Development and Verification of Low-voltage Protection Device for Nuclear Power Emergency Power Supply Systems

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Abstract

In nuclear power plant emergency power supply systems, the emergency diesel generator set (EDG) serves as the key power guarantee for safety-related loads. The reliability of its operation and the rationality of its protection configuration directly affect the achievement of nuclear safety goals. To address the practical requirements of low-voltage protection for the LHP/Q/S system, this paper proposes a design scheme for a novel low-voltage protection device, systematically elaborating on its overall architecture, the construction approach of the core circuit modules, and the structural implementation method. On this basis, an experimental verification platform was established to comprehensively test the key functions of the developed low-voltage protection device. The experimental results show that the device exhibits excellent performance in terms of measurement accuracy, operational reliability, and functional completeness, meeting the technical requirements of the nuclear power field for high-reliability low-voltage protection devices. This device can be applied in power systems with high demands for power supply reliability, such as nuclear power plant emergency power supply systems, demonstrating significant engineering application value and broad prospects for widespread adoption.

Keywords

Emergency diesel generator set (EDG), low-voltage protection relay, nuclear power plant safety.

1. Background and Requirements

In a nuclear power plant, the emergency diesel generator (EDG) is super important for ensuring the safe operation of the whole unit. [1]. To make sure the EDG can work safely and steadily at a nuclear power site, protecting and maintaining it is really important. Low-voltage protection relays can effectively prevent damage, directly affecting whether the nuclear unit can respond correctly in abnormal conditions and deciding if the whole nuclear power system can run safely.

Nowadays, nuclear power units have increasingly strict requirements for protection devices. Traditional relay protection devices are hard to meet EDG's requirements. [2]. For example, traditional products often have inflexible alarm mechanisms, narrow temperature ranges, poor electromagnetic compatibility, and insufficient human-machine interaction. Therefore, designing a targeted EDG protection device is crucial for the safe operation of the entire nuclear power plant. [3].

Based on the analysis, the performance indicators of the new low-voltage protective relay are as follows:

- Protection Function: Features undervoltage protection; dual channels, supporting either

stage I or stage II voltage detection needs.

- Measurement Accuracy: Voltage measurement accuracy meets Class 1 requirements, in line with the precision standards for safety equipment in nuclear power plants.
- Response Action: The stage I/II alarm delay can be set and adjusted flexibly according to actual on-site requirements. Power supply and consumption: Industry-standard 24 VDC power supply (operating range 18–30 VDC), with internal power consumption not exceeding 12 W.
- Reliability indices: Mean Time Between Failures (MTBF) of no less than 200,000 hours; Probability of Failure on Demand (PFD) not greater than 1×10^{-4}, complying with the reliability requirements for safety-related equipment in nuclear power plants.
- Environmental adaptability: Operating ambient temperature range of –20 °C to +70 °C, satisfying the stringent indoor and outdoor environmental conditions of nuclear power stations.
- Electrical interfaces: Rated measurement voltage of 66/115 VAC; frequency adaptability range of 40–70 Hz. Relay output contact load capacity no less than 24 VDC @ 2 A DC or 250 VAC @ 2 AAC.
- Mechanical interfaces: DIN-rail mounting; overall dimensions not exceeding 96 × 72 × 130 mm (W × H × D).

Others: Equipped with local voltage display, protection function enable/disable, and other human-machine interaction features.

2. Principle and Design

2.1. Circuit Principle

The undervoltage protection device adopts a modular circuit architecture featuring high cohesion and low coupling, as illustrated in Figure 1. Each functional module is designed independently with clear functions, while keeping expandable features. The main modules of the whole device include the power module, signal isolation and acquisition module, rectifier module, threshold detection module, delay control module, alarm module, display module, and speed lock module, among others [4].

