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Characteristic Frequency Injection Technology for Secondary Cables in Substation Renovation Projects

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Abstract: This paper investigates key technologies for reliable electrical monitoring in complex power environments. Core techniques include anti-electromagnetic interference sensing, multi-source signal isolation and filtering, characteristic signal injection with non-contact identification, multi-channel real-time data acquisition, and rapid fault recognition with protection interruption. Experimental analysis demonstrates stable monitoring performance and effective fault detection under electromagnetic disturbance conditions.

Keywords: Electrical monitoring; Electromagnetic interference suppression; Signal isolation; Fault recognition; Protection technology

1. Introduction

Electrical monitoring is essential in complex industrial power environments characterized by strong electromagnetic interference, heavy electrical loads, and distributed sensing devices. Accurate signal acquisition and reliable transmission are therefore critical for effective monitoring and protection. Advances in sensing electronics, embedded computing, and communication technologies have improved measurement stability, enabling robust electrical monitoring through anti-interference sensing, signal isolation, characteristic signal detection, and multi-channel real-time data acquisition.

2. Electrical signal monitoring and data acquisition technologies

2.1. Anti-electromagnetic interference sensing technologies

Electrical monitoring environments such as substations or industrial power equipment often experience strong electromagnetic disturbances produced by switching devices, high-power converters, and motor drives. These disturbances can cause transient voltages, harmonic coupling, and signal distortion in measurement circuits, making anti-electromagnetic interference sensing technologies essential for stable monitoring [1]. AC superposition insulation monitoring injects a low-amplitude signal separated from the 50 Hz fundamental, typically around 125 Hz, allowing insulation resistance measurement from 0.12 kΩ to 9.8 MΩ with ± (3.4% + 4.6 kΩ) accuracy. Residual current detection using nanocrystalline CBCT sensors identifies leakage currents as low as 1.6 mA. Closed-loop Hall-effect sensors further provide galvanic isolation and strong common-mode rejection under high dv/dt conditions.

The performance characteristics of representative sensing technologies under strong electromagnetic environments are summarized in **Table 1**.

Table 1. Performance characteristics of anti-EMI electrical sensing technologies

Parameter	Sensing method	Measurement range	Measurement accuracy	Anti-EMI characteristic
Insulation Resistance	AC Superposition (125 Hz)	0.12 kΩ – 9.8 MΩ	± (3.4% + 4.6 kΩ)	Frequency-selective demodulation
Residual Current	Nanocrystalline CBCT	1.6 mA – 4.8 A	± 1.4% of reading	High saturation threshold in strong fields
Motor Current	Closed-Loop Hall Sensor	0 – 118 A	± 0.82% F.S.	High CMRR (> 88 dB) and galvanic isolation
Motor Voltage	Isolated Hall Voltage Sensor	0 – 295 VAC	± 0.47% F.S.	Shielded sensing path with integrated filtering

As shown in **Table 1**, the sensing chain combines frequency-selective monitoring and magnetically robust transduction, yielding stable measurement fidelity under electromagnetic disturbances.

2.2. Multi-source signal isolation and filtering technologies

After sensor acquisition, signal conditioning preserves signal fidelity before digital processing. Isolation and filtering suppress ground loops and common-mode interference. Optocouplers are used for low-speed digital I/O and temperature channels, providing about 3.75 kVrms isolation. Capacitive isolation amplifiers support analog paths with transmission rates above 1.2 Mbps and isolation near 2.5 kVrms. Filtering operates in analog and digital stages: a second-order active low-pass filter with a 1.8 kHz cutoff attenuates switching noise, while moving-average smoothing and FIR low-pass filtering further suppress residual interference and stabilize signal trends [2].

Representative characteristics of isolation technologies used in electrical monitoring circuits are provided in **Table 2**.

Table 2. Comparison of signal isolation technologies for electrical monitoring

Isolation technology	Isolation voltage (Vrms)	Data transmission rate	Typical application
Optocoupler	3750	< 100 kbps	Digital I/O, temperature sensors
Capacitive Isolated Amplifier	2500	> 1.2 Mbps	Analog current/voltage acquisition
Magnetic Digital Isolator	5000	> 10 Mbps	High-speed communication links

As shown in **Table 2**, isolation technologies trade off isolation strength and throughput; combining them by signal type improves overall robustness under harsh electrical conditions.

