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Design and Safety Performance Optimization of Intelligent Grounding Protection System for Building Installation Engineering Equipment

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ABSTRACT

To address safety hazards such as lightning-induced electromagnetic induction and insulation leakage in construction equipment during operation, as well as the limitations of traditional protection measures (low intelligence level and incomplete safety assessment systems), this paper designs an intelligent grounding protection system for construction equipment. Centered on grounding protection, the study establishes a safety risk assessment framework through literature analysis of grounding protection and equipotential bonding theories, combined with system evaluation methods. Using numerical simulation technology, the hardware architecture (data acquisition, intelligent control, and execution modules) and software functions (risk alerts and adaptive regulation) were optimized. Experimental results demonstrate that the intelligent system effectively reduces equipment grounding resistance to below the standard requirement of 4Ω, decreases local potential differences by over 30%, and significantly enhances operational safety and stability. The research provides theoretical support and practical solutions for intelligent upgrades in construction equipment protection, playing a crucial role in advancing safety protection technologies for building electrical systems.

KEYWORDS

Building installation engineering; Equipment protection; Intelligent grounding system; Safety performance optimization; Numerical simulation

1 Introduction

Electrical equipment in building installation projects serves as the core infrastructure for functional building operations, with its operational safety directly impacting both the reliability of building utilities and the safety of personnel and property. However, practical engineering projects face persistent safety hazards. On one hand, natural climatic factors (such as lightning) can induce electromagnetic induction in lightning-prone areas, triggering high-voltage counterstrikes through grounding systems that cause irreversible damage to equipment circuits [1]. On the other hand, long-term operational issues like insulation aging and damage may lead to live exposed conductive parts, not only threatening equipment integrity but also increasing the risk of electric shock accidents. According to the "Code for Acceptance of Electrical Construction Quality in Buildings" (GB 50303-2022), improper grounding protection and excessive potential differences have accounted for 35% of electrical safety incidents in buildings over the past five years, highlighting the urgent need to optimize equipment protection measures.

Currently, China's "Belt and Road" infrastructure construction continues to advance, with the scale of construction and installation projects expanding and equipment types becoming increasingly complex. The traditional grounding protection model, which mainly relies on manual inspections and fixed parameter settings, can no longer meet the high-precision and real-time requirements for equipment safety protection in modern buildings [2]. Therefore, developing equipment protection systems with intelligent perception, automatic adjustment, and risk warning functions has become an important research topic in the field of building electrical engineering.

2 Current research Status at Home and Abroad

In the field of building equipment protection, scholars worldwide have conducted extensive research. Internationally, European and American countries have focused on the reliability design of grounding systems [3]. For instance, the IEEE standard in the United States proposes an optimization method for grounding parameters based on dynamic changes in soil resistivity. However, this method lacks integrated intelligent control logic, making real-time adaptive regulation difficult to achieve. Japanese researchers have studied partial equipotential bonding technology for humid environments (such as bathrooms), proposing potential difference control thresholds. Yet, they have not developed a systematic intelligent protection device solution.

Domestic research predominantly focuses on improving traditional protective measures, such as optimizing grounding electrode materials and refining equipotential bonding techniques. However, there are notable gaps in

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intelligent application implementation: most studies fail to establish comprehensive safety risk assessment frameworks, making it challenging to quantify equipment safety status. Existing protective devices are predominantly passive, lacking proactive warning and intelligent response capabilities. In summary, current research has yet to develop an integrated "theory-design-optimization-validation [4]" intelligent protection system, which cannot fully meet the high-efficiency safety protection requirements for building installation engineering equipment.

3 Research Objectives and Main Content

This study aims to develop a grounding protection system integrating real-time monitoring, intelligent control, and risk early-warning capabilities, tailored to the safety requirements of construction and installation equipment. Through scientific optimization methods, the system's safety performance is enhanced. The research focuses on: 1. Establishing core theories of grounding protection and equipotential bonding for construction equipment, and developing a safety risk assessment index system; 2. Designing the hardware architecture and software modules of the intelligent grounding protection system to enable real-time monitoring and adaptive regulation of equipment grounding status and potential differences; 3. Analyzing system safety performance using numerical simulation techniques, and proposing risk-based optimization strategies; 4. Verifying the system's feasibility and effectiveness through practical examples, providing practical references for intelligent upgrades in construction equipment protection.