The low-voltage protection relay uses a modular design, with each module independent and clearly divided in function. The power module mainly supplies power to the whole system, converting the 24V DC input into different voltage levels needed by various modules, including the filtering module, alarm module, and so on. The isolation sampling module mainly handles collecting the generator's voltage signal. After the signal goes through isolation and rectification, it gets sent to the rectification and conditioning module, where a rectifying and filtering circuit outputs a DC voltage signal that's linearly related to the input voltage and has an adjustable amplitude. The signal is then sent to the threshold detection module, where it is compared using an internal comparator and a preset threshold. Once the time reaches the preset value, the threshold detection module outputs an alarm signal. This alarm signal is then sent to the delay control module, which can adjust the alarm response time according to the system’s actual needs, and the output alarm signal is sent to the alarm module. After receiving an alarm signal from the delay control module, the alarm module activates the corresponding alarm relay. This module uses a bistable latching relay as the alarm output device, so it can maintain the correct alarm state even if the system loses power, which follows the fail-safe principle. At the same time, the remote alarm signal provides both normally open and normally closed contacts to meet the wiring needs of different control systems.

The speed locking module can be mainly used to prevent false alarms: for example, when the generator starts at a low speed, locking the low voltage alarm function can effectively avoid

false alarms and improve the accuracy of the entire equipment. In addition, the voltage display on the front panel can facilitate maintenance by on-site personnel and facilitate on-site operations [5].

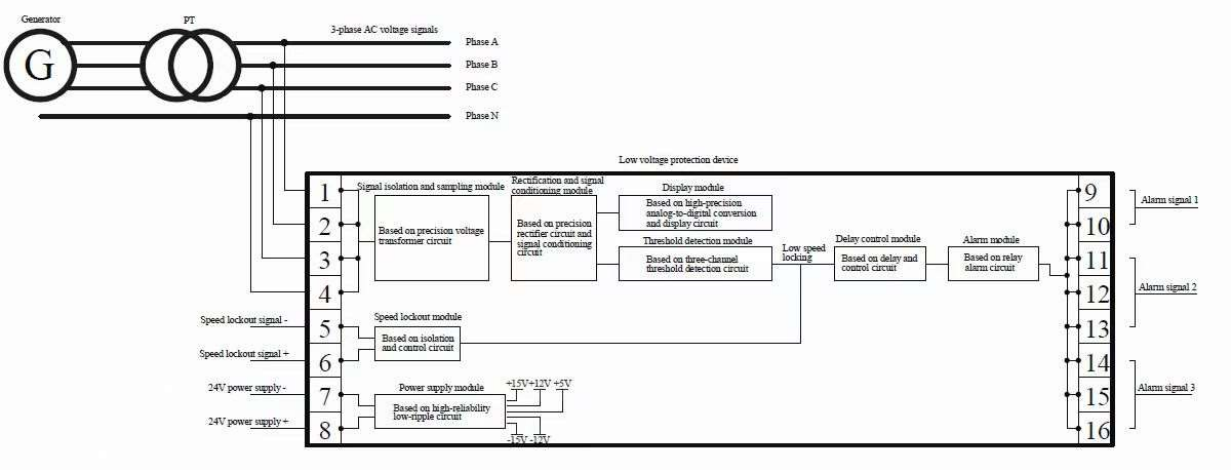

Figure 1. System architecture design diagram of the undervoltage protection device

2.2. Structural Design

This device uses rail mounting, making it easy to operate. The main functions of the front panel include the following parts:

- Voltage Display Unit: Shows the AC voltage value of the input relay.
- Status Indicator Unit: Used to display power-on and alarm light status information of the device.
- Control Unit: Used to control functions like alarms and delays on the device.

3. Testing and Verification

In order to ensure the verification of all functions and performance indicators of the low-voltage protection relay, comprehensive and detailed testing was conducted to ensure the completeness of the testing process. Afterwards, through testing data analysis, verify whether the design fully matches the requirements.

3.1. Test Environment

This verification test was conducted in a professional power system laboratory accredited with CNAS (China National Accreditation Service for Conformity Assessment) qualifications. The test environment is specified as follows:

- Ambient conditions: Temperature of 25 °C ± 2 °C, relative humidity of 45 %RH ± 5 %RH, and atmospheric pressure ranging from 86 kPa to 106 kPa.
- Test equipment: A high-precision three-phase standard power source (accuracy class: 0.05) is used as the voltage input source, and a digital oscilloscope (bandwidth: 200 MHz) is employed to record the operating time.
- Equipment under test (EUT): Three prototype units of the new undervoltage protection device (Serial Nos. 001, 002, and 003).

