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Issues in Generating Accurate In-Cabinet Response Spectra for Seismic Qualification of Electrical Equipment

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1. Introduction

South Korea experienced its biggest earthquake in recent history on September 12, 2016. The Gyeongju earthquake of magnitude (M_w) 5.4 has initiated a significant activity in the area of seismic safety for nuclear power plants. Initial reports indicate that the nature of this earthquake is similar to the recent findings from geophysical investigations in Central and Eastern United States (CEUS), i.e., the earthquake ground motions contain not only the low frequency content but also some high frequency content.

In the context of seismic safety assessment, high frequency motions are not likely to cause damage to structural systems as the displacements associated with such motions are relatively very small. Yet, past experience around the world has shown that electrical instruments such as relays, breakers, and contact switches can exhibit loss of functionality due to high frequency motions. These instruments must continue to operate as intended during and after an earthquake. The earthquake motion exhibited by such instruments is highly dependent on the dynamic characteristics of the cabinets and control panels on which they are mounted. The spectra to define input motions used in shake table testing of such instruments is therefore called in-cabinet response spectra (ICRS). In this paper, we review the current methods used for evaluating ICRS and evaluate applicability of each method and its appropriateness for practical use.

2. Current State of In-Cabinet Response Spectrum

2.1 EPRI NP-7146-SL: Background and Limitation

Two simple methods are proposed in EPRI NP-7146 SL guidelines [1]. These methods are based on in-situ modal test data of 45 cabinets and can be used for only those cabinets that satisfy a specified set of caveats. In one of the two, the screening factor method, peak floor spectral acceleration is amplified by a factor of 4.5 to obtain the peak incabinet acceleration. The same amplified acceleration is used in the complete frequency range of interest. This method modifies the narrow-band incabinet spectra to obtain broad-band clipped-peak spectra using knockdown factors of up to 0.6 (up to 40% clipping). It has been found that even though knockdown factors are used to evaluate the screening factor of 4.5, this method can give excessively conservative spectral accelerations for most situations. Conservatism is introduced by including amplification at locations where an instrument may never be mounted.

For cabinets in which the results of screening factor method are too conservative, a second method called the “simplified analysis" method is recommended. In this method, the fundamental cabinet frequencies, frequency dependent maximum pseudo participation factors and the modal damping ratios from in-situ modal tests of 45 cabinets are used. Several incabinet spectra are analytically generated using these dynamic properties for a range of cabinet fundamental frequencies. The final spectrum is obtained by enveloping the generated spectra for the 45 tests. The maximum pseudo participation factors used in the analytical solution are not for the particular cabinet under consideration. Further, there is no good way of estimating the fundamental frequency of the cabinet. For most cases, unrelated high values of maximum pseudo participation factors and enveloping of several individual incabinet spectra introduces excessive conservatism.

Every utility understands the limitations and approximations in using the SQUG factors or EPRI NP-7146 SL guidelines. However, the premise is that the factors are in general quite conservative and if a relay worked well during shake table testing at acceleration level (across a wide band of frequency – pretty much a flat ICRS) which is higher than the ICRS generated by using the factor then the relay is inherently qualified.

It has been noted by many researchers that the set of cabinets used in the study that forms the basis for EPRI NP-7146 SL are only a very small set among the type of cabinets found in most plants. It has also been acknowledged that the amplifications in other cabinets can be quite different from what forms the basis of EPRI 7146 SL. Subsequent research at NC State University identified that in some cases the ICRS generated by using the constant factors can be very conservative even if the smallest factors are used [2]. The same research also showed that in other cases the ICRS can be unconservative even if the largest factors are used.

In most cases, the fundamental mode of the cabinet is used to generate the amplifications. Subsequent research has shown that in many cabinets the fundamental mode is not necessarily the significant mode [2]. The most significant mode is typically the local mode of the panel or the frame of which a relay is mounted. It has also been shown that most analytical studies particularly those based on finite element analysis consider the cabinets to be fixed at their base. However, this is not true for cabinets that are anchored to the floor. Such anchored cabinets can have minor rocking/rattling of the whole cabinet and the behaviour at the mounting arrangement is quite complex and nonlinear [3]. It is also noted that in many cases, the mounting arrangement used in the shake table testing of actual cabinets is not identical to the one used for in-situ anchorage. This difference can lead to a significant change in ICRS for some cases.

2.2 Simplified Method: Ritz Vector Approach

Based on the discussion presented above, it can be observed that the significant cabinet mode evaluated from a finite element analysis and validated against experimental data represents a global cabinet rocking superimposed with the local mode of the plate or frame on which the instruments are mounted. A Ritz vector approach, in which the significant cabinet mode is taken as global rocking superimposed with local plate or frame modes, would give accurate results, i.e. the displacement u at a given instrument location can be expressed as:

$$u(\xi, \eta, t) = x_r(t)\phi_r(\eta) + x_g(t)\,\phi_g(\eta) + x_l(t)\phi_l(\xi,\eta) \qquad (1)$$

where $\phi_r(\eta)$, represents the Ritz vector for the rigid body rocking mode; $\phi_g(\eta)$ represents the Ritz vector for the global cantilever-type mode; and $\phi_l(\xi,\eta)$ represents the Ritz vector for the local mode shape of the plate or frame on which the instrument is mounted. Consistent with the coordinate system used in Gupta et al. [2], the symbols ξ and η denote the horizontal and vertical coordinates whereas $x_r(t)$, $x_g(t)$, and $x_l(t)$ represent the normal coordinates as a function of time t, for rocking, global bending, and local modes, respectively. A detailed discussion on the selection of Ritz vectors is presented in Gupta et al. [2] and Gupta and Yang [4]. For a cabinet of height L, the Ritz vector for the rigid body rocking mode can be simply taken as

$$\phi_r(\eta) = \frac{\eta}{L} \qquad (2)$$

Thus, equation 1 linearly transforms the motion at a given instrument location into an equivalent 3-DOF system. In situations where a global bending does not exist, the transformation results in an equivalent 2-DOF system as the term corresponding to $\phi_g(h)$ drops out of equation 1. The Ritz vector for the local mode shape $\phi_l(\xi,\eta)$ can be determined according to Blevins [5]. Eigenvalue problem for this equivalent simple system can be written as

$$\mathbf{KX} = \omega^2\mathbf{MX} \qquad (3)$$

where **K** and **M** are the equivalent stiffness and mass matrices, respectively, and **X** is the vector of generalized coordinates. Solution of the eigenvalue problem gives the frequency of significant cabinet mode and the corresponding eigenvector. Development of stiffness matrix **K** in case of a rocking mode requires some means of calculating the stiffness k_v of equivalent vertical spring for a particular cabinet mounting arrangement. Simplified expressions for doing so in various types of cabinet mounting arrangement are presented in Yang et al. [3]. Such a simplified Ritz vector based method can be easily implemented either through hand calculations or even through a MATLAB based code. Initial development of Ritz vector approach has been validated by comparison with results presented above as evaluated from experimentally validated finite element analyses.

3. Discussion

It is recommended that the methodology in EPRI NP-7146 SL based on a constant amplification factors is not appropriate under the current environment for seismic qualification. The constant amplification factors can be excessively conservative in some cases thereby rendering many electrical systems or relays to be seismically unfit for use in a plant. In other cases, the constant amplification factors can be unconservative. Therefore, they can result in incorrect ICRS for such cases.

The simplified method using Ritz vector approach can be a good alternative to the methodology in EPRI NP-7146 SL. However, application of the simplified method to an actual plant would require additional work collecting relevant information, finite element analyses, validation with experimental data, and development of the code or spreadsheets for implementing the approach.

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