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Evaluation Method and System Integration of Insulation Condition of Transformer High-voltage Bushing for Online Monitoring

Yubin Wang [1,*], Jie Li [1], Lidong Yan [1], Hua Fu [1], Wenpeng Sun [1], Meng Li [1], Xinge Xu [1], Chen Wang [1], Bihua Yin [1], Tianxu Zhang [1]

[1] State Grid Tianjin High Voltage Company

Abstract

As one of the key components in the design and application of transformers, the insulation performance of transformer bushings directly affects the safe and stable operation of the power system. Due to the long-term influence of multiple factors such as electrical stress, load fluctuations, and environmental conditions on transformer bushings, their actual application performance is likely to gradually deteriorate, and there is a potential risk of failure during system operation. Therefore, based on the research results of the application of online monitoring technology for the insulation performance of power plant transformer bushings in recent years, the principle and corresponding method schemes of online monitoring for the insulation performance of power plant transformer bushings have been clarified. Combined with practical cases, the application effects of software and hardware have been verified, thereby providing technical support for the management of power systems in the new era.

Key words

Transformer High-voltage bushing Insulation state; Online monitoring Sensor.

1. Introduction

As a core component of power transformers, the reliability of the insulation state of high-voltage bushings directly determines the safe operation of the entire substation. The traditional preventive test has a long cycle and requires staff to operate with power off. However, the final test results can only reflect the insulation state at the test time and cannot obtain the dynamic deterioration process of insulation performance. Therefore, with the support of existing theoretical technologies, it is necessary to comprehensively explore the insulation condition assessment methods and systems for online monitoring, transforming the design of the insulation condition assessment methods and systems for transformer high-voltage bushings from the traditional regular maintenance to condition-based maintenance. This is also an inevitable requirement for the construction of smart grids and digital substations in the new era. Essentially, a complete online monitoring system for bushings typically consists of three layers: Firstly, the perception layer is composed of various sensors installed at key positions such as the grounding wire at the end of the bushing screen and the oil pillow, which is mainly responsible for collecting the characteristic signals of the insulation status in real time. Secondly, the transport layer is responsible for reliably transmitting the analog or digital signals collected by the perception layer to the main control unit to ensure the quality of data transmission in a strong electromagnetic interference environment. Finally, the platform layer is responsible for the storage, processing, analysis and display of data, providing intuitive status assessment conclusions and decision support to operation and maintenance personnel.

The core of online monitoring lies in systematically assessing the health status of insulation by analyzing one or more characteristic parameters that can reflect insulation deterioration. Nowadays, scholars from various countries have proposed a variety of evaluation methods in practical exploration. For instance, some scholars have put forward the multi-parameter fusion diagnostic method, which overcomes the limitations of single-parameter diagnosis and enhances the accuracy and reliability of technical diagnosis by comprehensively analyzing the variation patterns of multiple complementary parameters. Some scholars have found that the dielectric loss factor (tanδ) and capacitance (Cx) are the most classic parameters for diagnosing the overall moisture and aging of insulation. When applied to online monitoring, the absolute value and increment of tanδ and the change rate of Cx can be tracked in real time through high-precision phase measurement technology. Some scholars believe that under operating voltage conditions, monitoring and analyzing the grounding current flowing through can effectively reflect the overall insulation condition. Some scholars have also proposed intelligent evaluation algorithms, such as regularizing and constructing a rule base based on the knowledge and experience of experts in the field. The system can match real-time data with the rule base to draw technical diagnostic conclusions. Historical data and its cases can also be utilized to train algorithm models such as support vector machines and deep learning, enabling them to construct automatic learning failure modes, accurately obtain multi-parameter data information, and more precisely complete state classification and life prediction. Therefore, this paper mainly studies the evaluation method and system design of the insulation state of transformer high-voltage bushings for online monitoring.

2. Methods

2.1. System Principle Analysis of Online Monitoring

The performance testing and analysis of insulating bushings for power plant transformers refers to a special method of monitoring and testing the performance of insulating bushings for transformers. Generally speaking, online monitoring technology is composed of a signal acquisition system, a sensor system and an analysis and diagnosis system. In combination with the monitoring process shown in Figure 1, the signal acquisition system will process and transmit the status information of the transformer insulation bushing obtained by the sensor, and pass it to the analysis and diagnosis system. After the system analyzes the relevant data signals, it enables the staff to quickly grasp the working performance of the transformer insulation bushing and evaluate its service life based on the working status Avoid potential security issues during system operation.