3.2. Key Requirements Test Procedure and Results Analysis

Real time display function: Load the input voltage signal to the device, and the front panel will display the corresponding voltage value in real time. By comparing the two, it can be found that the deviation of all test points is less than 0.06V. This result indicates that the function meets the design requirements.

Undervoltage alarm and delay setting function: First, the stage I and stage II alarms are preset with thresholds of 70VAC and 90VAC, respectively. The test conditions involve the normal voltage dropping suddenly from 100VAC to 80VAC and 50VAC. The test results show: Stage I alarm: When the voltage drops to 50VAC, the relay starts to operate after the set time is met, the corresponding alarm light turns on, and the relay functions correctly. The action time deviation in 10 repeated tests is less than 0.1 seconds. Stage II alarm: When the voltage drops to 80VAC, the relay starts to operate after the set time is met, the corresponding alarm light turns on, and the relay functions correctly. The experiment results show that this function fully meets the design requirements, with good repeatability, safety, and reliability.

Speed Lock Function: The test condition simulated the scenario of the generator just starting up. First, a lock signal was sent to the low-voltage protection relay, along with an AC voltage below the alarm threshold (50VAC). The test result showed that the alarm module didn't respond at all, indicating that the speed lock function of the low-voltage protection relay is working normally. Then, when the lock signal was removed, the alarm output responded correctly right away. The results showed that in repeated tests on all prototypes, the success rate was 100%, which means this function meets the design requirements and can effectively prevent false alarms when the generator first starts.

3.3. Equipment Qualification

Throughout the entire identification process, we developed a testing outline based on the characteristics of low-voltage protection relays and relevant industry standards. During the identification test process, we strictly followed the requirements of the identification outline and completed both basic tests and corresponding type tests, and the test results met the corresponding indicator requirements. Indicating that the low-voltage protection relay meets the corresponding design requirements.

3.4. Application Verification

T The low-voltage protection relay has completed functional and performance tests at the nuclear power site, and all data shows good performance, especially the speed locking function, which can effectively avoid false alarms and is crucial for the protection of EDG. The experimental results indicate that the device can effectively ensure the safe operation of nuclear power plants and is an important component of the entire nuclear power site.

4. Conclusion

This article successfully developed a low-voltage protection device that can be used for emergency diesel generator sets in nuclear power plants. The device features comprehensive innovations in system architecture, circuit design, human-machine interaction, and structural technology, offering significant advantages such as high precision, high reliability, strong anti-interference capability, and flexible configurable functions.

Experimental results show that key performance indicators of this low-voltage protection device, including voltage display accuracy, correctness of under-voltage protection operation, and delay accuracy, all exceed the design targets, with stable and reliable system operation. The successful application of this achievement will strongly ensure the safe and stable operation of nuclear power plant emergency power systems, providing solid technical support for the safe, autonomous, and controllable development of China's nuclear power industry.

References

[1] Li, M., & Zhang, W. (2021). Research on optimization of undervoltage protection logic for emergency diesel generator sets in nuclear power plants. Power System Protection and Control, 49(12), 112–119.

[2] Chen, Z. Y., & Huang, H. (2019). Research and application of undervoltage release device for diesel generator sets in nuclear power plants. Proceedings of the Chinese Society for Electrical Engineering, 39(15), 4456–4464.

[3] Li, Q., & Chen, F. (2020). Reliability analysis of emergency power supply system in nuclear power plants. Nuclear Science and Engineering, 40(4), 567–574.

[4] State Intellectual Property Office of China. (2023). An undervoltage protection device and method for emergency diesel generators in nuclear power plants (Chinese Patent No. CN202310123456.7).

[5] Wang, J. G. (2021). Application of digital relay protection technology in nuclear power plants. Automation of Electric Power Systems, 45(18), 155–162.