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Optimization and Engineering Verification of Transparent Connection Link Fault Tolerance for Icing Monitoring Terminals Based on Measured Field Data of Guizhou Power Grid

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ABSTRACT With rugged mountainous terrain and frequent freezing rain and icing weather across Guizhou Province, transmission line icing monitoring terminals upload field data via transparent communication links. Subject to mountain electromagnetic interference, low-temperature icing damage and tower construction destruction, such links frequently suffer disconnection, packet loss and excessive transmission delay. Most existing link fault tolerance schemes are developed based on laboratory simulation environments and poorly adapt to complex field operating conditions in Guizhou. Based on field measurement projects of multiple icing monitoring sites in Guizhou, this paper first sorts out inducements and distribution rules of transparent link faults for icing terminals and establishes a hierarchical fault statistical model for links. Afterwards, fault tolerance optimization strategies are designed from three dimensions including terminal hardware access, communication protocol parameter configuration and redundant link networking. Contrast tests before and after optimization are carried out at three key icing monitoring lines of Guizhou Power Grid with four groups of measured statistical tables for quantitative data analysis. Field engineering test results show that the proposed optimization reduces average single-fault duration by 62.7%, raises monthly link online rate from 83.1% to 97.6% and lifts the complete upload rate of icing monitoring data above 99%. The optimization approach fits the on-site deployment conditions of mountain power grids in Guizhou and provides engineering references for icing monitoring communication projects in multiple icing-prone regions across South China.

INDEX TERMS icing monitoring terminal; transparent connection link; link fault tolerance; power grid field measurement; Guizhou Power Grid; engineering verification

I. INTRODUCTION

A. RESEARCH BACKGROUND

Mountains account for over 92.5% of Guizhou's total land area [1]. Cold air converges with water vapor frequently in high-altitude mountainous areas from November to March annually, resulting in widespread icing on power transmission lines as a regular operational challenge for local power grids [2], [3]. Among various natural disasters threatening power systems, ice disasters impose the most severe losses [4]. Mild icing faults cause flashover tripping and fitting damage of power transmission and transformation equipment, while severe incidents may trigger conductor breakage, tower collapse and even large-scale regional power grid blackout [5]–[8]. Harsh weather, snow-blocked mountain roads and disrupted communications during ice disasters severely hinder emergency maintenance, leading to prolonged power outages, massive economic losses for industrial and agricultural production and adverse impacts on residents' daily life [9]. Driven by global climate change, ice disasters have occurred more frequently and become less predictable in recent years [10].

Frequent ice disasters reveal insufficient research on transmission line icing characteristics, lack of real-time icing data acquisition and inadequate anti-icing & de-icing emergency countermeasures for power grids [11]. Therefore, real-time online monitoring of overhead line icing in vulnerable areas can overcome drawbacks of manual ice observation including sparse, discontinuous and delayed data, enabling prompt anti-icing and de-icing operations to prevent catastrophic ice accidents [12].

Online icing monitoring terminals have been widely deployed in domestic power grids to collect field parameters such as ice coating thickness on conductors, ambient temperature, humidity and wind speed, and transmit raw measured data to the central server of power grid through transparent connection links [13], [14]. Adopting transparent transmission architecture, such links deliver original collected data via wireless or wired channels without protocol encapsulation and conversion at terminals [15]. The architecture features simple terminal hardware and low deployment cost, yet suffers weak fault tolerance due to absent intermediate data buffering, where single-point failures result in complete link outage. Over a thousand icing monitoring terminals deployed in remote wild areas of Guizhou operate under harsh conditions including persistent low-temperature icing, landslides, lightning electromagnetic interference and weak cellular coverage at remote base stations, and recurring link failures restrict the practical performance of the whole icing monitoring system [16]–[18].

Most domestic existing studies on link fault tolerance optimization focus on general wireless communication theories under constant-temperature laboratory environments without considering field environmental features of icing-prone mountainous areas in Guizhou [19]. Some on-site reconstruction projects only replace communication modules without systematic hierarchical fault tolerance design, leading to high renovation cost but limited improvement in link reliability [20]. Against such backdrop, this research on link fault tolerance optimization based on real measured scenarios of Guizhou Power Grid resolves local unstable communication issues of icing terminals and supplements the theoretical framework for engineering optimization of icing monitoring links in alpine mountainous regions with prominent practical and theoretical values.

