Seismic Screening of Components Sensitive to High Frequency Vibratory Motions

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INTRODUCTION AND BACKGROUND

Background

EPRI report *Program on Technology Innovation:The Effects of High-Frequency Ground Motion on Structures, Components, and Equipment in Nuclear Power Plants* [EPRI, June 2007] describes the evolution of site-specific probabilistic hazard-based seismic response spectra for prospective sites of new nuclear power plants in the Central and Eastern United States (CEUS). Most existing nuclear plants in the CEUS have been designed to earlier, deterministic response spectra in accordance with Regulatory Guide 1.60 that have dominant energy content in the frequency range of 2 to10 Hz. Many of the new standard nuclear plants also have similar deterministic seismic design response spectra that are used to develop the certified plant designs. The more recent site-specific probabilistic hazard-based ground motion response spectra for new plants in the CEUS have high frequency (HF) spectral content (greater than 10 Hz range) which exceeds design spectra scaled from Regulatory Guide 1.60 spectral shapes. These seismic response spectra, however, are associated with significantly less displacement and lower response spectra values in the low frequency (less than 10 Hz) range, and therefore are expected to be less damaging for plant structures and housed equipment than events with input motions having spectra similar to the Reg. Guide 1.60-based design spectra. Nevertheless, the site-specific ground motion response spectra developed using current seismic hazard analyses may result in exceedances of in-structure response spectra developed using the Regulatory Guide 1.60 type standard seismic design response spectra for CEUS plants on hard rock sites.

The cited EPRI report summarizes a significant amount of empirical and theoretical evidence, as well as regulatory precedents, which support the conclusion that such HF motions are non-damaging to virtually all types of nuclear plant structures, systems and components (SSCs). An exception to this is the functional performance of vibration sensitive components such as relays and other electrical and I&C devices whose output signals could be affected by HF excitation. The EPRI report recommends that a program be developed to provide guidance in identification and evaluation of these potentially HF-sensitive components for those CEUS new plant applications which result in HF exceedances.

Purpose

The purpose of this paper is to present the program guidance recommended in the foregoing EPRI report. Specifically, this paper addresses the following subjects:

- Criteria for determining those component types which may be sensitive to HF vibratory motion and which should be included in the scope of components which need to be evaluated in the cases where there are HF exceedances of a plant's design response spectra.
- Recommended generic screening procedures to assure that any safety-related components which are sensitive to HF vibratory motions are screened out (that is, not used), unless otherwise shown to be acceptable for their specific application.

The screening approach presented herein is intended as a supplemental evaluation to required seismic qualification methods in accordance with IEEE standards for those plants which have HF exceedances of their certified seismic design response spectra and which therefore require evaluation of potentially HF-sensitive components.

2 SUMMARY

Some of the new nuclear plants proposed for siting in the CEUS are being designed to site-independent, standard seismic design response spectra similar to Regulatory Guide 1.60 spectra which do not include significant HF content. Site-specific ground motion response spectra based on modern hazard analyses for some of these plants will likely show exceedances of their standard seismic design spectra in the HF range. Such exceedances have been shown to be non-damaging for virtually all nuclear plant structures, systems and components (SSCs), and need not be explicitly evaluated. The exception to this is the class of I&C and similar components which have shown some sensitivity to HF vibratory motions in past tests and applications. These component types include contact devices and sensors such as relays, contactors, switches and some measuring devices.

All seismic Category I active components will be seismically qualified in accordance with IEEE Standard 344 for the Certified Seismic Design Response Spectra (CSDRS) based required response spectra (RRS) as described in the plant license application. For those cases where the CSDRS do not envelop the site-specific ground motion response spectra (GMRS) in the HF range, it is recommended that safety-related applications of potentially HF vibration sensitive components be identified, evaluated and their acceptability determined by at least one of the following screening methods:

- Existing equipment qualification test data should be reviewed for applicability and adequacy of the test method and results.
- Systems/circuits containing potentially sensitive items should be reviewed for inappropriate/unacceptable system actions due to assumed change of state, contact chatter/intermittency, set point drifts or loss of calibration.
- HF vibration screening tests should be conducted to identify any HF sensitivities/abnormalities of the components. Several conventional test methods are recommended. Component function should be monitored and documented, followed by post-test functional testing.