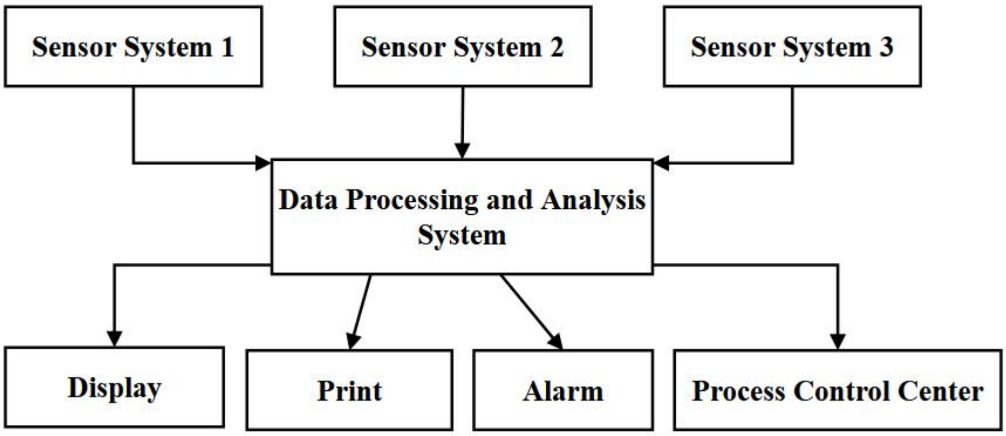

Figure. 1 Process Flowchart for Online Monitoring of Transformer Insulation Bushings

Performance On one hand, there is the offline detection method. The earliest approach for monitoring transformer bushing insulation performance was the offline detection method, which requires technicians to first de-energize the transformer bushing. After manual disassembly, simulated pressurized live operation analysis is conducted on the bushing to obtain insulation performance parameters, followed by comprehensive evaluation based on past operational experience. As the most common offline monitoring method, the bridge method (as shown in Figure 2) operates on the same principle as live bushing operation, offering significant practical value. However, it has limitations, particularly in that the voltage at both ends of the bushing cannot reach the actual busbar voltage. From a practical application perspective, this method is simpler to operate but demands substantial time and effort, requiring technicians with extensive experience.

