# Design and Application of a State Monitoring System for Transformers and Gas-Insulated Cable Switchgear

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**Abstract:** To ensure the safe operation of core equipment in the smart grid and to solve the problems of large blind spots, delayed warnings, and high costs in the traditional periodic maintenance model, this paper carries out the design and application research of a state monitoring system for transformers and gas-insulated cable switchgear (GIS). The system takes the Internet of Things and multi-sensor fusion technology as the core, builds a four-layer architecture of "perception–transmission–platform–application," uses multiple types of sensors such as UHF and fiber-optic temperature measurement to comprehensively collect key equipment parameters, adopts dual-channel data transmission through 4G/5G and optical fiber, and achieves intelligent diagnosis by combining wavelet packet decomposition and machine learning models, together with 3D visualization and a three-level warning module. Through laboratory testing and field verification in a 220 kV substation, the system achieves a fault-diagnosis accuracy ≥95% and data-transmission delay ≤50 ms, reduces manual inspection frequency by 60% and maintenance costs by 45%, effectively promoting the transformation of operation and maintenance modes toward "condition-based maintenance," and providing a reliable technical solution for the efficient operation and maintenance of smart grid equipment.

**Keywords:** transformer; Gas insulated cable switchgear (GIS); Status monitoring; Internet of Things; Multi sensor fusion

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## Introduction

Power transformers and gas insulated cable switchgear (GIS) are the core components of power grid operation, responsible for key functions such as energy transmission, distribution, and control. Their insulation status directly affects power supply reliability and grid safety. With the expansion of the power grid scale and the increase in equipment complexity, the traditional regular maintenance mode is no longer suitable for the refined operation and maintenance requirements of modern power grids. There are limitations such as large blind spots in maintenance, lagging fault warning, and high operation and maintenance costs. Partial discharge monitoring, as an effective means of evaluating the insulation status of equipment, can capture early defect signals and provide a scientific basis for condition based maintenance. In recent years, sensor technology, IoT architecture, and artificial intelligence algorithms have developed rapidly, and intelligent monitoring systems based on multi-source information fusion have become an important direction for the operation and maintenance of power equipment. This article is based on multi-sensor fusion and intelligent analysis technology to design an online monitoring system suitable for transformers and GIS equipment. Through hardware architecture optimization, software algorithm innovation, and engineering application verification, a complete equipment status monitoring solution is constructed to support the efficient operation and maintenance of smart grids.

## 1 Working principle of transformer and gas-insulated cable switchgear

Transformers transmit electrical energy through the principle of electromagnetic induction. The core components include the iron core, winding, insulation oil, and bushing. During operation, it is necessary to maintain the insulation performance of the winding and the stability of the iron core magnetic circuit to avoid faults caused by local overheating and insulation aging. Gas insulated cable switchgear (GIS) uses $SF_6$ gas as the insulation medium, integrating circuit breakers, isolating switches, and other components into a metal sealed enclosure. It has the characteristics of small footprint and excellent insulation performance. However, internal partial discharge, $SF_6$ gas leakage, or excessive humidity can easily lead to insulation failure, affecting the safe operation of the equipment. Both types of equipment require real-time monitoring of key parameters, such as dissolved gases in transformer oil, winding temperature, partial discharge signals, as well as $SF_6$ gas density, micro water content, and partial discharge characteristics of GIS equipment, to provide data support for equipment health assessment[1].

## 2 Overall Design of State Monitoring System

### 2.1 System design objectives and principles

The system design goal is to build an intelligent online monitoring system that integrates multi-source parameter collection, efficient data transmission, intelligent analysis and processing, visual display, and graded warning. In terms of real-time collection of full parameters, a distributed monitoring network is constructed through various sensors such as ultra-high frequency, ultrasonic, pulse current, fiber optic temperature measurement, and gas analysis to achieve comprehensive collection of dissolved gases in transformer oil, winding temperature, iron core grounding current, as well as $SF_6$ gas parameters and partial discharge signals of GIS equipment. The sensors need to work stably in a wide temperature range from -40 ℃ to +85 ℃ and a high humidity environment ≤95% RH, combined with dynamic gain adjustment and noise suppression algorithms to ensure accurate signal capture.

### 2.2 Overall System Architecture Design

The system adopts a layered architecture, including perception layer, transport layer, platform layer, and application layer. Deploying various sensors such as ultra-high frequency, ultrasound, temperature, and gas in the perception layer, combined with visual devices and handheld terminals, achieves comprehensive perception of device parameters and environmental status; the transmission layer uses fiber optic intranet as the main channel, supplemented by 4G/5G, LoRa, and WAPI wireless networks, to ensure secure data transmission through APN and meet the communication needs of different areas within the substation.

### 2.3 System functional requirement analysis

The system needs to meet multi-dimensional functional requirements, and the parameter acquisition function needs to cover the key operating parameters of transformers and GIS equipment, achieving a 24-hour continuous monitoring; the data processing function needs to complete signal filtering, feature extraction, and multi-source data fusion, eliminate environmental interference, and improve data quality; the state assessment function uses fault diagnosis algorithms to determine the health level of equipment and generate a health assessment report; the warning function triggers different levels of warnings based on parameter limits, abnormal trends, or serious faults to guide operation and maintenance decisions; the visualization function is based on 3D models and geographic information systems, providing a visual display of equipment status and fault locations.

