

## HIGH FREQUENCY SEISMIC TESTING OF POTENTIALLY SENSITIVITY COMPONENTS

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### ABSTRACT

Updated seismic hazards in the central and eastern United States (CEUS) often contain significant amounts of high-frequency vibratory motion. Previous studies concluded that high-frequency motions were, in general, non-damaging to components and structures that have strain- or stress-based potential failures modes. The studies also concluded that components, such as relays and other devices subject to electrical functionality failure modes, have unknown acceleration sensitivity for frequencies greater than 16 Hz.

The ability of some potentially sensitive power plant components to properly function during these high-frequency motions has been considered in prior studies but only in a limited manner. The Electric Power Research Institute (EPRI) conducted shake table testing of a diverse set of common nuclear power plant safety system components considered to be potentially high-frequency sensitive. These components are typically relays and other control devices with intermittent states, which are subject to change of state, contact chatter, signal change/drift, and other intermittent electrical functionality failure modes. Testing was conducted using a common test protocol for three-axis high-frequency input motion and monitoring of the component functional performance.

This paper will summarize the types of components evaluated in the test program, the test methods investigated within the program, and the results of seismic testing performed on a diverse group of 153 components using high-frequency input motions.

### INTRODUCTION

The risk posed by seismic events to nuclear power plants operating in the United States has been the subject of several studies conducted over the past three decades. An input to a plant seismic risk study is the seismic hazard associated with a given plant site. Recent seismic hazard studies for the operating plant sites have an increased high-frequency content in the seismic motions for the CEUS when compared to the safe shutdown earthquake (SSE) response spectrum used for the design of many plants. Figure 1 shows an example ground motion response spectrum (GMRS) derived from a seismic hazard with significant high frequency content.

The risk posed by seismic events to nuclear power plants (NPPs) operating in the United States has been the subject of several studies conducted over the past three decades. The prerequisite for any plant seismic risk study is the determination of the seismic hazard associated with a given plant site. Hazard studies for the operating plant sites conducted during the late 1980s concluded that, despite a large uncertainty in the seismic hazard results, there was increased high-frequency content in the resulting seismic motions for the CEUS when compared to the SSE response spectrum used for the design of many plants.

Equipment items important to safety within operating NPPs were seismically qualified for the in-structure or in-cabinet motions consistent with the SSE defined for each plant. The equipment was also evaluated,

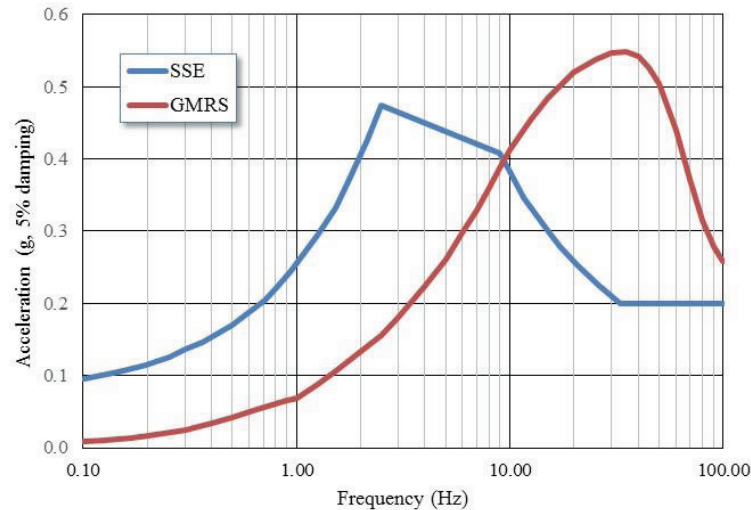


Figure 1. Example High Frequency Ground Motion Response Spectrum (GMRS)

