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Development of Safety Index Enhancement Technology for Seismically Sensitive Components of NPP through Fragility Test

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1. Introduction

Following the legislative enactment of the Accident Management Plan (AMP), the requirement to meet performance objectives through Probabilistic Safety Assessment (PSA) has highlighted the importance of reducing seismic PSA risk. In response to the Fukushima nuclear accident, the United States Nuclear Regulatory Commission (U.S. NRC) implemented the site-specific Ground Motion Response Spectrum (GMRS) to strengthen the seismic safety of nuclear power plants. Subsequent assessments revealed that, in certain plants, the design-basis seismic response spectrum was exceeded in the high-frequency range. An integrated review of seismic PSA risk-reduction requirements and GMRS evaluation outcomes identified seismically qualified components installed within electrical cabinets as significant contributors to both seismic PSA risk and high-frequency exceedance phenomena. These findings highlight the necessity of enhancing the seismic performance of such components to ensure compliance with safety objectives and to mitigate associated risks.

2. Objectives and Scopes

The objective of this study is to demonstrate the fragility seismic capacity of seismic safety–related components in domestic nuclear power plants, ensuring their structure integrity and functionality during seismic events, and to systematically compile the results into a structured database, ultimately contributing to the reduction of seismic PSA risk.

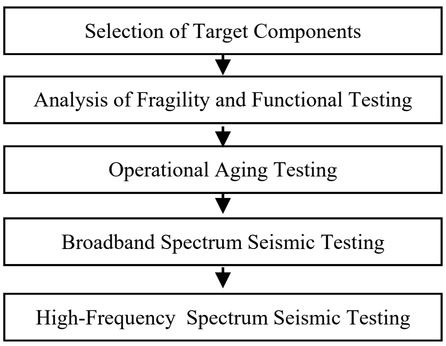

Fig. 1. Research and Development Implementation Framework

2.1 Identification and Selection of Target Components

To identify seismic safety–related components, a review was conducted of the seismic PSA data from domestic nuclear power plants and the component selection cases from the U.S. EPRI High Frequency Program [2], which addresses components sensitive to high-frequency seismic motion. Based on this review, the selection process was established below, and three component types electro-mechanical relays, electro-mechanical contactors and auxiliary relays were ultimately selected as the seismic safety–related component categories.

The selection process consisted of the following steps:

- Step 1: Selection of Class 1E components
- Step 2: Elimination of component types that do not undergo phase change
- Step 3: Elimination of component types with mechanical operating contacts
- Step 4: Elimination of digital/solid-state relay types

2.2 Functional Testing

In this study, to verify the functional integrity of the selected seismic safety–related components, functional testing of the target components will be performed in compliance with the technical requirements specified in IEEE C37.105 [6] and IEEE Std 649 [7]. The tests will be conducted under identical conditions before and after the seismic tests, measuring parameters such as contact transfer operation, operating time, release time, and electrical characteristics under load conditions. This procedure allows for quantitative assessment of potential functional degradation and verification of functional performance during the seismic qualification process.

2.3 Operational Aging Testing

The operational aging test requirements for seismic safety–related components prioritize the environmental conditions of the target components, such as service life and operating voltage/current. In cases where no specific data are available, the test methodology will be conservatively derived based on the manufacturer's specifications for the components.

2.4 Seismic Testing Method

To validate the fragility seismic capacity of the selected seismic safety–related components, seismic testing will be conducted in compliance with the technical requirements specified in IEEE Std 344 [4] and IEEE Std C37.98 [5]. The tests will follow the prescribed input motion profiles, frequency ranges, acceleration levels, and procedures defined in these standards, with the objective of verifying both the structural integrity and the functional performance of the components under seismic loading. In particular, functional monitoring will include the measurement of contact chattering events exceeding 2 ms are considered functionally significant. This ensures a consistent and standardized assessments of seismically sensitive components and provides a reliable basis for subsequent fragility evaluations.

2.4.1 Broadband Spectrum Seismic Testing

The broadband spectrum seismic test in this study is designed to achieve improvements in the Probabilistic Safety Assessment (PSA) safety indicators. The test targets a frequency range from 1 Hz to 50 Hz, and the Input Control Response Spectrum (ICRS) for each target component will be derived from its seismic qualification documentation. In cases where the ICRS is not available, the amplification factors for representative electrical cabinets provided in Table 5-10 of EPRI Report [3] will be applied. The initial input motion is set at 100% level corresponding to 0.3 g, and the input level will be incrementally increased until the maximum performance capacity of the component is reached, thereby conducting an ultimate seismic test. This approach aims to secure seismic margin across the entire frequency range and to obtain empirical data that contributes to enhancing PSA safety performance.

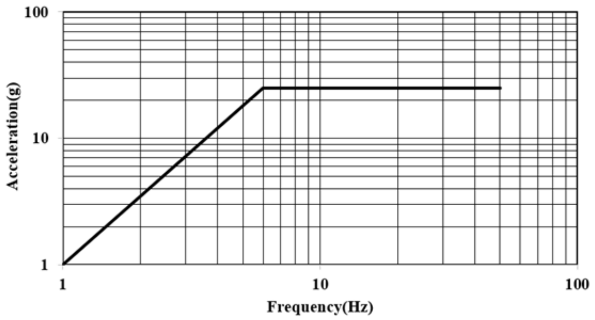

Fig. 2. Typical broadband spectrum shape.

2.4.2 High-Frequency Spectrum Seismic Testing

Additional fragility seismic testing based on the high-frequency spectra is planned to be conducted in preparation for the implementation of GMRS at domestic nuclear power plants. The testing methodology and results presented in the EPRI High Frequency Program [2] will be referenced to validate the high-frequency seismic performance of the target components. The tests will primarily address the 20–40 Hz frequency range, employing excitation levels from 14g to 20g with incremental steps of 1.25g This approach intended to establish the high-frequency seismic margin of the components.

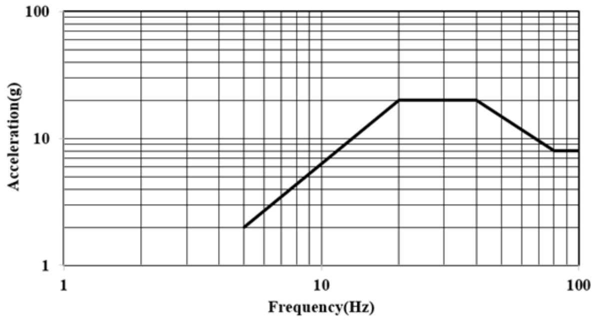

Fig. 3. Typical High-Frequency spectrum shape.

3. Conclusions

This study establishes a foundation for effectively reducing seismic PSA risk by systematically evaluating the seismic performance of safety-related components in domestic nuclear power plants and securing corresponding performance data. Furthermore, high-frequency seismic performance assessments are expected to enhance plant seismic safety in preparation for the implementation of the GMRS.

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