The objective of these screening evaluations is to provide assurance that unacceptable HF sensitivity/response of potentially vulnerable components is avoided. The overall screening process for HF-sensitive components is shown in Figure 4-1.

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CRITERIA FOR DETERMINING COMPONENTS WITH POTENTIAL HF SENSITIVITY

Characteristics of Components Sensitive to HF Vibratory Motions

The concern with potentially HF-sensitive components is related to the functionality of the devices when subjected to HF motions. Historically, concerns over functionality of components due to HF motions have been focused on: 1) devices that have inadvertently changed state, permanently or temporarily (i.e., chattered) or had their output signals affected as a result of vibratory motions: and, 2) non-ductile components such as ceramic insulators and cast iron components that have failed due to HF shock-type loads. The former group is characterized as having bi-stable contacts or other mechanisms loaded by springs and/or electromagnetic forces which can be actuated/moved by inertial forces. The latter group of devices has been screened by either avoiding use of brittle materials, or by seismic and operational qualification testing of components (such as breakers and switchgear) whose operation involves impact loads and also requires potentially brittle insulating materials. The inappropriate application of brittle materials in new plants can be addressed through design and quality assurance (QA) control. Additionally, there is no evidence to suggest that current seismic qualification methods are not adequate for conventional equipment such as switchgear and other rugged breakers. Therefore, the investigation of appropriate evaluation methods for potentially HF-sensitive components in new CEUS plants is directed to bi-stable devices such as relays, contactors, switches, potentiometers and similar devices, and those components whose output signal or settings (set-points) could be changed by HF vibratory motion. Observation of malfunctions of bi-stable devices has come mainly from seismic qualification tests and operating experience during which HF impact excitation (and likely high accelerations) caused relays to actuate resulting in inadvertent actions such as component trips and even plant shutdowns. It is understood that similar events have occurred in military and aerospace relays and contact devices due to mechanical or explosive shock loads. In addition, cases in which the output of sensing/measuring devices, such as pressure transducers and potentiometers, have changed due to vibratory motions have also been observed during seismic testing. Observation of relay/contactor malfunction in actual earthquakes has been very limited.

It is important to note that the experience of the individuals involved in the development of this paper (whose experience in the seismic qualification testing of nuclear plant components and other applications typically each exceeds 30 years), is that the actual safety significance related to possible functional malfunction of the aforementioned electrical and I&C devices is very low, and considering the technological advances in such devices and the move to inherently rugged solid-state components, makes this an extremely low challenge for new nuclear applications.

Failure Modes

The potential failure modes of the HF-sensitive component types and assemblies must be considered in order to demonstrate the suitability of the equipment for HF seismic environments. The following types of failure modes have been observed:

- Inadvertent change of state
- Contact Chatter
- Change in output signal or set-point
- Electrical connection discontinuity or intermittency (e.g., insufficient contact pressure)
- Mechanical connection loosening
- Mechanical misalignment/binding (e.g., latches, plungers)
- Cyclic strain effects (e.g., cracks in solder joints)
- Wiring not properly restrained
- Inadequately secured mechanical fasteners and thumb screw connections

Generic failure modes involving change of state, chatter, signal change/drift and connection problems due to design deficiencies are the main focus of the proposed HF screening. High frequency failures resulting from improper design of mounting, inadequate design connections and fasteners, mechanical misalignment/binding of parts and the rare case of failure of a component part, will result from the same structural failure modes as those experienced during low frequency content spectra qualification testing per IEEE Standard 344 using CSDRS-based RRS. Because the safety-related equipment will experience higher stresses and deformations when subjected to the low frequency excitation, failure modes are more likely to occur under the low frequency testing. Failure modes related to improper mounting, inadequate securing of connections, poor quality joints, etc., are addressed by quality assurance inspection and process/design controls.