in general, for a review level earthquake (RLE) under each plant’s Individual Plant Examination of External Event (IPEEE) Program. The SSE and RLE ground motions, however, did not typically include significant frequency content above 10 Hz. Studies conducted in the late 1980s provided guidance concerning the hazard-consistent ground motions for the CEUS that had maximum spectral values occurring in the 20 to 30 Hz range. EPRI NP-7498 (EPRI, 1991a) includes an appendix titled “Recommended Procedures to Address High-Frequency Ground Motions in Seismic Margin Assessment for Severe Accident Policy Resolution.” This appendix reviewed the bases for concluding that high-frequency motions were, in general, non-damaging to components and structures that have strain- or stress-based potential failures modes. It concluded that components, such as relays and other devices subject to electrical functionality failure modes, have unknown acceleration sensitivity for frequencies greater than 16 Hz. Therefore, the evaluation of high-frequency vulnerability was limited to components that are subject to intermittent states.

In 1991, the Nuclear Regulatory Commission (NRC) requested that each NPP conduct an IPEEE evaluation (USNRC, 1991a) to identify and report to the NRC all plant-specific vulnerabilities to severe accidents caused by external events. For the IPEEE Program, the issue of high frequencies was addressed in an indirect manner, focusing on a list of low ruggedness relays mutually agreed to by the industry and the NRC, with known earthquake or shock sensitivity (USNRC, 1991b). These specific model relays, designated as “bad actor” relays were identified in EPRI NP-7148 (EPRI, 1990). Rather than considering high-frequency capacity vs. demand screening, relays on this list were considered program outliers and were evaluated using circuit analysis, operator actions, component replacements, or site-specific testing.

### POTENTIALLY HIGH FREQUENCY SENSITIVE COMPONENT TYPES

During the initial new plant licensing activities in the 2005 timeframe, EPRI published two reports to provide additional information regarding the potential high-frequency vulnerability of nuclear plant SSCs. EPRI 1015108 (EPRI, 2007a) summarized a significant amount of empirical and theoretical evidence, as well as regulatory precedents, that supported the conclusion that high-frequency vibratory motions above about 10 Hz are not damaging to the large majority of NPP structures, components, and equipment. A potential exception to this conclusion was the functional performance of vibration-sensitive components such as relays and other electrical and instrumentation devices. EPRI 1015109 (EPRI, 2007b) provided guidance for identifying and evaluating potentially high-frequency sensitive components for plant applications that may be subject to possible high-frequency motions. The evaluation of potentially high-frequency sensitive components in plants was therefore directed to mechanically actuated bi-state control

devices (such as relays, contactors, switches, potentiometers, and similar devices) and those components whose output signal or settings (set-points) could be changed by high-frequency vibratory motion.

In response to current Fukushima related seismic re-evaluation activities, EPRI published report 1025287, (EPRI, 2013) with guidance for evaluating NPPs using new seismic hazards and GMRS. Included in that guidance is a list of component types that should be evaluated for potential high frequency sensitivities. EPRI 1025287 summarized the consideration of the previous evaluations as well as information from the AP1000 NRC licensing application reviews. Table 1 shows the items identified as the potentially high-frequency-sensitive component types to be evaluated.

Table 1: EPRI 1025287 High Frequency Confirmation Component Types

<ul style="list-style-type: none"> <li>• Electro-mechanical relays (e.g., control relays, time delay relays, protective relays)</li> <li>• Circuit breakers (e.g., molded case and power breakers – low and medium voltage)</li> <li>• Control switches (e.g., benchboard, panel, operator switches)</li> <li>• Electro-mechanical contactors (e.g., motor control center starters)</li> </ul>	<ul style="list-style-type: none"> <li>• Process switches and sensors (e.g., pressure, temperature, flow, limit/position)</li> <li>• Auxiliary contacts (e.g., for molded case circuit breakers, fused disconnects, contactors/starters)</li> <li>• Transfer switches (e.g., low and medium voltage switches with instrumentation)</li> <li>• Potentiometers (without locking devices)</li> </ul>
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## HIGH FREQUENCY TESTING

To support the seismic evaluations, EPRI developed a High Frequency Program that conducted high-frequency seismic testing of a diverse set of common plant control components. The Program’s goals were to:

- Provide data to evaluate high-frequency capacity of selected components for those plants who only had high frequency ground motion exceedances, and
- Determine the fragility of selected high-frequency sensitive components for those plants who were performing seismic probabilistic risk assessments (SPRA) or NRC-based seismic margin assessments (SMA).