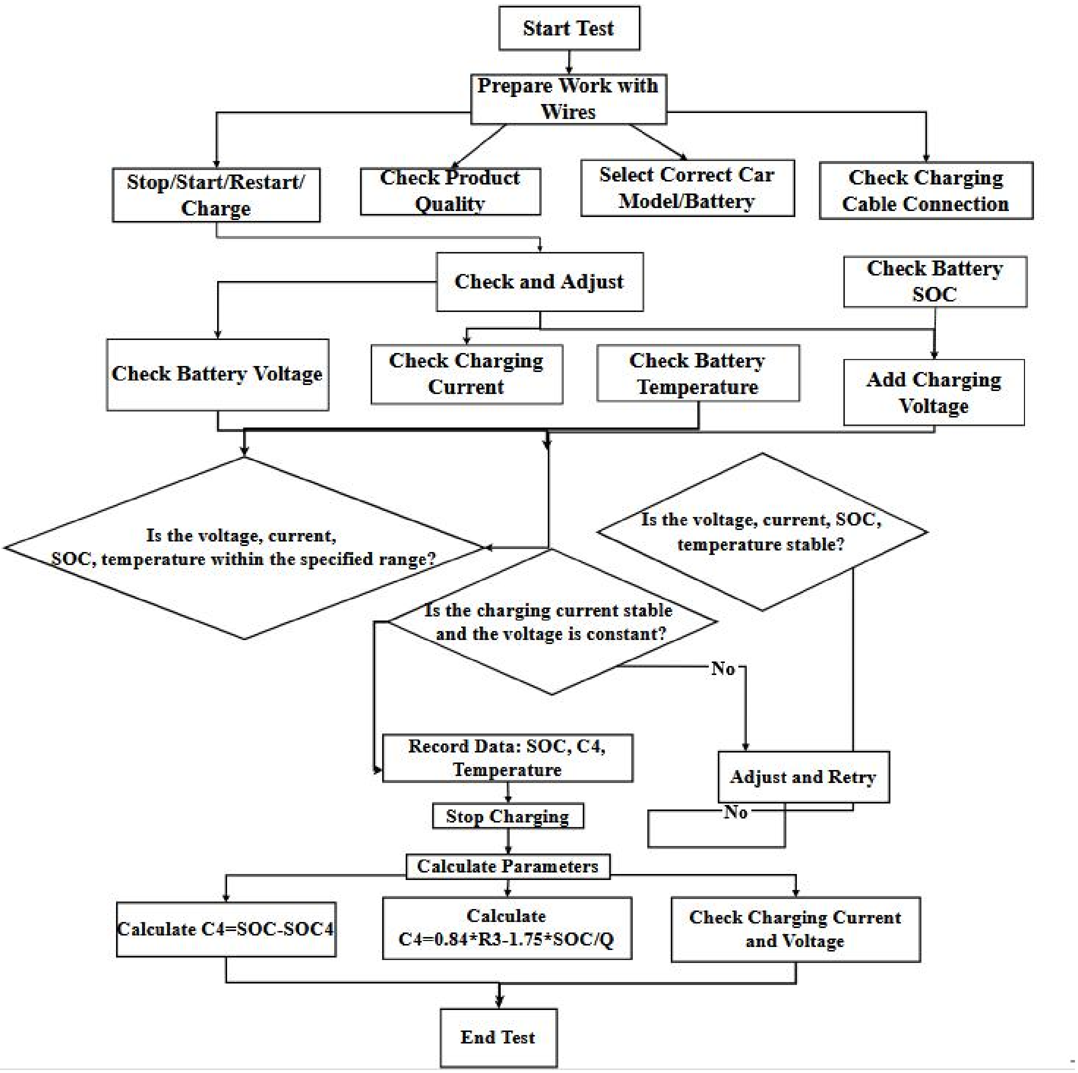

Figure. 2 Flowchart of the Bridge Method.

On the other hand, the online monitoring method. With the rapid advancement of modern computer technology, transformer bushing insulation monitoring technology centered on sensor technology has been widely adopted. This approach enables real-time collection of insulation performance parameters from transformer bushings through sensors. By leveraging computer technology to analyze the collected data, staff can conveniently monitor the operational status of transformer bushings via network platforms, promptly identify abnormal conditions, and swiftly propose effective solutions. The implementation of this technology reduces the workload of on-site measurements for personnel, controls repetitive testing tasks, and plays a positive role in ensuring the safe and stable operation of power systems in power plants.

2.2. Design Research of Transformer High-Voltage Bushing Insulation Condition

Assessment System for Online Monitoring Supported by the aforementioned technical theories, an online monitoring scheme for transformer bushing insulation performance was developed. The overall design includes the following components: 1. Sensors. The system employs active flux current sensors, specifically the BCT-2 model with a through-type installation structure. This sensor features high integration and temperature compensation

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capabilities, utilizing Mo alloy materials with deep negative feedback functionality to compensate for signal acquisition. Its current monitoring range spans from 100μA to 700mA, with detailed parameter specifications shown in Table 1.

Table 1. Parameter Analysis of BCT-2 Sensor

Parameter Information	**Specification Range**
Current Detection Range	100μA–700mA
Output Voltage Range	0–10V
Power Supply Parameters	±12 or ±15
Maximum System Angle Difference	±0.01°
System Nonlinearity	±0.005°
Maximum Ratio Parameter	±0.01%
Operating Temperature	–35°C to +55°C

Second, synchronous sampling. Both the casing terminal screen current signal and reference voltage signal are AC signals, resulting in continuous phase variations. To accurately calculate dielectric loss parameters, the data acquisition hardware design shown in Figure 3 must ensure synchronized sampling of current and voltage signals. Failure to maintain sampling synchronization would lead to inaccurate calculations, making it difficult to visually assess the casing's insulation performance. Assuming a stable 50Hz grid frequency with a 20ms signal period (equivalent to 360 degrees), each millisecond corresponds to 18 degrees of phase variation, causing significant deviations in actual data processing. Therefore, this research adopts a B-code synchronization scheme where distinct code elements have varying pulse widths. By precisely identifying code element information, synchronization and timing data can be efficiently extracted. In practical applications, code elements are configured with three pulse widths: 10ms, 8ms, and 2ms. Through microcontroller or decoding chip implementation, synchronized signals can be reliably obtained.