## 3 System hardware design

### 3.1 Sensor selection and layout

In terms of transformer sensors, high-precision sensors using chromatographic technology are used for gas monitoring in oil, and fault types are analyzed through the three ratio method and David's triangle method; partial discharge monitoring uses ultra-high frequency sensors with a sensitivity of ≤ 1pC, deployed on the walls of the main body to capture signals in the frequency range of 300MHz-3GHz; voiceprint vibration monitoring uses a vibration acceleration sensor with a frequency response of 0.1-10kHz, installed on the fuel tank wall to identify mechanical faults; the winding fiber optic temperature measurement adopts distributed fiber optic sensors, laid along the winding, with a temperature measurement accuracy of ± 0.5 ℃; monitoring of iron core clamps uses 0-10A range current sensors to determine multi-point grounding faults; the insulation monitoring of the casing adopts capacitive sensors to evaluate the degree of aging; it is also simultaneously equipped with digital meters to monitor oil temperature, oil pressure, and oil level. GIS equipment sensors include ultra-high frequency sensors deployed at cavity flanges or bowl insulators to monitor partial discharge.

### 3.2 Design of Data Collection Module

The data acquisition module adopts a high-speed sampling rate chip of ≥ 100MHz, supports multi-channel synchronous acquisition, has a resolution of 16 bits, and meets the requirements of high-precision signal acquisition. The module is equipped with an adaptive filtering algorithm to suppress power frequency interference, improve signal-to-noise ratio, and support dynamic threshold adjustment to cope with signal mutation scenarios. Design preamplifier and filtering circuits with adjustable gain to ensure signal quality, and use industrial grade chips resistant to electromagnetic interference to ensure stable operation in complex electromagnetic environments in substations. The module needs to cooperate with the edge computing gateway to transmit data through Modbus RTU, DL/T860 and other protocols, so as to achieve efficient connection between acquisition and processing[2].

### 3.3 Communication module and hardware interface design

The communication module supports 4G/5G, LoRa, and fiber optic communication, with a data transmission rate of ≥ 10Mbps and a breakpoint resume function to ensure that data is not lost. The edge computing gateway is integrated into the communication module to achieve local data pre-processing, such as feature extraction, exception data filtering, and reduce the cloud computing load. The gateway supports container deployment for easy function expansion. The hardware interface adopts standardized design, and the sensor interface supports RS485, Ethernet and other types. The communication interface is compatible with fiber optic ports and 4G/5G card slots. The power supply interface has overvoltage and overcurrent protection to ensure stable connection of various hardware modules. At the same time, it is compatible with devices from different manufacturers, which improves system scalability.

## 4 System software design

### 4.1 Overall software architecture

The software adopts a modular architecture, covering four major modules: data reception and storage, data processing and analysis, status assessment and warning, and human-computer interaction interface. The data receiving and storage module supports protocols such as IEC61850 and Modbus for data access. It uses PRP parallel redundancy protocol to ensure reliable transmission through dual Ethernet cards, and combines private network communication and data encryption technology to prevent illegal access. The edge preprocessing function reduces transmission redundancy; the data processing and analysis module is based on a streaming processing framework to achieve millisecond level response and support historical data backtracking; fault diagnosis algorithms and warning mechanisms are integrated into the state assessment and warning module.

### 4.2 Development of Data Processing and Analysis Module

The data processing and analysis module adopts wavelet packet decomposition technology to achieve multi-resolution analysis of signals, extract instantaneous frequency and energy features, and design feature extraction algorithms to complete automatic fault classification. Partial discharge data is processed using adaptive filtering techniques to eliminate environmental noise and enhance the sensitivity of detecting weak signals[3]. Introducing a machine learning hybrid model, combined with attention mechanism to enhance the attention of key features, to achieve short-term and long-term trend prediction of faults. Bayesian optimization is used for hyperparameter tuning, and an evaluation index system is designed to monitor model performance and automatically alert.

### 4.3 Design of Status Assessment and Early Warning Module

The state assessment module is based on data processing results, combined with historical operating data of the equipment and expert knowledge base, to construct a health state assessment model. It evaluates the health level of the equipment from the dimensions of insulation performance, mechanical performance, and thermal performance, generates health reports, and proposes maintenance suggestions. The warning module is equipped with a three-level warning mechanism: the first level warning (parameter limit exceeding) prompts manual inspection, the second level warning (abnormal trend) initiates automatic diagnosis, and the third level warning (serious fault) triggers emergency shutdown. Warning information is displayed in the form of pop ups, map annotations, global banners, etc.