The Program was implemented in two phases. The Phase 1 testing subjected a small sample of the component types identified Table 1 to three different types of high-frequency input motions in order to determine which test motion type and test procedure would provide the best basis for the testing in Phase 2 of the Program. The Phase 2 testing then performed using the selected input motion type and test procedures with a large diverse sample of the component types in Table 1.

Because licensing basis seismic qualification testing adequately addresses the lower frequency range, the high frequency test program focused on this higher frequency range. The primary focus of the EPRI high frequency testing program was the 20 to 40 Hz frequency range. A broader frequency range of 16 to 64 Hz was considered in Phase 1 testing to ensure that the focus on the 20 to 40 Hz range was sufficient.

### *Phase 1 Testing Methods*

Eleven test samples were selected as representative of the component types in Table 1. In general, the selected components were chosen to investigate contact chatter as the potential high-frequency sensitive

failure mode, as well as to cover a range of expected seismic capacity levels. Phase 1 testing was performed using five control relays, a pneumatic time delay relay, a contactor, two lockout relays, an induction disk protective relay, and a differential pressure switch. For testing purposes, the test samples were separated into groups and mounted to a specially designed test fixture with a natural frequency greater than 80 Hz. Components were mounted with the manufacturer recommended hardware, powered at normal operating voltages, and monitored for contact chatter on normally open and normally closed contacts. The acceptance criteria was typically 2 millisecond contact chatter per American National Standards Institute (ANSI C37.98-1987 (IEEE, 1998)).

Three types of test input motions were investigated in Phase 1: (1) sine sweeps, (2) random multi-frequency (RMF) motions, and (3) filtered random multi-frequency (FRMF) motions. In each case, the input motions were increased in amplitude until either the components failed, or had anomalous behavior, or the test machine limits were reached.

The sine sweep testing was conducted using a single-axis high capacity electro-magnetic table over the 16 to 64 Hz frequency range. The components were tested in each primary direction (i.e., front-to-back, side-to-side, vertical) in the de-energized (non-operate) state and the energized (operate) state. Each group of components was subjected to an increasing frequency sine sweep at selected constant acceleration levels in each direction. Each individual sine sweep test was performed with a sweep rate of one octave per minute and required 2 minutes to complete. Acceleration levels were incrementally increased until contact chatter on all instrumented component channels was reached or table motion limits were reached.

The RMF test series subjected each group of mounted components to independent tri-axial, random multi-frequency input test motions with a strong motion duration of approximately 13 seconds. Each axis of motion was independent but had the same general response spectrum shape and amplitude. Testing was conducted using a tri-axial servo-motor driven table the desired waveform control in the high-frequency range. Acceleration levels were incrementally increased until contact chatter on all instrumented component channels was reached or table motion limits were reached. RMF testing was performed using three different sets of input motions derived from the standard response spectrum shape in ANSI C37.98-1987. Figure 2 shows the three different input motions used in the RMF testing: (1) 16 to 32 Hz broadband motion designated as RMF1, (2) 24 to 48 Hz broadband motion designated as RMF2, and (3) 20 to 40 Hz broadband motion designated as RMF3.

The FRMF test series used wide-band multi-frequency independent random input motions along two primary axes with a set of narrow-band filtered motions along the third axis. The FRMF testing was intended to simulate either in-structure response or high-frequency local panel in-cabinet response, which is typically dominated by front-to-back or side-to-side responses; therefore, the filtered motions were limited to those two directions. Additionally, comparison of the fragility response spectra for both the FRMF and RMF motion allowed a high-frequency “clipping factor” to be defined to be used to convert an in-structure or in-cabinet demand (response spectrum) to an effective wide band motion for comparison to an equivalent RMF fragility test spectrum.