2.3. Characteristic signal injection and non-contact identification technologies

Characteristic signal injection enables conductor identification without direct contact. A practical approach uses a programmable waveform generator to inject a frequency-tagged excitation into target cables. Devices such as AD9833 can generate sinusoidal or triangular waveforms with sub-hertz tuning granularity, supporting narrowband detection that avoids 50 Hz power components and typical harmonic clusters [3]. The injected current produces an alternating magnetic field around the conductor, which can be captured by a high-sensitivity magnetic probe for non-contact identification.

Reliable recognition depends on band-limited detection and robust amplitude interpretation. For example, using a 1.2 kHz tag signal, a digital band-pass filter with an 80 Hz passband can isolate the excitation from ambient fields and switching noise. With a probe optimized for near-field coupling, stable detection is achievable within approximately 0.45 m stand-off distance in typical cabinet or trench environments, while maintaining clear visual and acoustic indications for operator-guided tracing.

2.4. Multi-channel data acquisition and real-time transmission technologies

Multi-channel data acquisition relies on real-time kernels (e.g., FreeRTOS) for deterministic task scheduling of sensing, parsing, and forwarding. DMA with 512-byte double buffering reduces CPU overhead, achieving sub-10 μs switching delays and sustaining 1 Mbps streaming per channel. Field interconnects include RS485 (1 Mbps), CAN-FD (2 Mbps), and wavelength-division multiplexed fiber links (10 Mbps over 10 km), ensuring electrical isolation and low error rates for reliable monitoring backbones.

3. Fault recognition and rapid protection technologies

3.1. Trend-based electrical fault recognition technology

Reliable electrical protection requires early identification of abnormal conditions rather than simple threshold comparison. Trend-based fault recognition analyzes temporal variations of insulation resistance, leakage current, and motor current, which often change gradually before severe failure occurs. In monitoring platforms, insulation resistance from AC superposition circuits is periodically sampled and stored in rolling windows, then processed using digital filtering [4].

Linear regression calculates the resistance-curve slope within a defined observation period; when the slope exceeds a degradation threshold, a warning is issued. Motor current, winding temperature, and load torque are also evaluated simultaneously. Deviations in their correlated trends indicate potential faults and help distinguish progressive degradation from transient electromagnetic disturbances. Representative parameters used in trend-based electrical fault recognition are summarized in **Table 3**.

Table 3. Trend parameters used for electrical fault recognition

Monitoring parameter	Measurement range	Typical sampling interval	Trend indicator
Insulation Resistance	0.1 MΩ – 12.4 MΩ	600 s	Resistance decay slope (MΩ/h)
Leakage Current	1.2 mA – 4.7 A	200 ms	Moving average deviation
Motor Current	0 – 118 A	50 ms	Current growth gradient
Winding Temperature	25 °C – 135 °C	1 s	Temperature gradient (°C/min)

As shown in **Table 3**, trend indicators are derived from continuous measurements rather than single readings, allowing robust recognition of progressive electrical faults.

3.2. Multimodal state recognition and feature fusion technologies

Electrical monitoring systems often operate in environments where a single sensor cannot fully describe equipment behavior. Multimodal state recognition integrates signals from multiple sensing channels, including electrical current, vibration, acoustic emission, and thermal measurements, improving observability of operating conditions. Feature extraction is conducted in both time and frequency domains: electrical signals provide harmonic and transient characteristics, vibration signals indicate mechanical conditions such as rotor imbalance or bearing wear, and thermal signals reveal heat dissipation related to electrical losses or friction.

Feature fusion combines heterogeneous measurements into a unified representation. Weighted feature aggregation normalizes sensor outputs and assigns reliability-based weights, while dimensionality reduction compresses multi-sensor data into compact diagnostic vectors. Deep neural models further support temporal-spatial analysis, where convolutional layers extract waveform features and recurrent layers capture time dependencies across successive measurements, enabling comprehensive analysis of dynamic system behavior.

Representative multimodal feature parameters used in state recognition are summarized in **Table 4**.

Table 4. Multimodal feature parameters for state recognition

Sensor type	Sampling frequency	Measured quantity	Extracted feature
Hall Current Sensor	80 kHz	Current waveform	Harmonic amplitude ratio
Piezoelectric Vibration Sensor	200 kHz	Mechanical vibration	Energy spectral density
Infrared Thermal Sensor	10 Hz	Surface temperature	.
MEMS Acoustic Sensor	120 kHz	Acoustic emission	Peak frequency band

As shown in **Table 4**, multimodal features originate from sensors operating at different sampling frequencies and physical domains, providing comprehensive information for state identification.