### 4.4 Human Computer Interaction Interface Development

The human-computer interaction interface covers homepage overview, comprehensive monitoring, real-time monitoring, intelligent analysis, system settings, alarm management, user management, and role management functions. The overview of the homepage displays the overall operating status and key indicators of the equipment; comprehensive monitoring presents the distribution and topological relationships of equipment through geographic information systems; real time monitoring uses color coding (red/yellow/green) to visually display device status and supports second level data refresh; the intelligent analysis module provides PRPD graph, waveform analysis, and historical data trend comparison functions; alarm management categorizes and displays warning information, supporting fault tracing; The system settings and user management module ensure system security and permission control. The interface supports PC and mobile access, with simple and intuitive operation, meeting the needs of different operation and maintenance scenarios[4].

## 5 System testing and application verification

### 5.1 Laboratory testing

During the laboratory testing phase, a simulated substation environment is set up to comprehensively verify the hardware and software of the system. In hardware testing, detect the acquisition accuracy of sensors under different temperature, humidity, and electromagnetic interference conditions to ensure that the error meets the design requirements; test the transmission speed and stability of the data acquisition module and communication module, and verify the effectiveness of the breakpoint resume function. Software testing injects simulated fault signals to verify the accuracy of feature extraction and fault diagnosis of data processing algorithms, and evaluates the response speed and warning level matching of the warning module. The test results show that the sensor acquisition accuracy error is ≤ 2%, the data transmission delay is ≤ 50ms, and the fault diagnosis accuracy is ≥ 95%, meeting the system design specifications. The comparison of multi-scenario test data is shown in Table 1:

Table 1: Comparison of Multi-Scenario Test Data

| Test Dimension | Test Indicator | Laboratory Simulation Scenario | 220kV Substation Field Scenario | Design Standard | Scenario Difference Analysis |
|---|---|---|---|---|---|
| Hardware Performance | Sensor Measurement Accuracy Error | ≤1.2% | ≤1.8% | ≤2% | Complex electromagnetic environment on site leads to slightly higher error than in the lab, but still meets standards |
| | Data Transmission Delay | ≤35ms | ≤48ms | ≤50ms | Concurrent transmission from multiple devices on site pushes delay close to the limit, but still within requirements |
| | Resume Transmission Success Rate | 100% | 99.8% | ≥99.5% | Laboratory network is stable; on-site signal fluctuations have minor impact |
| Software Efficiency | Fault Diagnosis Accuracy | 97.2% | 95.6% | ≥95% | On-site faults are more complex, but accuracy still meets design standards |
| | Warning Response Time | ≤2s | ≤3s | ≤5s | Larger on-site data volume slightly increases response time |
| | Consistency Between Warnings and Faults | 100% (simulated faults) | 100% (3 actual faults) | ≥98% | Hardware and software are well adapted; on-site validation confirms reliability |
| Application Effectiveness | Data Collection Accuracy | - | ≥98.5% | ≥98% | Achieves 24-hour real-time collection of all parameters, capturing instantaneous abnormal signals |

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| | Reduction Rate of Manual Inspections | - | 60% | ≥50% | Remote monitoring replaces many on-site inspections, significantly improving efficiency |
| | Reduction Rate of Maintenance Costs | - | 45% | ≥40% | Accurate warnings reduce blind maintenance and resource consumption |
| | Reduction Rate of Unplanned Downtime | - | 30% | ≥25% | Early defect detection reduces the risk of fault escalation |

## 5.2 On site application deployment

Select a 220kV substation for on-site deployment, which is equipped with 2 main transformers, 10 interval GIS equipment, and supporting cable switchgear. The equipment will operate for 5-10 years. Install and debug various sensors in the perception layer; deploy oil chromatography analysis devices and partial discharge sensors in transformers; install $SF_6$ gas monitoring and ultra-high frequency sensors in GIS equipment; and configure the corresponding monitoring components in cables and switchgear. Deploy a station monitoring platform for the data collection and communication layer, with each device equipped with a dedicated collection module. Centralized devices communicate through Ethernet, while remote devices use 4G transmission; deploy servers, databases, and mobile operation and maintenance apps at the software layer, complete integration and debugging with existing systems on the site, and ensure stable system operation[5].

## 5.3 Analysis of Test Results and Application Effectiveness

After the system runs, the test results show that in terms of monitoring capability, it can achieve 24-hour real-time collection of all parameters, with a data accuracy rate of ⩾ 98%, and capture instantaneous abnormal signals missed by multiple manual inspections. In terms of warning accuracy, three internal discharge defects of GIS equipment were successfully warned, and the accuracy of the warning was 100% consistent with the actual fault. The operation and maintenance personnel promptly dealt with them to avoid the expansion of the fault.

# 6 Conclusion

The transformer and gas insulated cable switchgear status monitoring system designed in this article is based on multi-sensor fusion and intelligent analysis technology, and constructs a hierarchical architecture online monitoring system to achieve full parameter acquisition, intelligent diagnosis, and graded warning of equipment. Laboratory testing and on-site application verification have shown that the system has stable performance and complete functions, which can effectively improve equipment operation and maintenance efficiency, reduce fault risks, and provide reliable technical support for the construction of smart grids. In the future, we can further integrate digital twin and 5G edge computing technologies, optimize fault prediction algorithms, expand the application of the system in new energy stations and industrial distribution scenarios, and continue to promote the intelligent upgrade of power equipment operation and maintenance.

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