Components Potentially Sensitive to HF Motions

Based on the above considerations, the following component types are considered potentially sensitive to HF motions and should be screened following the procedures and criteria provided in Section 4.

- Electro-mechanical relays (e.g., control relays, time delay relays, protective relays)
- Electro-mechanical contactors (e.g., Motor Control Center (MCC) starters)
- Circuit breakers (e.g. molded case and power breakers – low and medium voltage)
- Auxiliary contacts (e.g., for Molded Case Circuit Breakers (MCCBs), fused disconnects, contactors/starters)

- Control switches (e.g., benchboard, panel, operator switches)
- Transfer switches (e.g., low and medium voltage switches with instrumentation)
- Process switches and sensors (e.g., pressure/diff. pressure, temperature, level, limit/position, and flow)
- Potentiometers
- Digital/solid-state devices (mounting and connections only)

Non-ductile components and internal parts include those made of such materials as cast iron and ceramics. Standard commercial components which require non-ductile parts for function (e.g., circuit breakers) will be tested in accordance with traditional test standards; components otherwise fabricated of brittle materials should be avoided or justified on a case-by-case basis.

A significant additional consideration with regard to sensitivity to HF excitation is the fact that many systems and circuits in new plants will utilize digital, solid state components and replacements for traditional electro-mechanical components. Available shock and vibration test data and many years of experience with solid-state, digital components in military, aerospace and commercial computer/electronics applications has demonstrated that when properly mounted, these devices are inherently rugged and are not functionally sensitive over the entire frequency range of interest. Therefore, the only potential concerns with digital or solid state components are component mounting and connections. Any significant mounting and connection issues will be detected during IEEE 344 qualification testing of the certified design component which will result in a redesign and re-qualification.

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GENERIC HF SCREENING PROCEDURES AND CRITERIA

As noted in the introduction, the intent of the process presented herein is to screen components, which have been fully seismically qualified for the certified design in-structure motions, to demonstrate that any additional potential HF vulnerabilities are addressed. The screening approach is a supplemental evaluation to insure that those plants which may have site-specific HF exceedances of their CSDRS do not have potential HF vulnerabilities.

Figure 4-1 shows that the screening process consists of three parallel paths, each of which can accomplish the goal of demonstrating that HF vulnerabilities are not present in qualified components. First, we note that the equipment or component to be screened must be one of the potentially vulnerable types noted in Section 3.3. Next, the screening can be accomplished using any of the following alternate procedures, in any order: 1) utilization of existing qualification data that includes input motions in the HF range, 2) control/logic circuit evaluation that demonstrates that any potential intermittency of component function which may be due to HF excitation (e.g., change of state, chatter, signal change/drift and/or connection discontinuity) cannot cause any unacceptable system response, or 3) performance of a HF screening test which demonstrates lack of HF sensitivity. Each one of these processes are discussed below. If any component is found to have HF sensitivity, an alternate non-sensitive CSDRS qualified component must be found.