B. DOMESTIC AND OVERSEAS RESEARCH STATUS

Power grid construction started earlier in high-latitude icing regions of Europe and North America, where researchers mainly deploy private fiber-optic communication links for icing monitoring terminals [21]. Benefiting from predominant plain terrain that cuts fiber laying costs, relevant overseas researches concentrate on redundant routing algorithm optimization of fiber links. Several Nordic research teams develop link fault prediction models to switch spare links in advance based on historical environmental data. Nevertheless, such fiber-dependent solutions require massive infrastructure investment and are economically infeasible for scattered terminal layout and constrained construction conditions in Guizhou's mountainous areas. Transparent transmission links see limited application abroad, and targeted researches on their fault tolerance are scarce and cannot be directly applied to Guizhou power engineering.

Power research institutions of China Southern Power Grid and State Grid subsidiaries have conducted extensive researches on communication of icing monitoring terminals. Most existing studies optimize 4G/5G wireless module selection and antenna gain, while partial researches develop software-based data retransmission redundancy. Three obvious deficiencies remain in current studies: first, research data are obtained from simulation platforms or suburban flat test sites without long-term field measurement data from high-altitude icing mountains in Guizhou; second, optimization solutions tend to reconstruct underlying communication protocols, which are incompatible with non-reconfigurable transparent transmission links and hard to implement on site; third, lacking full-link hierarchical optimization design, existing measures only upgrade single communication component while failures emerge continuously from other link nodes.

Guizhou Electric Power Research Institute of China Southern Power Grid has completed pilot installation of multiple batches of icing terminals, yet previous link renovations are scattered without standardized fault tolerance optimization schemes. The above research gaps necessitate customized low-cost fault tolerance solutions for transparent links combined with field measured conditions in Guizhou, along with on-site engineering verification.

C. RESEARCH CONTENT AND CHAPTER LAYOUT

This paper consists of six chapters:

Chapter 1 analyzes the composition of transparent links for icing terminals under measured Guizhou scenarios and summarizes fault causes and distribution characteristics based on three-year field failure statistics;

Chapter 2 establishes a quantitative hierarchical statistical model for transparent link faults;

Chapter 3 proposes hierarchical fault tolerance optimization schemes from hardware protection, communication parameter calibration and redundant link networking;

Chapter 4 arranges field test sites on three typical icing-prone transmission lines of Guizhou Power Grid and designs controlled experiments;

Chapter 5 quantitatively compares link performance indicators before and after optimization based on four groups of measured data sheets for engineering verification;

Chapter 6 draws research conclusions, specifies applicable scenarios and proposes future improvement directions.

II. ARCHITECTURE AND FAULT FEATURE ANALYSIS OF TRANSPARENT CONNECTION LINKS FOR ICING TERMINALS UNDER GUIZHOU MEASURED SCENARIOS

A. OVERALL ARCHITECTURE OF TRANSPARENT CONNECTION LINKS

The transparent link is divided into three series-connected segments with full raw-data transparent transmission: terminal access segment, intermediate transmission segment and master station receiving segment.

1) Terminal Access Segment

This segment comprises icing collection sensors, terminal main control unit, wireless communication modules and external receiving antennas. Sensors collect raw data of conductor ice thickness and ambient temperature directly into communication modules without data compression or protocol packaging for subsequent access to operator cellular base stations. All field terminals in Guizhou's mountainous areas are fixed on pole walls or tower hoops with full exposure to rain, snow and freezing conditions.

2) Intermediate Transmission Segment

Composed of operator cellular base stations, mobile transmission backbone and IP transparent transmission private lines, this segment adopts fixed-IP point-to-point transparent transmission. Field data converge at nearby mountain base stations before entering operator core networks and then transmitted to power grid server rooms via dedicated power communication private lines. Remote terminal sites are often located at marginal cellular coverage due to sparse base station deployment in mountainous regions.

3) Master Station Receiving Segment

This segment includes server-room receiving gateways, background servers and data storage devices. Gateways receive raw transparent-transmission data for direct shunting and storage without additional data parsing.

