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Regulatory and Design Perspectives on Applying Test Automation to Protection Systems of Small Modular Reactors (SMRs)

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1. Introduction

Small Modular Reactors (SMRs) have attracted considerable attention as next-generation nuclear power systems due to their advantages in safety, economics, and modular design [1]. SMRs consist of multiple independent low-power modules that can operate in an integrated manner, with each module designed to achieve safe shutdown independently even under Design Basis Accident (DBA) conditions. In this structure, where multiple modules must be operated with limited manpower, system configurations that integrate automation and operational support functions from the early design phase are essential.

The digital protection system is a key safety system that automatically initiates protective functions during abnormal or accident conditions. Its reliability must be maintained through periodic surveillance testing and functional verification. In conventional large nuclear power plants, some surveillance tests have relied on manual operator actions, reflecting historical design and operational environments [2]. However, in highly automated SMR structures, such approaches impose limitations in terms of repeatability, human error potential, and operator burden. Therefore, an automated testing framework must be incorporated from the initial design phase.

This paper reviews the test structures and regulatory requirements of digital protection systems, and examines the necessity and design considerations of applying automated testing methods suitable for SMRs.

2. Analysis of Protection System Test Structures and Regulatory Requirements

2.1 Test structures of protection systems

The digital protection system maintains high reliability through three types of tests:

- Surveillance Test : Periodic verification of system availability, partly requiring manual operator actions.
- Functional Test : Verification of specific protective functions by configuring system operating conditions.
- Self-Diagnostic Test : Continuous real-time diagnostics performed by the internal logic of the digital controller [2].

Surveillance and functional tests often involve manual actions, which may reduce repeatability, increase the potential for human errors, and add operator workload. Therefore, in SMRs, a transition to a structured testing system utilizing self-diagnosis and automation is required [1].

2.2 Regulatory requirements

To ensure the reliability and functionality of digital protection systems, regulatory bodies such as the US NRC, IEEE, and IAEA have provided various requirements. These requirements cover testing types, frequency, methodology, and conditions for the acceptance of self-diagnostic features. Table I summarizes representative guidelines.

Table I: Regulatory requirements for protection systems

Category	Standards/Guides	Key contents
Design criteria	IEEE Std 603-2018	Testability and functional independence requirements
Surveillance test	NRC RG 1.118 (Rev.3)	Periodic surveillance tests, clarity on means and intervals
Functional test	IEEE Std 338-2012 NRC RG 1.22 (Rev.5)	Tests under plant operating conditions, execution during operation allowed
Self-diagnostic Test	NRC RG 1.152 (Rev.3) IEC 60880:2006	May substitute periodic tests if reliability is demonstrated

NRC regulatory guides allow adjustment or partial replacement of periodic tests if the reliability of self-diagnostic functions is demonstrated [2]. IEC 61513 and IEC 62340 emphasize systematic verification and testability of self-diagnostics, while some NUREG reports note that when automated testing replaces manual testing, repeatability and independence must be ensured.

This indicates that automated testing is not merely a functional improvement but requires reliability equivalent to manual testing for regulatory acceptance.

2.3 Regulatory acceptance of automated testing

Automated testing can be accepted within the existing regulatory framework when specific conditions are satisfied, as confirmed by various documents and practical cases. The main examples are summarized as follows:

- Scope of regulatory guidance (general): NRC Regulatory Guide 1.152 (Rev.4) specifies that when the reliability of self-diagnostic functions in digital safety systems is adequately demonstrated, certain Channel Operability Tests may be reduced or replaced [2]. In addition, NUREG-0800, BTP 7-17 provides design and review criteria for self-tests and surveillance tests, thereby offering procedural grounds for regulatory review of automated testing [3].

- Platform approval case (NuScale HIPS): The NRC issued a Safety Evaluation Report (SER) for NuScale's FPGA-based Highly Integrated Protection System (HIPS) platform, concluding that the built-in diagnostic and self-test features could be applied to safety-grade digital systems [4]. Subsequently, the NuScale Standard Design received final Design Certification in 2023, representing the first case in which automated test functions were formally incorporated into a protection system platform during the regulatory approval process.

- Test optimization approval case (AP1000/Vogtle): Data obtained from First Plant Only Tests (FPOT) and First Three Plant Only Tests (F3POT) at the Sanmen and Haiyang units in China were utilized during the licensing process for the identically designed Vogtle Units 3 & 4. Southern Nuclear submitted a License Amendment Request (LAR) to the NRC seeking deletion of redundant tests, and the regulator credited the plant data, thereby approving the removal of certain repeated test items [5]. This case demonstrates that plant data sharing across identical designs can be recognized at the regulatory level as a means of test program optimization.

- International guidance (IAEA SS-G-8): The IAEA recommends establishing structured testing frameworks that combine surveillance testing with self-diagnostic testing, thereby emphasizing automated testing as a systematic measure for ensuring safety [6].

These cases collectively indicate that automated testing is not merely an operator convenience but a safety assurance measure that can be conditionally accepted by regulatory authorities.

3. Design considerations for automated testing

Automated testing for SMR protection systems must be integrated from the early design phase. Key considerations are summarized in Table II.

Table II: Design considerations for automated testing

Category	Considerations
Test coverage	Integrate self-diagnostic functions and periodic tests to ensure comprehensive coverage
Technical reliability	Verify accuracy, repeatability, and credibility of automated test results
Design integration	Incorporate automated testing architecture at the early design stage
Regulatory alignment	Ensure consistency with Technical Specifications and regulatory requirements

These considerations emphasize that testing should be treated not simply as procedural verification but as a structural element of the system design. For next-generation nuclear systems such as SMRs, automated testing represents an essential design requirement to simultaneously secure both reliability and operational efficiency.

4. Conclusions

This study examined regulatory and design perspectives on applying automated testing to SMR protection systems. While large nuclear power plants have maintained testing frameworks partly dependent on manual operator actions, SMRs require structurally integrated approaches that leverage self-diagnosis and automation.

Case studies from NuScale and AP1000 demonstrate that automated testing can be realized within the current regulatory framework, and under certain conditions, regulatory bodies are willing to accept such approaches. In particular, IEEE standards and NRC regulatory guides permit flexibility in testing intervals and methods if automated testing provides equivalent reliability to manual testing.

Therefore, test automation must be recognized as a fundamental design requirement in SMRs, ensuring both operational efficiency and enhanced safety, and should be incorporated from the initial design stage.

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