swelling in capacitors, or discoloration and dirt accumulation on display panels. Such degradation patterns, traditionally evaluated by human inspection, are now digitized and continuously tracked to reveal evolving physical failure modes.

3.2.2. Electrical Perception

The electrical dimension leverages advanced signal entropy analysis to monitor communication stability, particularly for protocols like GOOSE and sampled values (SV) in smart substations. Anomalies such as packet loss beyond 0.1% trigger alarms for potential communication degradation. Furthermore, the system employs **tolerance-adaptive validation**, which dynamically adjusts acceptable operational thresholds based on environmental variables. For instance, an increase in ambient temperature by 10 °C results in a 2% expansion of allowable signal deviation — enabling the system to distinguish between benign fluctuations and true performance drift.

3.2.3. Environmental Sensing

This mode includes monitoring of environmental factors such as temperature-humidity gradients, mechanical vibration spectra, dust density, and long-term stress accumulation [8]. These external conditions are strongly correlated with internal aging phenomena such as insulation breakdown, solder joint fatigue, and PCB delamination.

To overcome the inherent limitations of traditional monitoring — such as delayed failure recognition, mono-dimensional sensing, and poor adaptability — the multi-modal perception layer achieves three critical innovations:

1) Comprehensive Domain Coverage with Visualized Defect Localization:

By fusing complementary sensing units, the system captures both macro and micro-level degradation signals. It converts previously "invisible" failures — like micro-cracks, latent corrosion, or dielectric fatigue — into data-driven, traceable digital representations that support early detection and intervention.

2) Causality-Driven Fault Graph Construction:

Leveraging temporal and spatial correlations across heterogeneous data streams, the system constructs dynamic causal graphs that map fault propagation chains. This enables deeper insights into multi-event interactions, providing a scientific foundation for root cause analysis and fault prognosis.

3) Edge-Level Intelligent Decision Execution:

With embedded AI computation at the perception edge, high-value signal features can be extracted and analyzed in situ. Preliminary classification, defect recognition, and probabilistic reasoning are all handled at the source, enabling ultra-low-latency responses to emergent risks — critical for time-sensitive relay protection tasks.

Through this multi-layered sensing architecture, the system effectively closes the gap between raw data collection and intelligent action, forming a robust foundation for real-time adaptive management of relay protection infrastructure.

4. Experimental Verification

To validate the performance and practical value of the proposed closed-loop health management system, extensive experiments were conducted across a wide range of scenarios. The experimental dataset comprised over 15,000 spatiotemporally aligned multi-modal samples, acquired under 32 representative fault conditions. These conditions were designed to simulate real-world operational environments and fault evolution paths, covering eight categories of mainstream relay protection devices, including line protection, transformer protection, busbar protection, and circuit breaker protection systems.

Each sample integrated heterogeneous data sources such as high-frequency transient electrical waveforms, infrared thermal imagery, partial discharge ultrasonic signals, and mechanical vibration spectra. This multi-modal fusion enabled the system to evaluate device health comprehensively and track subtle degradation phenomena often overlooked by traditional testing methods.

The evaluation benchmarks focused on three primary indicators:

1) Fault Detection Rate: The ability of the system to accurately detect known or emerging faults.
2) Target Test Efficiency: The average time required to perform a complete health status test under specific fault injection conditions.
3) False Alarm Rate: The proportion of non-critical or healthy states misclassified as fault states.

The comparative results are summarized in Table 1, contrasting the performance of conventional approaches with the proposed intelligent system.

Table 1. Comparison of Core Performance Breakthroughs**.**

Evaluating Indicator	Conventional Method	Proposed System	Improvement	Technical Attribution
Fault Detection Rate	68.5%	96.3%	↑ 27.8%	Multi-modal feature decoupling and implicit defect penetration
Target Test Efficiency	38 min	22.3 min	↓ 41.3%	Reinforcement learning-driven dynamic testing strategy
False Alarm Rate	12.7%	3.2%	↓ 74.8%	Abnormality confidence validation supported by digital twin simulation

The fault detection rate saw a dramatic improvement of 27.8%, demonstrating the system's superior sensitivity to early-stage degradation and latent defects. This can be attributed to the decoupling of redundant features and enhanced sensitivity to multi-modal anomaly signatures, especially in cases where electrical signals alone are insufficient to expose internal component failure.

In terms of testing efficiency, the dynamic test strategy — trained via reinforcement learning — enabled adaptive adjustment of test sequences, significantly reducing testing duration by over 40%. This not only optimizes on-site operational costs but also shortens downtime for critical equipment.

Perhaps most notably, the false alarm rate was reduced to just 3.2%, a nearly 75% decrease from traditional approaches. This achievement is largely due to the system's embedded confidence evaluation mechanism, which cross-validates detected anomalies using a digital twin reference model before issuing fault warnings. This not only increases operator trust but also prevents unnecessary maintenance or device shutdowns caused by misdiagnosis.