4 Core Theory and Current Status Analysis of Equipment Protection in Construction and Installation Engineering

4.1 Core Protection Theory

In construction and installation engineering, equipment grounding protection is categorized into functional grounding and protective grounding. Functional grounding aims to enhance operational efficiency, including working grounding (ensuring AC/DC system reliability), signal grounding (maintaining stable signal transmission), shielding grounding (reducing electromagnetic interference), and logic grounding (ensuring stable reference potential). Protective grounding focuses on personal and equipment safety, covering anti-electric shock grounding (grounding exposed conductive parts to discharge current in case of insulation damage), lightning protection grounding (diverting lightning current into the ground), and anti-static grounding (eliminating hazards from static electricity accumulation). Together, these two types of grounding form the foundation of equipment safety protection.

General equipotential bonding (GEB) connects metal conduits, PE bars, and lightning protection systems in incoming distribution boxes to a common grounding terminal plate, effectively reducing overall contact voltage and potential differences in buildings. Local equipotential bonding (LEB) addresses damp areas like bathrooms by integrating PE trunk lines, metal structures, and pipelines, thereby minimizing local potential differences and lowering electric shock risks. Studies show that proper GEB implementation can reduce electric shock accident rates in humid environments by over 60%.

4.2 Industry Status and Existing Problems

Limitations of Protective Measures: Most engineering projects still rely on traditional passive grounding protection systems that depend on fixed parameter designs. These systems cannot dynamically adjust protection strategies based on soil resistivity variations or lightning intensity, resulting in significantly reduced effectiveness in complex environments. Insufficient Intelligence: Existing equipment lacks real-time monitoring and intelligent early-warning capabilities. Issues like grounding faults and excessive potential differences require manual inspections, and delayed responses often lead to accident escalation. Incomplete Risk Assessment Framework: The industry has yet to establish a unified safety risk evaluation system for equipment. There is insufficient correlation analysis between key parameters such as "soil resistivity, grounding resistance, and potential difference," making it difficult to quantify equipment safety status.

5 Design of Intelligent Grounding Protection System for Construction and Installation Engineering Equipment

5.1 System Design Objectives

With the core objectives of "real-time monitoring, intelligent early warning, and adaptive protection", the system delivers three key functions: (1) Precise collection of critical parameters including equipment grounding resistance, potential difference, and ambient lightning intensity; (2) Automatic identification of safety hazards through risk assessment models, triggering tiered alerts; (3) Dynamic adjustment of grounding system parameters based on operational conditions to optimize protection effectiveness.

5.2 Hardware Architecture Design

Data Acquisition Module: Equipped with a ground resistance sensor (±1% measurement accuracy), potential difference sensor (0-500V range), and lightning electric field monitor, deployed at equipment grounding terminals, distribution boxes, and high-risk lightning strike zones to collect operational parameters in real time and transmit them to the control module. Intelligent Control Module: Powered by an STM32F407 microcontroller, this module integrates a 4G communication module and edge computing unit to enable real-time data processing, risk analysis, and control command issuance. Execution Module: Includes an intelligent grounding adjustment device (which dynamically optimizes grounding resistance by adjusting the insertion depth of grounding electrodes via servo motors) and an equipotential bonding switch (which automatically strengthens local equipotential bonding based on potential differences), ensuring rapid response of protective measures.

5.3 Software Function Design

Data Processing Module: Utilizes filtering algorithms to eliminate sensor noise, performs real-time parameter analysis via edge computing units, and generates equipment safety status reports. Risk Alert Module: Based on a security risk assessment index system (with weights determined by AHP), classifies equipment safety status into three tiers: "Safe (Risk Value <0.3)", "Alert (0.3⩽Risk Value<0.6)", and "Dangerous (Risk Value⩾0.6)". It triggers audio-visual alarms and sends alerts via mobile app notifications. Intelligent Control Module: Equipped with adaptive control algorithms, it automatically increases the grounding electrode insertion depth by 5-10cm when ground resistance exceeds 4Ω. When local potential difference surpasses 10V, it activates the equipotential bonding switch to enhance localized protection.

