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STUDY OF SUPPORT AMPLIFICATION FACTORS FOR VARYING FREQUENCY & MASS RATIOS OF EQUIPMENT MOUNTED ON SUPPORT

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ABSTRACT

IEEE 693 is a seismic standard written to provide a uniform guidance and criteria for seismic qualification of Substation and Switchyard type electrical equipment. In many respects, this standard is similar to IEEE 344 for seismic qualification of nuclear safety-related equipment. Depending on equipment voltage class and operational importance, the IEEE 693 Standard requires seismic qualification by shake table testing, dynamic analysis, static analysis, or simply by performance experience during past earthquakes.

Typical Substation/Switchyard equipments are often large pieces of equipment, having some porcelain or composite insulator components, with not much inherent ductility. These equipment are often mounted on support structures that vary in complexity, from a single steel pole to a complex steel frame structure. Often times, the equipment manufacturer must perform the seismic qualification of the equipment (a catalog-type item), not knowing the design details of the support structure. For such scenarios, the IEEE 693 Standard requires a uniform amplification factor of 2.5 on the ground motion, in order to allow for possible amplifications by the support structure. The real amplification factor will depend on the dynamic characteristics of both the support and the equipment, which in turn depends on the mass and stiffness of each piece, hence their fundamental frequencies. The equipment to support frequency and mass ratios define the dynamic characteristics of the combined system.

A research project was undertaken, sponsored by Electric Power Research Institute, to study the variability of this amplification factor based on variations of frequency and mass ratios of the stand-alone equipment to the support. All together 80 scenarios were considered, corresponding to 4 sets of support stand-alone frequencies of 5, 10, 20 & 33 Hz. For each of these 4 support frequency categories, 20 variations of frequency and mass ratios were studied. The mass ratios of equipment to the support were kept constant at 5 ratios of 0.1, 0.5, 1, 2 and 4. However, for each support stand-alone frequency, and each mass ratio, 4 different frequency ratios were considered which varied for each category of support stand-alone frequency. Time-history analyses of a simplified 2DOF model (representing both the support and the equipment) were performed, followed-up by time-history analyses of corresponding SDOF model representing the stand-alone equipment.

This paper discusses the methodology and the results of these variation studies. Comparison of equipment response parameters from the 2DOF model (explicitly modeling the support and the equipment) vs. the SDOF model representing the stand-alone equipment were performed to study the validity of the prescribed amplification factor of 2.5 for situations where the support characteristics are unknown. In addition the results exhibit various trends in terms of support amplification for varying mass ratio, frequency ratio, as well as support frequency.

INTRODUCTION

IEEE 693 Standard (Ref. 1) defines the seismic qualification requirements for electrical equipment that are used in Substations. These qualification procedures range from inherently acceptable, to qualification by analysis (either static or dynamic), and qualification by shake table testing, depending on voltage class of the equipment, as well as their relative importance to the operations of a Substation. Most Substation equipment are generally mounted on some kind of a support structure, as such the Standard also addresses the influence of support structures on overall seismic response of the equipment.

In particular, Section 5.5.4 of the latest official release of the Standard (2005 edition) discusses qualification of equipment mounted on a support structure whose properties are “not known”. For these situations, an amplification factor of 2.5 is recommended to account for amplification effects of the support structure whose properties are “not known” at the time of qualification of the equipment. Furthermore, for bushings mounted on a transformer (whose dynamic properties are also not known at the time of testing of bushing), an amplification factor of 2.0 is recommended by the Standard to allow for possible amplification effects of the transformer. The Standard is somewhat inconsistent in specifying two different amplification factors (2.0 v. 2.5), in this regard.

A research project, sponsored by Electric Power Research Institute (EPRI), was undertaken to better understand this issue. The objective of the research conducted in this project, was to study the dynamic amplification of support structures, considering various equipment to support mass and frequency ratios. The results provide a good representation of variability of support amplification factor for a cross-section of dynamic characteristics of the combined system that is typically found in Substations. The results provide a technical justification for the factor of 2.5 that is currently specified by the Standard, and provide some additional insights with respect to the variation of this amplification factor vs. parameters such as support stand-alone frequency, equipment to support mass ratio, and equipment to support frequency ratio.