Figure 3 shows a composite of the target response spectra for the FRMF motions. The narrowband motions were applied along each horizontal axis, one at a time, at the 1/6 octave center frequencies between 17.8 and 44.9 Hz (21.2 Hz, 23.8 Hz, 26.7 Hz, 30.0 Hz, 33.6 Hz, 37.8 Hz). Each FRMF motion was applied separately in the component front-to-back direction and the side-to-side direction. For example, one test series was conducted with the broadband motion in Figure 3 applied in all three directions plus one of the

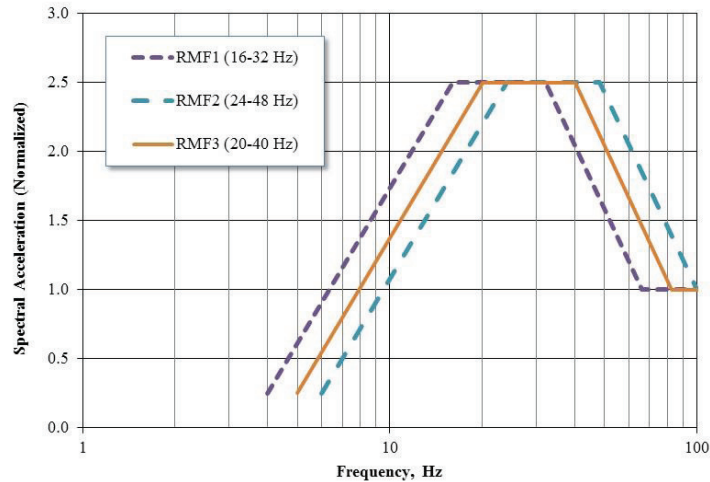


Figure 2. Random Multi-Frequency Response Spectra

narrowband motions superimposed in the front-back direction. Acceleration levels were incrementally increased until contact chatter on all instrumented component channels was reached or table motion limits were reached. Following that test series, the next test series was conducted with the broadband motion in all three directions and the next narrowband motion superimposed in the front-back direction. After testing was performed with each of the six narrowband motions in the front-back direction, testing was repeated with the six narrowband motions in the side-side direction.

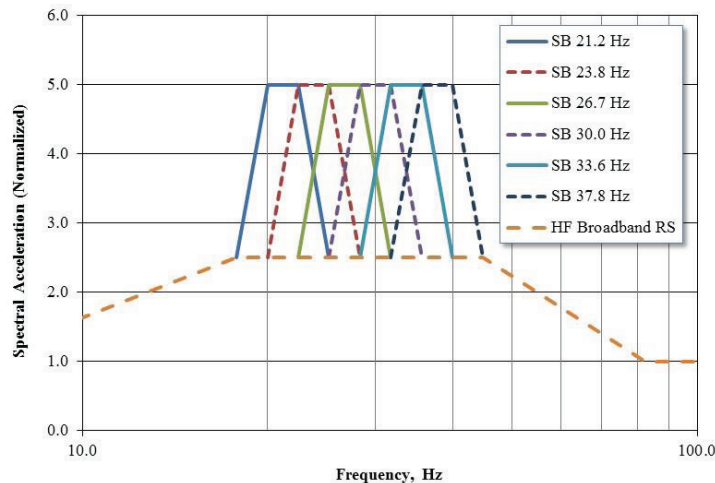


Figure 3. Random Multi-Frequency Response Spectra

### *Phase 1 Testing Conclusions*

The Phase 1 study confirmed (EPRI, 2013) that the high-frequency chatter of contact devices was model-specific. Some of the components sustained the full test machine limits without contact chatter. Other components had contact chatter occur in one type of test motion and not in another type of test motion. Thus, the best means to identify any frequency sensitivity is to test a device for an input motion that can be directly related to the expected frequency content of the component mounting point motion.

The 20 to 40 Hz RMF input motion was determined to be the best motion to conduct the multi-axis testing. The use of other input motions required considerable effort and did not provide better information for determining if high-frequency sensitivity existed for a given component.

