

Temperature Rise Characteristics of Conductors in Electrical Penetrations of Nuclear Power Plants and Temperature Monitoring Technology Research

Yi Liu^{1, a}, Zhanhai Yu^{2, b} and Wei Wei^{1, c}

¹Suzhou Nuclear Power Research Institute Co.Ltd, Suzhou, 215004, China

²China Nuclear Power Operations Co., Ltd., Shenzhen, 518031, China

^a963016760@qq.com, ^byuzhanhai@cgnpc.com.cn, ^cP196525@cgnpc.com.cn

Abstract: As specialized electrical equipment for medium-voltage power, low-voltage power, instrumentation and control, and coaxial cables penetrating the inner and outer sides of the containment, nuclear power plant electrical penetrations primarily function to maintain power transmission and signal communication for electrical equipment. Their sealing and insulation performance are critical to ensuring the integrity of the reactor pressure boundary. To address the issues of organic material aging and conductor heating in electrical penetrations during long-term operation, this paper investigates and validates the heating characteristics and temperature monitoring methods for electrical penetration conductors, based on the actual conditions of electrical penetrations in a domestic NPP. By establishing a temperature rise experimental platform that includes a containment mock-up, temperature rise tests were conducted on the electrical penetration conductor assemblies to study the conductor heating characteristics.

Keywords: Electrical penetration; temperature monitoring; operational assessment.

1. Introduction

The electrical penetration of a nuclear power plant is a specialized electrical device installed on the containment of a nuclear reactor, used for cables to pass through the containment. In typical electrical penetrations of nuclear power plants, the key insulation and sealing materials exhibit significant aging mechanisms[1]. After long-term operation, the performance of these key materials gradually deteriorates, which may affect the electrical and mechanical functions of the electrical penetrations.

In accordance with the relevant requirements of the “Periodic Safety Review of Nuclear Power Plants”, temperature monitoring during the long-term operation of electrical penetrations can provide measured evidence for evaluating the validity of the original qualification conclusions for electrical penetrations. However, since the penetrations are in a sealed state, the internal temperature is difficult to measure using traditional wired methods. The main content of this study includes two aspects: (1) achieving internal temperature measurement while maintaining the sealing integrity of the penetrations; (2) investigating the heating characteristics of the conductors in electrical penetrations.

2. Conductor Heating Characteristics Study

2.1. Experimental Prototype Configuration

Considering that control and instrumentation electrical penetrations primarily carry control and instrumentation signals, with very low current and minimal temperature rise, the study of conductor heating characteristics in electrical penetrations focus mainly on power-type electrical penetrations. Therefore, when configuring the experimental prototype of electrical penetrations, the following principles

are applied: (1) One set of medium-voltage power electrical penetrations, configured according to “3+1”; (2) Two sets of low-voltage power electrical penetrations (one set for AC and one set for DC).



Figure 1. Low-voltage conductor, and Medium voltage conductor component

Prior to the tests, the cables were subjected to electrical inspection and testing. Each test group was operated at 60% and 100% of the rated current, with each energization lasting no less than 7 hours, and the duration of each individual test no less than 14 hours. Temperature data were collected and saved in real time during the tests, revealing the following heating characteristics.

2.2. Arrangement of Temperature Monitoring Points

The temperatures at different positions of the electric penetration vary[2]. Considering the symmetrical structure

and installability of the electric penetration, two temperature sensors are installed at both ends of the conductor assembly, three sensors are installed inside, two temperature sensors are installed at the cylinder end.

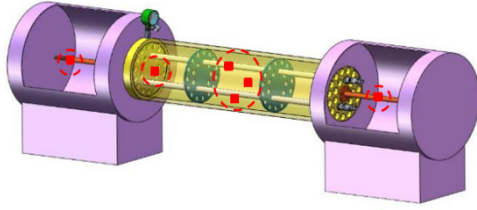


Figure 2. Temperature Measurement Point Arrangement

2.3. Implementation of the Temperature Rise Test

When conducting the temperature rise test for electrical penetrations, it is necessary to further consider the actual installation condition of the electrical penetrations. In this case, a containment mock-up shall be installed to simulate the actual installation scenario. During the current-carrying test of the electrical penetrations, the setup should be as close as possible to the actual on-site conditions. Meanwhile, the specific current settings for the test equipment are detailed in Table 1.