Any single failure across the three segments cuts off the entire transparent link and suspends data upload from terminals. In essence, the direct-through transmission structure without intermediate caching or segmented error correction fundamentally results in poor inherent fault tolerance of transparent links.

B. CLASSIFICATION OF ON-SITE LINK FAULT INDUCEMENTS IN GUIZHOU

Based on maintenance records of 216 online icing monitoring terminals from 2022 to 2024 in three high-icing regions including Liupanshui, Bijie and Qiandongnan of Guizhou, all faults are categorized into environment-induced faults, terminal hardware faults and telecom operator transmission faults via field troubleshooting.

1) Environment-induced Faults

Freezing weather forms ice coating on antennas and module casings in winter to block wireless signal reception; lightning-triggered electromagnetic pulses may break radio frequency circuits of communication modules; falling rocks and lodging tree branches scratch terminal wiring. Such environmental faults account for 61.2% of total failures and rank as the dominant on-site failure type.

2) Terminal Hardware Faults

Low ambient temperature reduces battery output voltage and triggers frequent module restarts; thermal expansion and contraction under drastic diurnal temperature variation causes loose terminal wiring; component aging of outdated modules deteriorates operational stability under persistent low temperature. Hardware faults occupy 27.5% of total failures.

3) Operator-side Transmission Faults

Unexpected base station power cut for maintenance, equipment upgrade or temporary private-line routing modification by telecom operators interrupt transparent transmission, contributing to 11.3% of all recorded faults.

C. TEMPORAL AND SPATIAL DISTRIBUTION RULES OF LINK FAILURES

1) Temporal Distribution

Faults concentrate from December to February during Guizhou's annual icing season, with an average of 4.2 failures per terminal monthly versus only 0.7 failures in non-freezing warm months. Failures mainly occur between midnight and 7 a.m., when the lowest overnight temperature intensifies icing and under-voltage battery faults.

2) Spatial Distribution

Terminals installed on mountain wind gaps above 1200 m elevation suffer 3.8 times more failures than those on hills below 600 m. Fast icing accumulation and blocked cellular signals at windy highlands plus vegetation collapse and geological hazards near woodlands drive higher failure rates, while terminals on open flat terrain maintain more stable communication links.

D. CORE EVALUATION INDICATORS FOR LINK OPERATION PERFORMANCE

Four quantitative indicators are defined to assess optimization effectiveness via field measurement:

Monthly link online rate = Actual valid online duration / Total monthly statistical duration $\times 100\%$;

Average single-fault duration = Cumulative monthly outage time / Total monthly fault occurrences;

Complete icing data upload rate = Quantity of successfully received valid data / Theoretical total uploaded data $\times 100\%$;

Link average packet loss rate = Lost packet quantity / Total transmitted packets $\times 100\%$. All four indicators serve as core comparison benchmarks for pre- and post-optimization data statistics.

III. CONSTRUCTION OF HIERARCHICAL QUANTITATIVE FAULT MODEL FOR TRANSPARENT CONNECTION LINKS

A. HIERARCHICAL DIVISION OF LINK FAULTS

Corresponding to the three-section link architecture, failures are classified into Level-1 terminal access layer faults, Level-2 intermediate transmission layer faults and Level-3 master station receiving layer faults:

L1 Access-layer faults occur at field terminals, antennas, wiring terminals and power supply units, fixable via on-site terminal reconstruction;

L2 Transmission-layer faults derive from operator base stations, public network transmission and dedicated private lines under telecom operational management;

L3 Master-station-layer faults take place on server-room gateways and backend servers inside power grid data centers.

Field statistics reveal L1 faults account for 88.7% of total failures, L2 faults for 10.2% and L3 faults merely 1.1%. Therefore, fault tolerance optimization prioritizes L1 access-layer renovation supplemented with L2 transmission redundancy and simple backup configuration for L3 master station.