TECHNICAL APPROACH

The methodology was based on an analytical evaluation to better understand the dynamic behavior of equipment mounted on a support structure with varying frequency and mass ratios. The equipment and the support structure were modeled as a 2DOF oscillator having dynamic properties in a single direction. This 2DOF oscillator has two lumped masses: m_1 (representing the mass of the support structure), and m_2 (representing the mass of the equipment). The stiffnesses of each “stand-alone” part of the oscillator were assigned such that the natural frequency of each stand-alone oscillator is f_1 for the support structure, and f_2 for the equipment. These two stand-alone oscillators were mounted on top of each other forming a 2DOF oscillator representing the equipment mounted on the support. The combined system has two modes denoted by f_{11} and f_{22} representing the 1^{st} and 2^{nd} modes of the combined system, whose frequencies are different that f_1 and f_2, unless the ratio of m_2/m_1 is very small. The combined 2DOF oscillator was then analyzed dynamically using an input time history compatible with the IEEE 693 spectral shape anchored to 1.0g PGA representing high performance level qualification. Combined damping of 2% was assigned to the model.

The second part of the research included studying the equipment stand-alone response subject to 2.5 times the ground motion (or the IEEE 693 spectral shape anchored to 2.5g). This 2.5 factor represented the current recommendation of the Standard when support characteristics are not known. The time history (TH) analysis of the stand-alone equipment (which has frequency f_2) was performed using a SDOF model of the equipment having identical properties to the equipment portion of that used in the 2DOF model.

These two sets of analyses were repeated for 80 analysis cases with the parametric variation discussed below to obtain a broad cross-section of equipment to support structure dynamic interaction.

- Study 5 mass ratios of m_2/m_1 = 0.1, 0.5, 1.0, 2.0 and 4.0
- Study 4 frequency ratios f_2/f_1 (varies depending on support stand-alone frequency)
- Study 4 support stand-alone frequencies of f_1 = 5, 10, 20 & 33 Hz.

These variations represent 5 (mass ratios) x 4 (frequency ratios) x 4 (support frequencies) = 80 variations of equipment vs. support structure dynamic properties. As such, 80 sets of TH analyses were performed for the coupled 2DOF oscillator. Another 16 sets of TH analyses were performed for the stand-alone equipment subject to 2.5 times the input ground motion. Equipment stand-alone TH analyses cases were only 16 sets, because in the 2DOF model, the desired mass ratio range was achieved by changing m_1 (support mass), thus for the equipment part, only 16 variations of the stand-alone equipment needed to be studied. From each of these two sets of analyses, the following response parameters were extracted which are of interest:

- Plots of response spectra at base of the equipment from analysis of the coupled system vs. the input spectra (IEEE 693 spectral shape anchored to 1.0g PGA). These plots provide a range of amplification factors at various frequencies of interest to show whether the amplification factor of 2.5 occurs over a narrow frequency range, and if so what frequency range.

- Comparison of peak acceleration, and displacement response at the equipment mass point in the coupled analysis vs. the stand-alone analysis subject to 2.5 times the ground motion. These comparisons provide insights as to what scenarios are associated with support-induced amplification of input motion that approach the suggested factor of 2.5.

- Comparison of peak force response at the base of equipment from the coupled 2DOF analysis vs. the stand-alone SDOF analysis subject to 2.5 times the ground motion. This would be another measure of response, and in general is expected to follow the acceleration response ratio discussed above.

Study of the last 2 bullets above provided technical justification of whether a factor of 2.5 is sufficient or should be changed. Figure 1 shows the technical approach used for analyses of the 2DOF model representing the combined system, vs. the SDOF model representing the equipment stand-alone model. Figure 2 shows the standard response spectra that are defined in Annex A of the IEEE 693 Standard (Ref. 1). Note that this figure is extracted from IEEE 693 Standard and is for high Required Response Spectrum (RRS) thus anchored to a PGA of 0.5g. For all analyses performed here, spectra (and thus associated TH) are anchored to 1.0g PGA. Figure 3 shows the plot of the synthetic time history function which is again a standard feature prescribed by the 693 Standard (Ref. 1) in order to have some consistency among qualification of various equipment by different vendors.