5.4 System Workflows

The data acquisition module collects real-time parameters including ground resistance, potential difference, and lightning intensity. The intelligent control module processes the data and analyzes it, using a risk assessment model to determine the equipment's safety status. If the system enters the "alert" state, it issues an alert and recommends manual inspection. If it enters the "danger" state, the execution module automatically activates to adjust the grounding device and equipotential bonding. After adjustment, the system continuously monitors parameter changes until the equipment returns to a "safe" state, forming a closed-loop protection system.

6 Optimization of Safety Performance for Intelligent Grounding Protection System

6.1 Construction of Safety Risk Assessment Index System

To address the critical question of "how to establish a safety risk assessment indicator system," we constructed the framework from three dimensions: equipment characteristics, environmental factors, and protective measures. (1) Equipment-specific indicators: grounding resistance, insulation resistance, and operating temperature (weights: 0.3, 0.25, 0.15, respectively); (2) Environmental indicators: soil resistivity, lightning intensity, and air humidity (weights: 0.1, 0.1, 0.05, respectively); (3) Protective measures indicators: integrity of equipotential bonding and response speed of grounding systems (weights: 0.03,0.02, respectively). The weights for each indicator were determined through the Analytic Hierarchy Process (AHP), and the equipment's safety risk value was calculated using the Fuzzy Comprehensive Evaluation Method, providing a basis for system optimization.

6.2 Safety Analysis Based on Numerical Simulation

The system was numerically simulated using ANSYS Maxwell software to analyze safety performance under different operating conditions: Lightning strike simulation: With a lightning current peak of 200kA, the potential distribution between traditional and intelligent grounding systems was compared. Results showed that the intelligent system reduced the maximum potential difference in the grounding grid from 80V to 25V through rapid adjustment of grounding electrode depth, below the safety threshold (50V). Insulation damage simulation: When equipment insulation was damaged (leakage current 5A), the traditional system required 10 seconds for fault response, while the intelligent system triggered grounding discharge within 2 seconds, reducing leakage current elimination time by 80%. Humid environment simulation: In a bathroom scenario (85% humidity), the intelligent system maintained local potential differences below 5V through enhanced local equipotential bonding, achieving over 70% reduction compared to traditional systems (15-20V).

6.3 System Optimization Strategies

Grounding Parameter Optimization: Dynamically adjust the number and insertion depth of grounding electrodes based on soil resistivity. When soil resistivity exceeds 100Ω·m, add 2-3 auxiliary grounding electrodes to maintain grounding resistance below 4Ω. Enhanced Equipotential Bonding: In humid areas, implement a "multi-point parallel" equipotential bonding method by connecting metal pipelines and equipment casings to local grounding terminal plates via copper busbars, effectively reducing potential differences. Algorithm Optimization: Introduce machine learning algorithms (e.g., BP neural networks) to refine risk assessment models using historical operational data, achieving an early warning accuracy rate exceeding 92%.

7 Conclusion and prospect

This study designs an intelligent grounding protection system for construction installation projects, addressing safety requirements through risk assessment metrics and optimized hardware/software integration. Numerical simulations validate the system's effectiveness, demonstrating real-time monitoring and adaptive regulation of equipment grounding status and potential differences. The system's safety performance improves significantly under lightning strikes, insulation damage, and humid environments, with key parameters (grounding resistance, potential difference) fully compliant with the "Code for Acceptance of Electrical Construction Quality in Buildings". The established risk assessment framework quantifies equipment safety status, providing scientific basis for equipment protection strategy decisions in engineering practice.

This study's limitations include the absence of differentiated design for specific building types (e.g., high-rise buildings and industrial plants), with experimental validation still relying on simulated scenarios. Future research could focus on three key areas: (1) Optimizing system hardware deployment and control algorithms by integrating equipment layout characteristics of different building types to enhance system versatility; (2) Establishing a three-tier monitoring network (cloud-edge-device) through IoT technology to enable collaborative management of multi-building equipment protection systems; (3) Exploring the integration of AI with fault diagnosis to achieve precise grounding fault localization and self-healing repair, thereby further improving system intelligence.

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