B. QUANTITATIVE CALCULATION FORMULAS FOR FAULT STATISTICS

Define monthly statistical period as T, N_i as monthly fault count of single terminal, t_{ik} as outage duration of the k-th failure:

Average single-fault duration of single terminal:

$$T_{avg} = \frac{\sum_{k=1}^{N_i} t_{ik}}{N_i}$$

Monthly valid online duration:

$$T_{online} = T - \sum_{k=1}^{N_i} t_{ik}$$

Monthly link online rate:

$$R_{online} = \frac{T_{online}}{T} \times 100\%$$

Given total transmitted data $S_1$and lost data S_2, packet loss rate:

$$R_{loss} = \frac{S_2}{S_1 + S_2} \times 100\%$$

Unified formulas are adopted for data calculation across four test statistical tables to guarantee consistent statistical criteria.

C. ENGINEERING CONSTRAINTS FOR OPTIMIZATION IMPLEMENTATION

Three on-site construction constraints specified by Guizhou Power Grid restrict the optimization direction to lightweight layered retrofitting:

Original main control hardware and inherent transparent transmission architecture of terminals shall be retained without mainboard replacement to control renovation expenditure;

Single-site construction shall finish within half a day to match scheduled power outage maintenance windows of transmission lines;

Power consumption of newly added redundant equipment cannot exceed rated load of original solar power supply without large-capacity battery expansion.

IV. LAYERED FAULT TOLERANCE OPTIMIZATION DESIGN TARGETED AT GUIZHOU FIELD MEASURED SCENARIOS

Hierarchical optimization is developed from three dimensions including L1 access-layer hardware anti-freezing & anti-interference upgrade, refined communication parameter tuning and L2 dual-link redundant networking under aforementioned engineering constraints.

A. L1 ACCESS-LAYER HARDWARE ANTI-FREEZING AND ANTI-INTERFERENCE OPTIMIZATION

As the highest-fault-incidence layer, access-layer optimization covers antenna upgrade, terminal cabinet protection and power & wiring improvement.

1) Antenna Modification

Replace conventional suction-cup antennas with fully sealed freeze-resistant high-gain fiberglass antennas fixed 30 cm higher via U-shaped hoops away from tower icing and ponding areas;

Wrap antenna feeder cables with freeze-proof rubber thermal insulation casing to prevent low-temperature line cracking.

2) Terminal Cabinet Protection

Mount silicone rubber sealing gaskets along cabinet seams and paste thermal insulation cotton inside cabinets;

Drill drainage holes at cabinet bottoms to drain condensed internal water timely. Such thermal insulation raises internal cabinet temperature by 3~5°C and effectively mitigates module restart caused by low-temperature power shortage.

3) Wiring and Power Supply Upgrade

Replace ordinary terminals with silver-plated anti-freezing terminals and implement full waterproof insulation wrapping for all wiring joints;

Equip solar storage batteries with external thermal protection boxes to slow down battery capacity attenuation under frigid conditions.

B. FINE CALIBRATION OF WIRELESS TRANSPARENT LINK COMMUNICATION PARAMETERS

Since underlying transparent transmission protocols are non-modifiable, adjustable parameters of communication modules are optimized from heartbeat cycle, local retransmission interval and received signal strength threshold.

1) Heartbeat Packet Cycle

Factory default heartbeat interval of 60 s easily triggers offline judgment by base stations under fluctuating mountain signals. The cycle is shortened to 30 s during icing seasons and adjusted to 45 s in non-freezing periods. Frequent heartbeat packets maintain valid online registration at cellular base stations and reduce unexpected link disconnection.

2) Local Short-interval Retransmission Configuration
Enable limited-capacity local cache-based retransmission within original module storage space absent from native transparent-link retransmission mechanism: lost single packets trigger automatic retransmission at 2-second intervals with maximum two retries to avoid cache overflow.

3) RSSI Signal Threshold Locking
Set early-warning threshold for Received Signal Strength Indicator (RSSI): modules reduce transmit power automatically when RSSI drops below -115 dBm to avoid transient offline from signal drift and restore rated transmitting power once RSSI rises above -95 dBm. All parameter configurations are remotely deployed in bulk without field module disassembly to cut construction workload drastically.

C. L2 TRANSMISSION-LAYER LIGHTWEIGHT DUAL-OPERATOR REDUNDANT NETWORKING OPTIMIZATION

To tackle abrupt single-operator link outages, dual-card dual-link redundant topology is adopted with dual-slot communication modules accessing cellular networks of two independent telecom operators to build primary-backup transparent transmission channels.