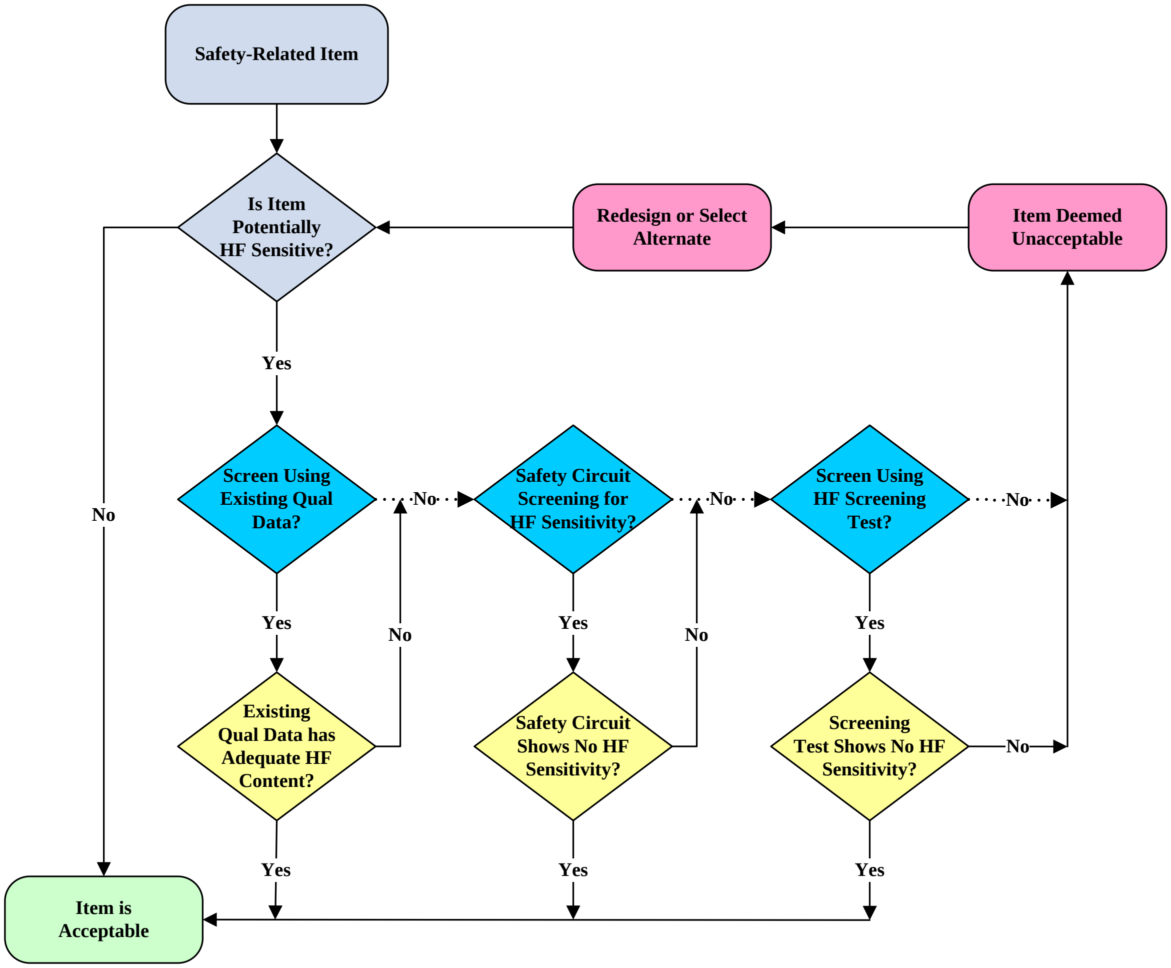

Figure 4-1
High Frequency Screening Process

Use of Existing Qualification Data

For more than the past 30 years, safety-related active components have been seismically qualified for NPP service using IEEE Standard 344 random multi-frequency type test input motions that contained additional HF content which is greater than specified for low frequency (LF) design motions. This additional HF content has been included either intentionally or unintentionally as an artifact of seismic testing. Intentional HF content, such as inclusion of BWR hydrodynamic response, has also been added to seismic test motions for some components, to demonstrate component function for concurrent seismic and hydrodynamic loads (such as BWR SRV activation during a seismic event). HF content may also be present due to the test system response to the input waveform caused by looseness and/or rattling of the shaker table mechanical joints, the test fixturing, or the test specimen itself. Localized equipment vibration/impacting can occur due to looseness and/or rattling of enclosure connections, doors, and internal panels. Methods identified in IEEE 344-87 or later should be considered for demonstrating that seismic test motions include adequate HF content in the 25 to 50 Hz range. Thus, the evaluation of existing LF qualification test data may be acceptable to demonstrate lack of sensitivity of equipment/components for HF excitation.