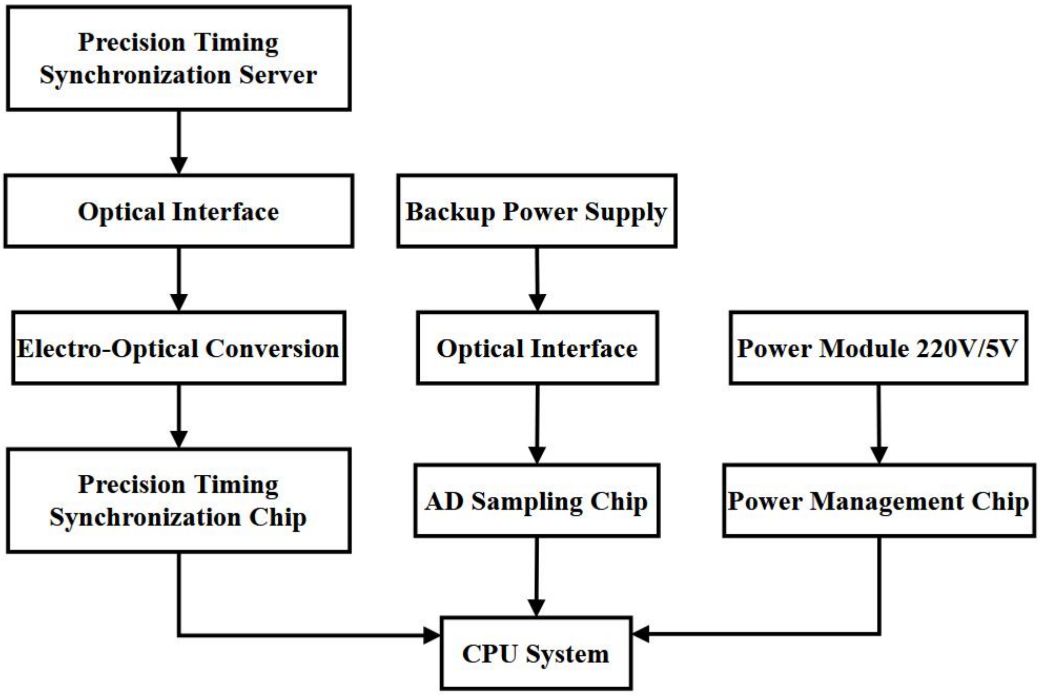

Figure. 3 Hardware Configuration for Data Acquisition.

Third, signal processing. The signals captured by the sensor require amplification before reaching the restricted area to ensure accurate data conversion. In this research system, the AD627 chip was selected for its adjustable amplification gain through resistors and nonlinearity below 40ppm, resulting in lower noise and minimal temperature sensitivity in practical applications. For the sampling scheme, the 16-bit precision AD7606 chip was chosen, supporting 8-channel data acquisition with a 200kSPS sampling rate and an analog input resistance of up to 1MΩ.

Fourth, data communication. The system in this study adopts RS485 bus mode to transmit the data collected by the acquisition unit to the backend via wired connection. Practically, this method effectively suppresses common-mode interference through differential transmission, with a transmission range of up to 3 kilometers, fully meeting the basic requirements for electrical field wiring.

3. Results

After completing the hardware design of the bushing monitoring unit, we implemented reset initialization operations to configure core parameters of internal registers, addressing practical application requirements for transformer high-voltage bushing insulation assessment. During the main loop phase, the system waits for the preset sampling interval before checking for synchronization signals. Upon signal receipt, both the monitoring unit and reference unit initiate synchronized signal sampling. The RS485 bus then transmits processed data to the backend server.