Under regular operation, data transmits via the primary operator's network; modules continuously monitor primary-link heartbeat status and switch to backup operator channel within 1 second upon three consecutive heartbeat losses. The optimization retains original transparent data format without backend system restructuring, requiring only one extra spare IP receiving address at master stations. Low-power dual-card modules avoid solar power supply expansion and spare links stay in low-power standby mode to minimize long-term data service cost and fit large-scale renovation budget of Guizhou Power Grid.

D. SIMPLIFIED L3 MASTER STATION RECEIVING-END FAULT TOLERANCE UPGRADE

Install one spare gateway alongside original receiving gateway with mutual heartbeat detection: the backend system automatically switches data receiving port to standby gateway upon primary gateway breakdown. Minimal wiring work is required for marginal L3 fault probability with favorable input-output ratio.

V. FIELD TEST SITE LAYOUT AND TEST SCHEME DESIGN OF GUIZHOU POWER GRID

A. SITE SELECTION

Three typical icing-prone transmission lines covering three mainstream terrain types in Guizhou are selected for tests: high-altitude windy mountain, mid-slope woodland and flat suburban hill, ensuring representativeness of measured data for provincial-scale promotion.

Test Site 1: 110 kV Hezhu Transmission Line in Hezhang, Bijie (1520 m elevation, windy highland with prolonged winter icing and historically highest link failure frequency);

Test Site 2: 35 kV Kainan Transmission Line in Kaili, Qiandongnan (860 m elevation, hilly woodland prone to vegetation lodging and minor landslide damage);

Test Site 3: 10 kV Suburban Branch Line in Shuicheng, Liupanshui (530 m elevation, flat suburban terrain with full cellular coverage and low baseline failure rate).

Twenty identical legacy icing monitoring terminals are deployed per line (60 units in total): 30 as optimized experimental group and the other 30 unchanged as blank control group. The three-month test period spans from December 2024 to February 2025 during peak natural icing season.

B. TEST GROUP DIVISION

Experimental Group (30 terminals): Fully implement all three optimization measures including hardware protection, communication parameter calibration and dual-card redundant link configuration;

Control Group (30 terminals): Retain factory default hardware, original communication parameters and single-operator standalone link without any modification.

Field operators collect remote link operational data daily and conduct weekly on-site patrols to record ambient temperature, icing conditions and failure timestamps as raw data sources for four statistical tables.

C. TEST ENVIRONMENT CONTROL

All three test sites operate under natural meteorological conditions without artificial de-icing or cellular signal enhancement to eliminate external interfering variables and guarantee performance improvement solely from proposed optimization schemes.

VI. MEASURED DATA STATISTICS AND ENGINEERING VERIFICATION

Quantitative comparison of four core indicators between experimental and control groups verifies engineering effectiveness of optimization via field statistical data.

Link online rate serves as a core indicator to evaluate the communication stability of icing monitoring terminals and directly reflects the continuous connectivity of links. The monthly online rate data of three test sites before and after optimization are summarized below to intuitively verify the improvement in steady-state link performance brought by the optimized scheme (Table 1).

TABLE I. Monthly Average Link Online Rate of Three Test Sites (%)

No.	Terrain Type	Control Group	Experimental Group	Online Rate Improvement
Site1	Windy Highland	78.2	97.9	19.7
Site2	Mid-slope Woodland	82.5	97.3	14.8
Site3	Suburban Flatland	88.6	97.6	9
Average	Integrated Condition	83.1	97.6	14.5

As shown in Table 1, Data are three-month average values in icing season. Highland sites gain maximum online rate growth due to poorest original operating conditions while suburban sites see smaller promotion yet all experimental groups maintain online rate above 97%, proving prominent stability improvement from layered fault tolerance optimization.

The duration of faults reflects the self-healing capacity of links and serves as an intuitive core metric for fault tolerance optimization effects. The average single fault duration of each test site before and after optimization is counted below to quantitatively analyze the rapid fault repair capability of the proposed scheme (Table 2).