Sine sweep testing demonstrated conclusively that for most relay models, contact chatter is more prone to occur in the low-frequency region of the sine sweep rather than within a high-frequency region.

Filtered multi-frequency narrow-band inputs resulted in peak spectral fragility values that were two to three times the fragilities obtained using wide-band multi-frequency input motions. The application of the relations used in EPRI TR-103959 (EPRI, 1994) for clipping of a narrow-band spectrum to obtain an estimate of an equivalent wide-band spectral level was validated. Therefore, the clipping factor used for low-frequency fragility evaluations is also valid for high-frequency fragility evaluations.

### Phase 2 Testing

Phase 2 testing was performed using the 20 to 40 Hz RMF input motion shown in Figure 2 and detailed in EPRI 3002002997 (EPRI, 2014). The test samples were selected to be representative of component types in Table 1 and typical of components installed in operating nuclear power plants. The test sample selection was based on reviews of the most common utility components tested in the EPRI Generic Equipment Ruggedness Spectra (GERS) (EPRI, 1991b) and the EPRI Seismic Qualification Reporting and Testing Standardization (SQRSTS) (EPRI, 2009) programs. Selection was made by judgment to include commonly qualified and procured items, different manufacturers, model configurations, subcomponents present, voltage/current rating, and a diverse but representative sample of components, and a variety of expected seismic capacity levels.

A total of 153 components were tested, which are representative of components in operating nuclear plants such as relays, contactors, switches, and other similar devices whose output signal or set-points could be potentially changed by high-frequency seismic motions. The largest category was control relays since older plants were designed using relay logic for system control and thus have extensive numbers of control relays used for both control logic and terminal device control. This distribution of test samples is graphically presented in Figure 4.

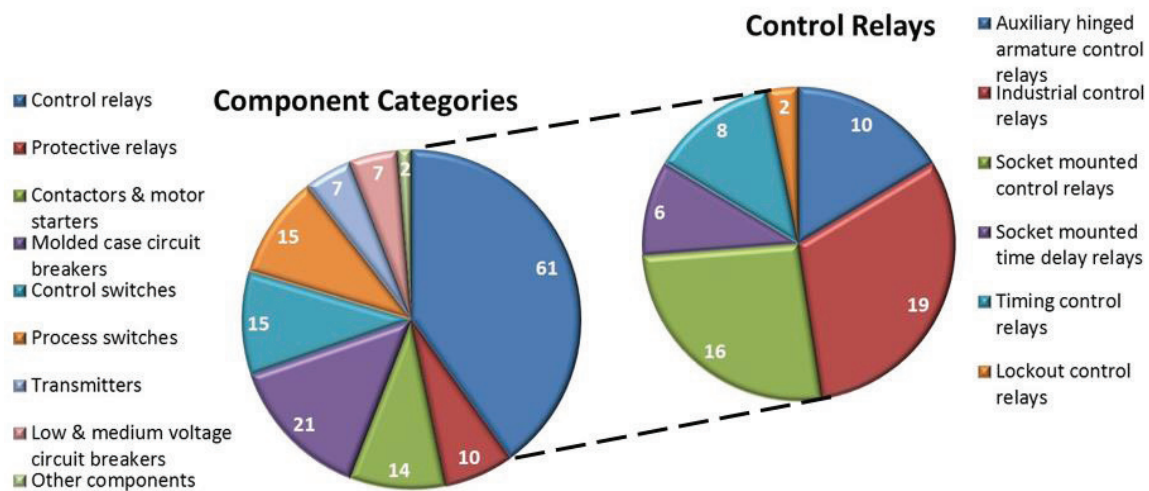


Figure 4. Distribution of Tested Components

Testing was performed in nine separate test weeks spaced out over a ten-month period. Approximately fourteen to twenty items were tested during each test week. Within each test week, the items were further divided into groups of one to five components mounted on a common test fixture and subjected to increasing levels of input motion until a discontinuity (contact chatter, voltage, or current output) in the monitoring circuit was observed for each component or the limiting table motion was reached.