Table 1. Current setting of Medium voltage electrical penetration assembly

component number	Quantity	Specifications	rated current	Remarks
A	1	1250MCM	640A	U phase
B	1	1250MCM	640A	V phase
C	1	1250MCM	640A	W phase
D	1	250MCM	/	grounding

After completion of the temperature rise test, it is expected to obtain multiple temperature rise data points at different locations for three prototype electrical penetrations, and Based on the component end temperature rise limits and the barrel end temperature rise limits provided in the electrical penetration design, the electrical penetration temperature rise simulation model is corrected to ensure its accuracy. The resulting model can then serve as the basis for inverse calculation in subsequent non-contact temperature measurements.

an infrared probe is primarily used to detect the temperature at the end of the conductor assembly. Additionally, considering the advantage of infrared area thermography over infrared spot thermography in terms of vibration resistance, the feasibility of replacing infrared spot thermography with infrared area thermography should be investigated during the implementation of subsequent specific schemes[4]. The optimal non-contact temperature measurement method should be identified. The design of the non-contact temperature measurement is shown in Figure 3.

3. Temperature Monitoring System Prototype Development

3.1. Non-contact Temperature Measurement Design

When employing non-contact temperature measurement,

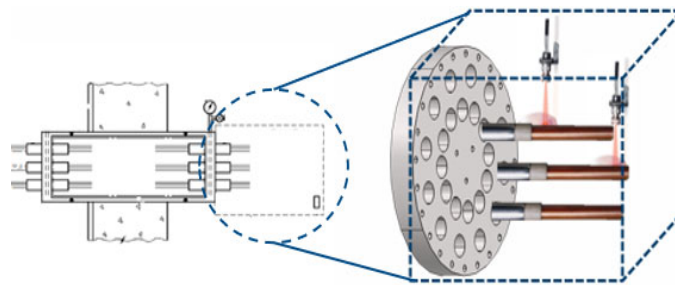


Figure 3. Design of non-contact temperature measurement

The experimental process employs a comparative validation between contact-based and non-contact-based methods to ensure the accuracy of non-contact temperature measurement. Additionally, necessary calibration and installation corrections are performed during the specific installation of temperature measurement probes to guarantee the accuracy of the temperature measurement results.

3.2. Design of Electromagnetic Induction Power Supply and Backup Power Supply

Non-contact temperature measurement probes inevitably

consume a certain amount of electrical energy during operation. Considering that the actual installation conditions of electrical penetrations make it unlikely for external power supplies to be available on-site, it is necessary to explore the feasibility of harvesting power via electromagnetic induction on the prototype. Meanwhile, to ensure the reliable operation of the non-contact temperature measurement probes, it is essential to equip them with necessary backup power sources. For the selection of backup power sources, super capacitors or high-capacity explosion-proof batteries can be considered. Additionally, for low-voltage power (DC) electrical penetrations, only the backup power solution is considered.

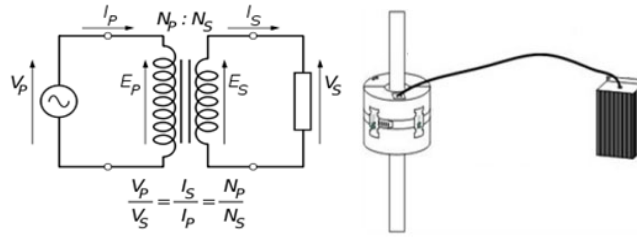


Figure 4. Obtaining energy through electromagnetic induction

3.3. Design for Wireless Transmission of Monitoring Data

In order to accurately obtain multi-point temperature distribution information, the temperature data of each node collected and stored is remotely transmitted to the Internet of Things cloud platform. Using the data transmission method of LoRa self-organization network combined with 4G communication technology[4,5], the communication data link is kept between the node units and gateways in the network, so that the temperature data can be sent back to the ground terminal server in real time through the optimal channel. LoRa combines digital frequency spread, digital signal processing and forward error correction coding technology, with the characteristics of long distance, low power consumption and high reliability; 4G base station density and high overlap coverage are the main carrier network of mobile communication at present, which can be directly interconnected with mobile cloud platforms to form a human-computer interaction interface.