4. Conclusion

The online monitoring technology for power plant transformer bushing insulation performance studied in this paper has established two practical detection methods. The software and hardware components of the system design were developed to meet the requirements of online monitoring solutions, while corresponding parameter configurations were completed. This approach not only fulfills the demands of smart grid development in the new era but also provides a practical solution for online bushing performance monitoring research. From a long-term perspective, the insulation condition assessment methods and system designs for high-voltage transformer bushings oriented towards online monitoring serve as valuable guidance for future development.

References

[1] Zhanfei Lei, Yang Li, Haozhou Wang, et al. Design and application of online monitoring system for insulation of converter transformer grid-side high-voltage bushing [J]. Ningxia Electric Power, 2023(3): 29–33.

[2] Mengyu Shao, Bo Qi, Shusheng Zheng, et al. Simulation study on the propagation law of partial discharge electromagnetic waves in valve-side bushing of converter transformer [J]. Proceedings of the CSEE, 2024, 44(13): 5398–5408, insert 32.

[3] Zhen Hao, Changming Jiang, Huan Li, et al. High-frequency partial discharge monitoring technology based on current transformer at transformer bushing elevated seat [J]. High Voltage Engineering, 2025, 51(3): 1126–1134.

[4] Hanbo Zheng, Jiaxing Jing, Xiaoqing Luo, et al. Defect identification and insulation condition assessment of oil-paper insulated bushing based on multi-source fusion [J]. Power System Protection and Control, 2023, 51(20): 119–128.

[5] Hubo Xie, Shijie Han, Dingdong Qian, et al. Partial discharge detection of transformer bushing based on EFPI sensor [J]. Insulators and Surge Arresters, 2024(4): 140–148.

[6] Qingbo Mao, Xiuzhong Gong, Dongwei Shi, et al. Transformer bushing defect treatment method based on the whole process tracking management model [J]. Enterprise Management, 2023(S02): 370–371.

[7] Shuguo Gao, Chenmeng Xiang, Lili Wang, et al. Fault monitoring method for transformer bushing and elevated seat based on vibration and ultrasonic composite signals [J]. Insulators and Surge Arresters, 2024(1): 177–186.

[8] Ziyao Wang, Hui Liang, Wei Wang, et al. Online abnormal recognition method for transformer bushing based on infrared image data domain transformation and Inception-CNN network [J]. High Voltage Engineering, 2023, 49(8): 3425–3436.

[9] Guobiao Shen, Weiju Dai, Liangxing Tang, et al. Seismic performance evaluation and improvement measures of high-voltage bushing based on finite element method [J]. Transformer, 2023, 60(12): 34–39.

[10] Menghui Huang, Tao Jiang, Jianjun Dong, et al. Temperature prediction of box-type transformer high-voltage bushing based on LSTM [J]. Electrical Measurement & Instrumentation, 2023, 60(10): 171–176.

[11] Zengxin Pu, Bo Li, Jie Bai, et al. Dissolved gas prediction in transformer bushing oil based on time series prediction algorithm [J]. Power Big Data, 2025, 28(2): 27–37.

ISSN: 2790-5209 Vol 3, No.1, 2025
[12] Jun Lu, Xiaonong Guo, Wang Zhu, et al. Real-time damage identification of transformer bushing structure under seismic action [J]. Vibration. Testing and Diagnostics, 2024, 44(6): 1159–1166.

[13] Qing Xie, Chenchen Qi, Zhaoxuan Xiao, et al. Condition assessment of oil-paper insulated valve-side bushing based on extendable cloud model and comprehensive weighting [J]. High Voltage Apparatus, 2023, 59(7): 136–144.

[14] Gang Lv, Jun Deng, Yubing Shi, et al. Heating fault detection method of power transformer bushing based on improved SDG [J]. Mini-Micro Systems, 2024, 40(11): 53–56.

[15] Gaoquan Ma, Na Zhou, Mengfei Xie, et al. Typical insulation fault identification method of transformer oil-paper bushing based on GWO-KELM model [J]. Power System and Clean Energy, 2023, 39(5): 38–48.

[16] Lu Zhang, Yang Li, Haibao Mu, et al. Fast measurement method of dielectric response of transformer bushing under impulse voltage excitation [J]. High Voltage Apparatus, 2023, 59(6): 147–153.