Most of the testing was performed using the shake table shown in the left side of Figure 5, which is capable of shaking a total payload up to about 500 lbs (225 kg), including the test fixture, with very fine acceleration control in the high frequency range. Some test items were too large for that shake table so some testing was performed using the shake table shown in the right side of Figure 5, which has a total payload capacity of about 10,000 lbs. (4,500 kg).

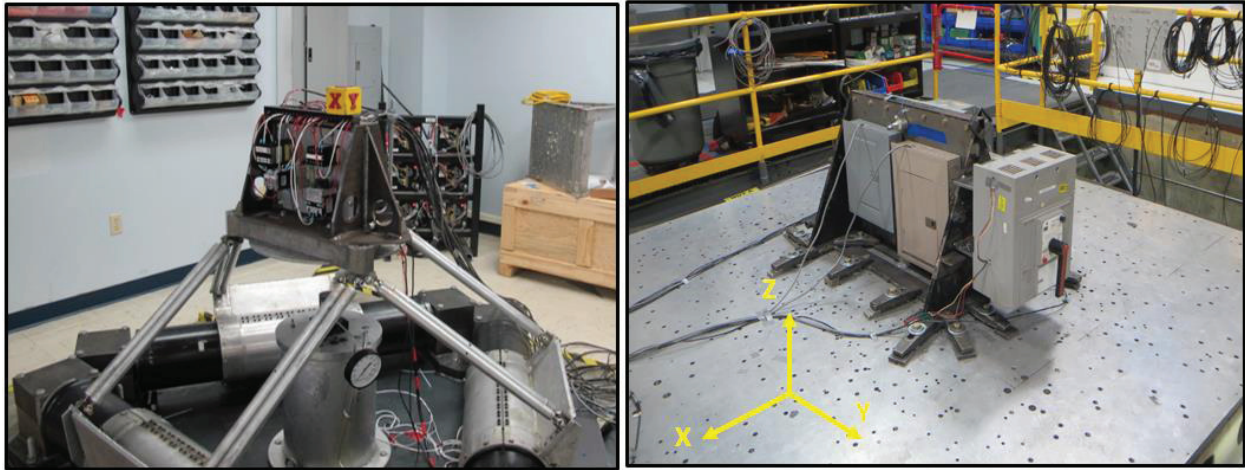


Figure 5. QualTech E Tri-Axial Shake Tables with Mounted Components

### *Determining Component Capacities*

In order to have a single measure of component capacity, a procedure was developed to determine an average estimate of the independent three-axis motion. This procedure can best be described by considering an example. Figure 6 shows a set of three-axis response spectra corresponding to a specific component test. Each test response spectrum was averaged over the plateau region of the test RMF spectrum shape (20 to 40 Hz) to obtain an effective average spectral level, which served to anchor the target RMF spectrum shape achieved in each direction during the test run. The overall effective spectral level achieved during the run was then estimated by computing the geometric average of the spectral levels achieved in each direction. For the example test run shown in Figure 6, the 20 to 40 Hz spectral accelerations were 11.93g in the x-direction, 12.63g in the y direction, and 11.80g in the z-direction. The final component test capacity level is given by:

$$SA^* = [(11.93)(12.63)(11.80)]^{1/3} = 12.11g \quad (1)$$

This acceleration level was used to scale the target RMF spectral shape to yield the effective component test capacity spectrum. This same procedure was used to determine each component's test capacity level, using the highest successful test run for each component without chatter or malfunction.