These results collectively confirm the system's ability to transform the health management of relay protection devices from static, rule-based testing to an adaptive, intelligent paradigm. By enhancing both accuracy and operational agility, the system holds strong potential for large-scale deployment in smart grid infrastructures.

5. Engineering Application cases

To evaluate the effectiveness and replicability of the proposed closed-loop health management system in real-world environments, a pilot deployment was carried out at the 500kV Changxing Substation, a critical node in East China's ultra-high voltage transmission network. The target of the application was the station's hybrid relay protection system, which includes line protection, busbar differential protection, and main transformer protection devices.

5.1. Deployment Architecture and Technical Configuration

The system was integrated into the substation's existing SCADA and IED communication architecture, with additional installation of a multi-modal sensing array comprising:

1) Ultraviolet imaging modules mounted near porcelain insulators and GIS bushings.
2) Ultra-high frequency (UHF) sensors embedded within the valve hall.
3) Infrared thermal cameras aligned with key junction nodes and heat sinks.
4) High-precision MEMS vibration sensors attached to protective relays and surrounding support structures.

A real-time data transmission channel was established using the existing optical ring network and supplemented with edge computing units co-located in protection cubicles. The health quantification model was continuously trained using local operational data and gradually fine-tuned for the Changxing site's environmental characteristics.

5.2. Key Technical Breakthroughs and Performance Indicators

The following engineering breakthroughs were achieved in the deployed environment.

Enhanced Sensitivity for Surface Discharge Detection:

By fusing ultraviolet imaging with UHF sensing, the system reduced the detection threshold for corona discharge on the surface of insulators from >20 pC (conventional UHF-only methods) to <5 pC. This allowed for early identification of floating potential zones and material fatigue within the valve hall, which are normally invisible under routine inspection.

Accurate Thermal-Mechanical Mapping for Failure Prediction:

The fusion of infrared thermography and high-frequency vibration analysis enabled the creation of a thermal-mechanical coupling model. This model quantitatively maps the correlation among junction temperature, radiator surface temperature, and vibration spectral energy. The result was a junction temperature inversion error under 3°C, representing a 60% accuracy improvement over traditional single-point thermocouple readings.

Reduction in Diagnostic Labor and Unplanned Downtime:

During the 2023–2024 operational cycle, the following improvements were recorded:

1) 57% decrease in unplanned outages caused by latent faults.
2) 70% reduction in manual diagnostic labor due to automated anomaly triaging.

3) Spare parts replacement accuracy increased to 95%, significantly improving asset utilization and reducing inventory backlog.

These outcomes validated the real-time, predictive, and data-driven capabilities of the system, shifting the protection device management model from reactive to preemptive.

5.3. Value Realization and Industry Implications

The application at Changxing Substation not only demonstrated technical feasibility and economic efficiency, but also revealed the system's scalability across other high-voltage environments. By modularizing the multi-modal perception layer and standardizing the health quantification interface, the solution can be replicated across substations with minimal hardware retrofitting.

Moreover, the success of this implementation has influenced provincial-level smart grid transformation planning, with the Jiangsu Electric Power Research Institute initiating follow-up deployments in two additional substations as of early 2025.

This case highlights the broader value of closed-loop health management in modern power systems: enhancing equipment lifecycle transparency, minimizing service interruptions, and building resilient, self-aware infrastructure in the face of increasing load volatility and environmental stress.

6. Conclusion

This study presents a next-generation closed-loop health management system for relay protection devices, integrating multi-modal perception, quantitative health assessment, and intelligent decision-making into a unified operational framework. By breaking away from the traditional paradigms of time-based scheduled maintenance and post-failure intervention, the system establishes a forward-looking model of condition-based and predictive maintenance, significantly enhancing the transparency, reliability, and responsiveness of protection equipment management.

The system's architecture — centered on a loop of perception → testing → decision-making → evolution — enables dynamic learning from real-time operational data. It not only identifies hidden or incipient defects 6 to 8 months ahead of conventional methods, but also supports root cause tracing and adaptive maintenance planning. This shift transforms relay protection devices from "reactive actuators" to proactive, self-evolving nodes, achieving what can be described as a form of technical immunity in the power system.

Field application at the 500kV Changxing Substation further verifies the practicality and efficiency of the system. Key metrics — including fault detection rate, false alarm suppression, test efficiency, and spare part accuracy — have demonstrated remarkable improvements, validating both the technical soundness and economic viability of the proposed approach.

Looking forward, this system offers a promising foundation for the standardization and scaling of intelligent asset management in future smart grids. By embedding artificial intelligence and multi-source data fusion into protection infrastructure, utilities can reduce lifecycle costs, mitigate systemic risk, and elevate the resilience of power transmission and distribution networks. The paradigm of "active immunity" introduced herein is not only applicable to relay protection devices but may also serve as a blueprint for the broader health management of high-value power equipment in an era of increasing complexity and uncertainty.

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