When uploading data, the gateway supports data transmission via 4G network. In case of poor or unavailable 4G connectivity, it can switch to WiFi for data upload, which also reduces the deployment cost of the transmission network. Temperature data is transmitted in real time by the LoRa gateway to the terminal OneNET server. The real-time temperature distribution of the measured object can be visualized on the OneNET interface. Multi-level temperature thresholds for each measuring point can be set at the system terminal to enable early warning and alarm for graded faults.

The underlying layer of the wireless transmission system consists of multiple terminal temperature-measuring nodes. The LoRa terminal nodes are connected to buzzer alarm lights, controllers and infrared temperature sensors to collect temperature information and trigger early warnings. The controller generates synchronous signals: on one hand, it drives the infrared sensors to start temperature data acquisition; on the other hand, it sends synchronous pulses to the buzzer alarm lights to activate temperature early warnings. The LoRa gateway receives data from temperature nodes within the monitoring area and transmits the data synchronously to the OneNET host for real-time display. Users can set partitioned temperature thresholds for multiple measuring points on the OneNET interface according to the actual operating conditions of electrical penetrations, realizing automatic early warning and alarm for graded faults. This establishes a complete remote centralized management system for temperature monitoring, early warning and alarming of electrical penetrations.

3.4. Development and Verification of Temperature Monitoring System Prototype

The prototype adopts STM32L051C8T6 as the main

controller, equipped with MLX90614 non-contact infrared temperature sensor, and integrates 4G remote transmission, SD local storage and remote monitoring platform. The sensor incorporates a thermopile detector and signal processing chip with a temperature resolution of 0.01 °C and factory calibration, communicating with the MCU via I²C/PWM. The system consists of a low-power MCU and Quectel 4G module, supporting cloud data upload, resume transmission after interruption, curve visualization and multi-terminal access. Non-contact measuring modules are installed at both ends of conductor assemblies. The acquisition module transmits data every 2 minutes. The maximum communication range of the hub module is 20 m, and transmit power adapts to 4G signal strength. A single battery can last for 5 years to realize long-term remote temperature monitoring.

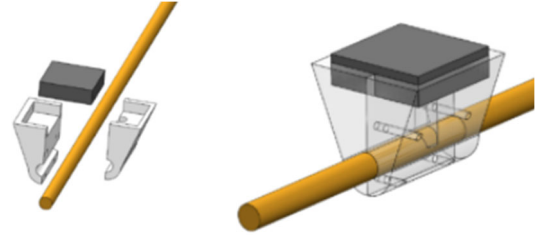


Figure 5. Installation of non-contact infrared test device

4. Conclusion

This study takes the electrical penetration of a domestic nuclear power plant as the research object. By investigating the progress of monitoring technologies for electrical penetrations in nuclear power plants both domestically and internationally, and reviewing the application of non-contact infrared thermometry, electromagnetic induction power harvesting, and wireless transmission technologies in the electric power industry, this study establishes the specific approach for developing a prototype of an environmental monitoring system for electrical penetrations. The developed system can obtain the temperature of conductors inside the housing of electrical penetrations.

(1) The developed infrared temperature monitoring system can establish internal and external relationship models based on information such as conductor assembly specifications, ambient temperature, input current, and terminal temperature, thereby providing the internal temperature range.

(2) Develop two sets of temperature rise test prototypes: contact and non-contact end types. The non-contact prototype can upload measurement data to the server in real time via LoRa network combined with 4G technology, enabling real time display and historical data review.

(3) The ambient temperature in the containment during normal operation is 15°C to 40°C, and the ambient temperature during the temperature rise test is 30°C to 40°C. The actual maximum internal temperature of the penetration

body is 58°C, which has a margin of 12°C compared to the allowable maximum temperature of 70°C. This verifies the reasonableness of the 70°C qualification condition for penetrations and provides a design basis for the long-term operational effectiveness evaluation of electrical penetrations.

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