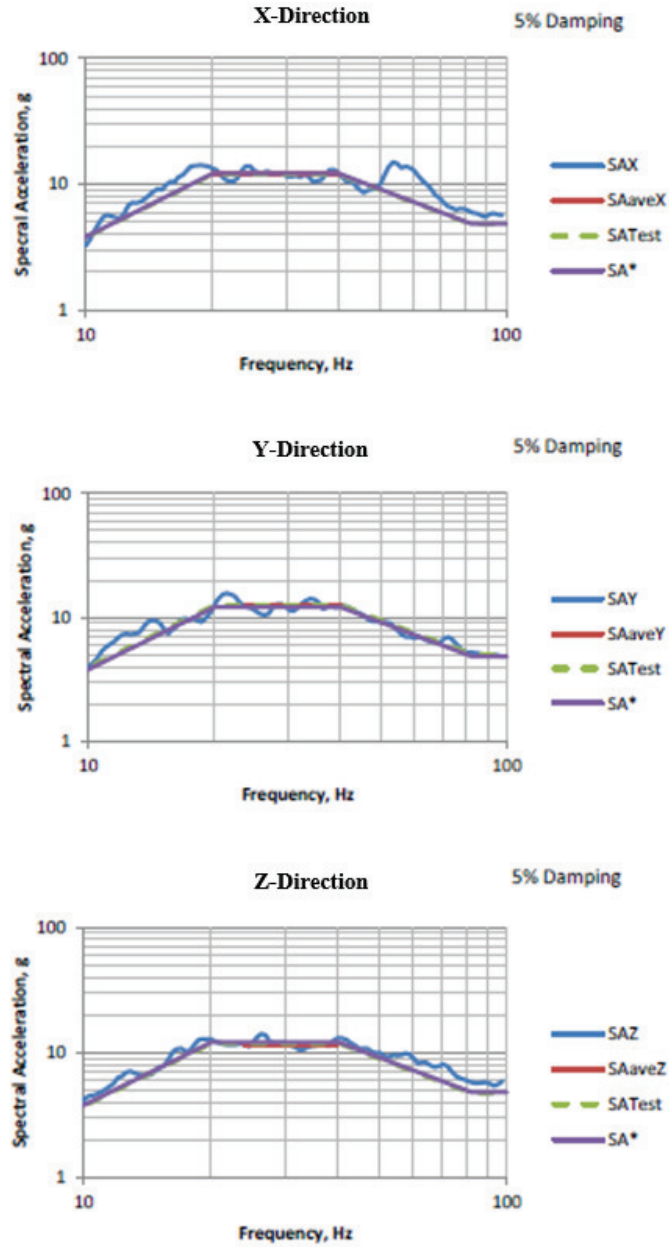


Figure 6. Three-Axis Response Spectra from a Typical Test

## HIGH FREQUENCY TEST RESULTS

A large majority of components tested in the High Frequency Program were tested to the shake table limits without chatter or malfunction. Some components did have chatter occur at lower levels of high-frequency table motion. For the components that chattered at spectral accelerations below 10g, the high-frequency capacities were compared with results from prior low-frequency testing (4.5 to 16 Hz). In all cases where components chattered in a high-frequency test, chatter also occurred in the low-frequency test at an equal or lower input acceleration level.

Sample results from EPRI 3002002997 (EPRI, 2014) are shown in Figure 7 for contactors and motor starters. The solid blue bars represent components that successfully passed at the shake table limits without

chatter or malfunction. The full capacity response spectrum for those components is the 20 to 40 Hz RMF3 response spectrum shape in Figure 2 scaled such that the peak spectral acceleration is equal to the acceleration shown in the bar chart. The crosshatched bars represent components that successfully passed at the acceleration shown but had chatter at higher test levels. Lastly, the red lines for the last two components represent the low frequency capacity for those components. Figure 8 shows a comparison of the high-frequency and low-frequency capacities for the Cutler-Hammer C80DG contactor in Figure 9.