Circuit Evaluation

Safety-related I&C circuits are often designed to accommodate any potential intermittency of component function. The review and evaluation of the control/logic circuits which interface with the component should be conducted by the I&C system designer by assuming that HF content causes an intermittent disruption of component function. If it can be documented that such an assumption does not cause inappropriate system actions or set point drifts, then the consequences of any potential HF-sensitivity is not relevant and need not be considered. This functional screening of systems qualified for certified design conditions for lack of adverse system responses caused by additional potential HF sensitivities can be a viable alternate screening procedure.

HF Screening Test

A high frequency screening test can also be used to demonstrate lack of component sensitivity to high frequency vibration. It should be noted that this test is not a qualification test but rather, is intended as a vibration stressor to insure that components sensitive to HF vibration are not present in the set of qualified certified design equipment and functional systems.

Review of rock-structure interaction effects (excluding the foundation motion incoherency effect) indicates that (EPRI, 2006) high frequency effects are associated with about 50 Hz or less. It is recommended that HF screening tests be conducted over the one octave frequency range between 25 and 50 Hz. The 25 Hz starting point insures sufficient overlap with a CSDRS-based component qualification frequency range up to approximately 33 Hz. In order to sufficiently stress components to insure that any HF sensitivities present are activated, it is recommended that test motions be conducted using a representative input floor spectral acceleration (SA) of 5g (5% damping) over the frequency range of 25-50 Hz or for enclosure and/or rack mounted components (tested independent of the mounting configuration), a representative input motion level is recommended that would cause a constant spectral acceleration of SA = 15g (5% damping) over the frequency range of 25-50 Hz. This is the approximate generic spectral level used by the SQURTS test group (EPRI, 1996) for generic testing of equipment mounted components.

The recommended screening methods are 1) sine sweep , 2) sine beat testing at 1/6 octave intervals, or 3) random multi-frequency time history consistent with a constant spectral acceleration. In each case, the test should be performed over the frequency range 25-50 Hz. The test input screening level would be determined by the relation, A=(SA)/Q, where A is the maximum acceleration of the test table and Q is the amplification factor required to achieve the spectral acceleration value, SA, for the particular type of screening test chosen.

Example test amplification factors associated with 5% damping for each type of test are as follows:

- Sine Sweep (log or linear rate)
  (Qss = 9-10) (Octave/min)
- Sine Beat at 1/6 octave frequency spacing [25, 28, 31.5, 35.5, 40, 45, 50 Hz]
  (5 cycle/beat, Q5sb = 0.56)(10 cycle/beat, Q10sb = 7.6),
  5 beats or more per frequency
- Random Time History (Qr = $\sqrt{(10)}$ = 3.2, duration > 15 - 20 sec)

Examples of peak test motion amplitude for each type of screening test for the case of a floor mounted equipment component are as follows:

  - Sine Sweep, SA = 5g, Qss = 10, A = 5/10 = 0.5g
  - Sine Beat, SA = 5g, Q5sb = 5.56, A = 5/5.56 = 0.90g
  - Random Time History, SA = 5g, Qr = 3.2, A = 5/3.2 = 1.56g

Function should be fully monitored during the screening test followed by post-test functional testing. The duration of motion would be chosen based on data acquisition limitation and or the number of total cycles desired. Each of the above screening test types offers some test flexibility. For example, the sine sweep can be conducted at a faster rate which would result in a lower Q. This would allow data acquisition over a more reasonable test duration period. The value of A used for the peak test motion would then be increased to achieve the target SA screening level. In general, the screening tests can be conducted using sequential single-axis input motions (applied to each specimen principal axis) since the intent of the testing is to stress the component to determine if any HF sensitivities are present. If desired, the random time-history can be conducted using simultaneous multi-axis independent inputs.

5 CONCLUSION

The screening approach presented in this paper provides a supplemental evaluation process for potential HF vulnerabilities in equipment and components for those plants which have HF exceedances of the CSDRS. The recommended generic screening process assures that any potentially HF sensitive safety-related components are screened out, unless otherwise shown to be acceptable for their specific application.

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