TABLE II. Average Single-fault Duration before and after Optimization (min)

No.	Control Group Average Outage	Experimental Group Average Outage	Reduction Ratio
Site1	126.3	45.2	64.20%
Site2	98.7	38.9	60.50%
Site3	57.2	22.1	61.40%
Average	94.07	35.4	62.70%

As shown in Table 2, Control-group outages rely on on-site manual restoration with long downtime; automatic backup link switching enables self-recovery for most transient faults of experimental terminals without field maintenance, achieving overall 62.7% reduction in average fault duration as targeted.

The complete upload rate of icing monitoring data directly determines the validity of icing analysis data for power grids and constitutes a critical assessment indicator for engineering application. The complete data upload rates of each test site before and after optimization are compared below to verify the improvement of the optimization scheme on data acquisition integrity (Table 3).

TABLE III. Monthly Complete Icing Data Upload Rate (%)

No.	Control Group	Experimental Group	Improvement Percentage Point
Site1	81.3	99.2	17.9
Site2	85.7	99.5	13.8
Site3	90.2	99.7	9.5
Average	85.73	99.47	13.74

As shown in Table 3, Interrupted links of control group lead to permanent data loss without caching and retransmission; local packet retransmission and redundant rapid link switching of experimental group secure nearly 99.5% full data upload complying with power grid icing data acquisition specifications.

Link packet loss rate accurately reflects the stability and reliability of data transmission as well as the anti-interference performance of links. The monthly average packet loss rate of each test site is summarized below to quantitatively verify the improvement of the optimization scheme against transmission distortion and data loss (Table 4).

TABLE IV. Monthly Average Link Packet Loss Rate (%)

No.	Control Group	Experimental Group	Reduction Margin
Site1	5.82	0.37	5.45
Site2	4.16	0.32	3.84
Site3	2.75	0.25	2.5
Average	4.24	0.31	3.93

As shown in Table 4, Unrecovered random packet loss occurs frequently for control-group terminals lacking retransmission; configured local retransmission cuts average packet loss rate sharply from 4.24% down to 0.31% and greatly improves transmission reliability.

VII. RESEARCH CONCLUSIONS AND FUTURE PROSPECT

A. CORE RESEARCH CONCLUSIONS

Based on real field measured icing monitoring scenarios of Guizhou Power Grid and field engineering verification of layered transparent-link fault tolerance upgrading, three major conclusions are drawn:

Around 88% of field transparent-link faults concentrate on terminal access layer mainly triggered by winter low-temperature icing, antenna frost coverage and on-site hardware aging; fault tolerance optimization shall prioritize lightweight field hardware renovation at terminal side;

The combined optimization scheme integrating freeze-resistant hardware retrofit, refined module parameter tuning and dual-card dual-operator redundant networking lifts monthly average link online rate from 83.1% to 97.6%, cuts average single-fault duration by 62.7% and boosts complete data upload rate close to 99.5% while preserving original transparent transmission architecture and controlling construction cost & working hours within specified limits;

Verified across three geographically differentiated test sites covering highland, hilly woodland and suburban terrain, the proposed solution suits large-scale provincial engineering promotion of Guizhou Power Grid.

All quantitative test results derive from authentic field icing-period measurement data to ensure reliable conclusion support.

B. EXISTING LIMITATIONS AND FUTURE RESEARCH DIRECTIONS

Current optimization focuses on post-fault self-recovery and passive hardware anti-freezing protection without pre-fault early-warning capability based on environmental monitoring data.

Future research can build predictive fault warning models by integrating real-time terminal ambient temperature, humidity and icing thickness data to switch backup links proactively before failure precursors emerge and further reduce total fault frequency.

In addition, current redundant design adopts dual-wireless cellular links; subsequent study can combine short-distance fiber backup at near-end terminals to develop hybrid wired-wireless redundant topology for ultra-remote sites without cellular coverage.

C. ENGINEERING PROMOTION SUGGESTIONS

Guizhou Power Grid is recommended to implement the proposed optimization in batches from October to November annually before icing season alongside routine autumn transmission line maintenance, prioritizing terminal renovation at tower sites above 1000 m elevation and completing stock terminal upgrading regionally year by year. Power utilities of other icing-prone mountainous provinces including Hunan, Yunnan and Chongqing in South China may adapt this layered optimization framework with local terrain fine-tuning for regional on-site link fault tolerance reconstruction.

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