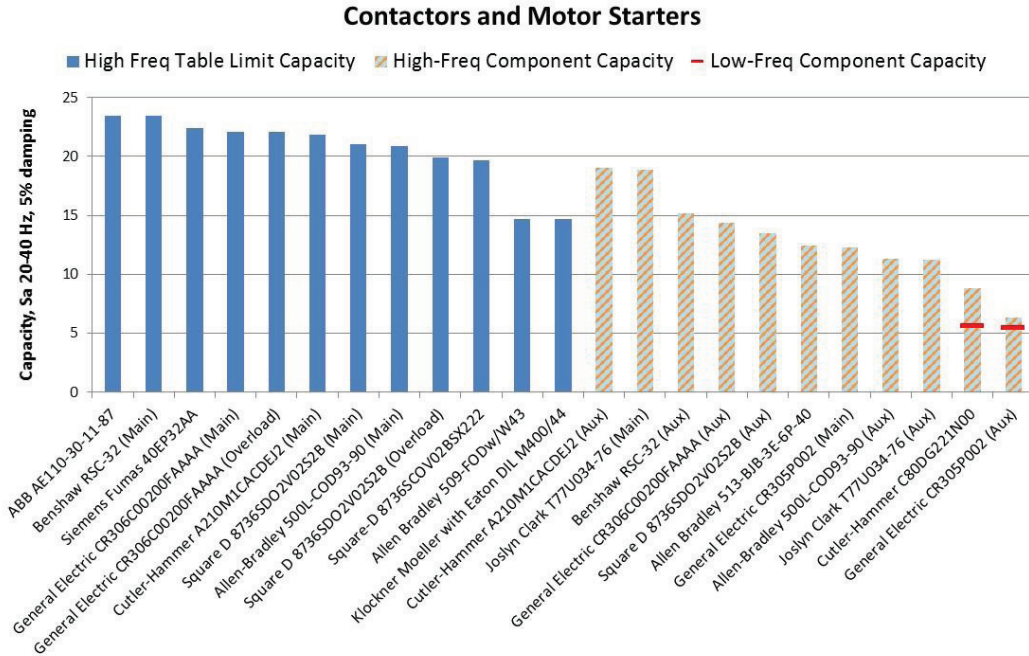


Figure 7. High Frequency Component Capacities – Contactors and Motor Starters

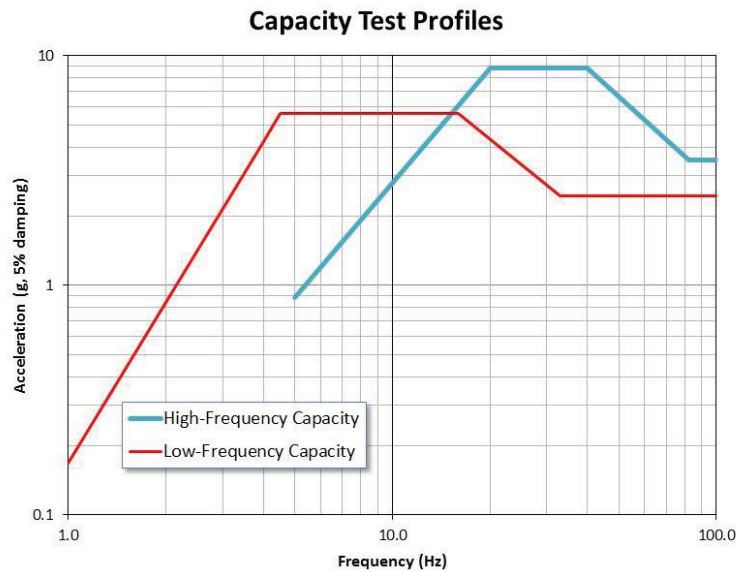


Figure 8. Comparison of High-Frequency and Low-Frequency Capacities

The primary result of the High Frequency Program is the conclusion that while some components are sensitive to vibration, no unique high-frequency sensitivities were identified. Some components are sensitive to vibration in general, but that sensitivity is not increased in the high-frequency region [xx].

## SITE-SPECIFIC HIGH FREQUENCY EVALUATION CRITERIA

Work is underway to develop a limited scope evaluation process for U.S. NPPs where new ground motion estimates have high frequency levels beyond the original plant design basis. If the ground motion exceedances are limited to the high frequency region above 10 Hz, a simplified evaluation would be used based on the CDFM method in EPRI NP-6041 (EPRI, 1991c) with amplification factors for in-structure and in-cabinet response. If there are more extensive ground motion exceedances, including below 10 Hz, guidance is being developed for considering the high frequency motions in the fragility calculations for the components.

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