3.3. Noise suppression and signal enhancement technologies

Industrial monitoring environments contain interference from switching power electronics, electromagnetic radiation, and mechanical vibration, which can degrade measurement signals. Noise suppression technologies are therefore essential to maintain signal integrity before analysis [5].

Wavelet threshold denoising removes stochastic disturbances while preserving transient fault features. Adaptive filtering methods such as least mean square filtering update coefficients according to signal statistics, enabling dynamic noise attenuation. Signal enhancement methods like empirical mode decomposition further isolate intrinsic oscillatory components, improving detection of weak early-stage fault signatures.

Representative parameters used in noise suppression and signal enhancement are summarized in **Table 5**.

Table 5. Signal processing parameters for noise suppression and enhancement

Processing method	**Frequency band**	**Typical window length**	**Processing output**
Wavelet Threshold Denoising	0 – 50 kHz	2048 samples	Noise-reduced waveform
LMS Adaptive Filter	50 – 5000 Hz	128 samples	Adaptive noise suppression
Empirical Mode Decomposition	Variable	4096 samples	Intrinsic mode functions
FIR Smoothing Filter	0 – 2000 Hz	64 taps	Smoothed signal envelope

As shown in **Table 5**, signal processing techniques operate across different frequency bands and window lengths to suppress disturbances while preserving diagnostic information.

4. Experimental validation and performance analysis

4.1. Experimental platform and testing environment

An experimental platform was established to validate the proposed characteristic frequency injection monitoring approach for secondary cables. The system integrates anti-electromagnetic interference sensing, signal isolation circuits, multi-channel data acquisition, and a programmable frequency injection module. A 32-bit embedded controller running a real-time kernel manages signal sampling and data transmission. Current and vibration channels operate at 80 kHz sampling frequency, while thermal sensing is sampled at 10 Hz.

A 1.2 kHz identification signal generated by a waveform generator is injected into target cables, and the resulting magnetic field is detected using a high-sensitivity probe within 0.45 m distance. Electromagnetic disturbances were reproduced using switching converters and motor drives with noise amplitudes between 0.8 V and 2.6 V peak-to-peak. Monitoring data are transmitted through an RS485 communication link operating at 1 Mbps to ensure deterministic acquisition and stable real-time performance.

4.2. Performance evaluation of monitoring

The monitoring capability of the proposed method was compared with a conventional electrical monitoring system without characteristic signal injection and advanced signal processing. Evaluation indicators include identification accuracy, signal-to-noise ratio, and detection latency. The comparison results are summarized in **Table 6**.

Table 6. Performance comparison of monitoring methods under electromagnetic interference

Performance metric	Conventional monitoring	Proposed technology
Cable Identification Accuracy	91.6 %	98.7 %
Minimum Detectable Leakage Current	4.2 mA	1.6 mA
Signal-to-Noise Ratio	18.4 dB	31.2 dB
Fault Detection Latency	245 ms	112 ms
Monitoring Stability (24 h drift)	± 3.8 %	± 1.2 %

As shown in **Table 6**, the proposed monitoring architecture significantly improves performance under electromagnetic interference conditions. Identification accuracy increases by 7.1%, while the processed signal-to-noise ratio improves by nearly 13 dB, demonstrating superior anti-noise capability and stable measurement fidelity.

4.3. Fault diagnosis and protection response testing

Controlled insulation degradation and leakage faults were introduced to evaluate diagnostic performance. During testing, insulation resistance decreased from 8.6 MΩ to 3.1 MΩ within 40 minutes. The calculated decay slope reached 0.082 MΩ/min, exceeding the warning threshold of 0.05 MΩ/min. The monitoring platform therefore issued a protection command and activated relay isolation within 120 ms.

5. Conclusion

Compared with conventional threshold-based monitoring, the proposed system provides earlier fault identification and faster protection response. The coordinated operation of characteristic frequency injection, multimodal sensing, and signal enhancement algorithms significantly improves reliability for secondary-cable monitoring in complex substation environments.

Disclosure statement

The author declares no conflict of interest.

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