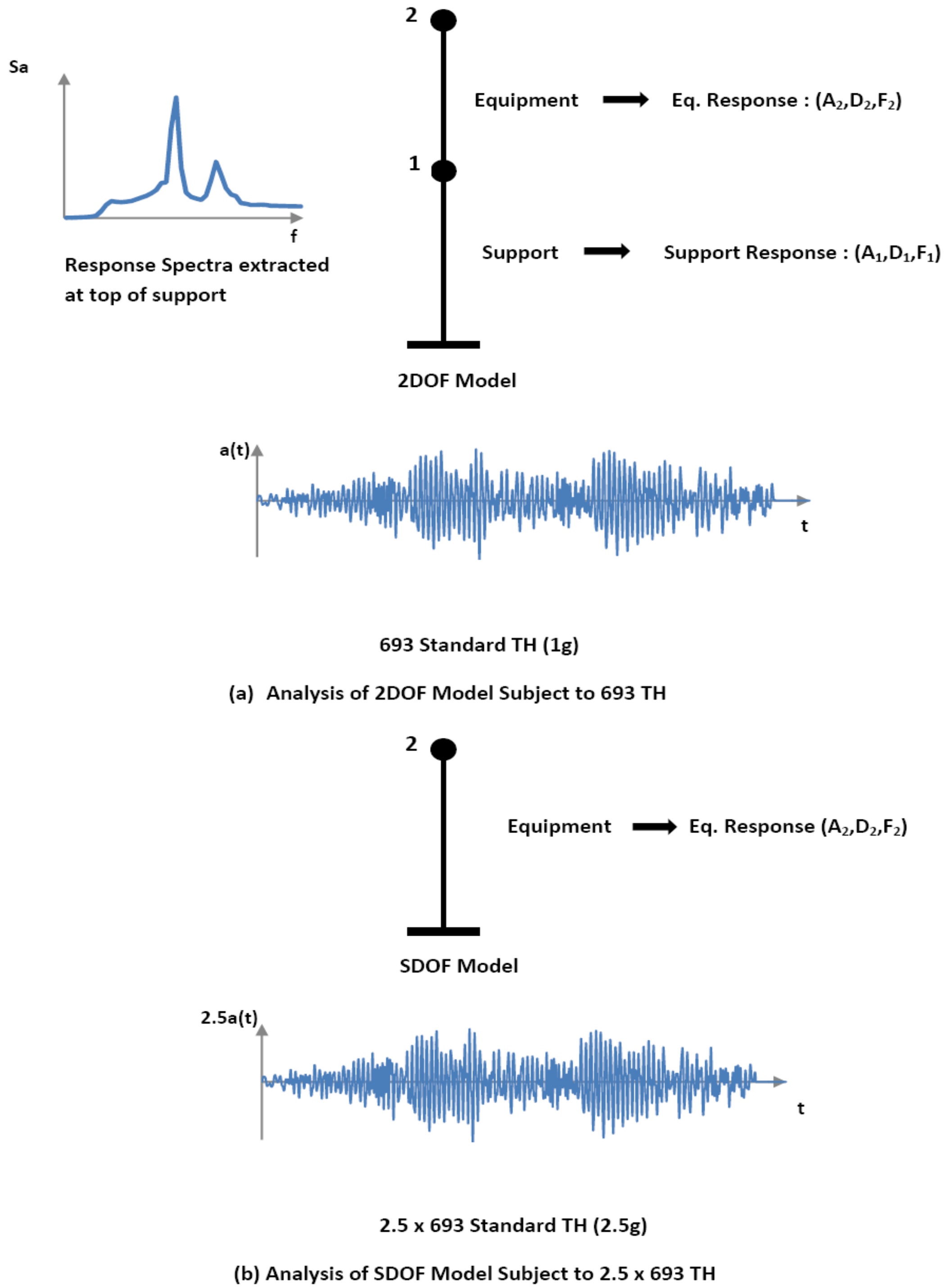

Figure 1: Technical Approach for Studying the Support Amplification Factor

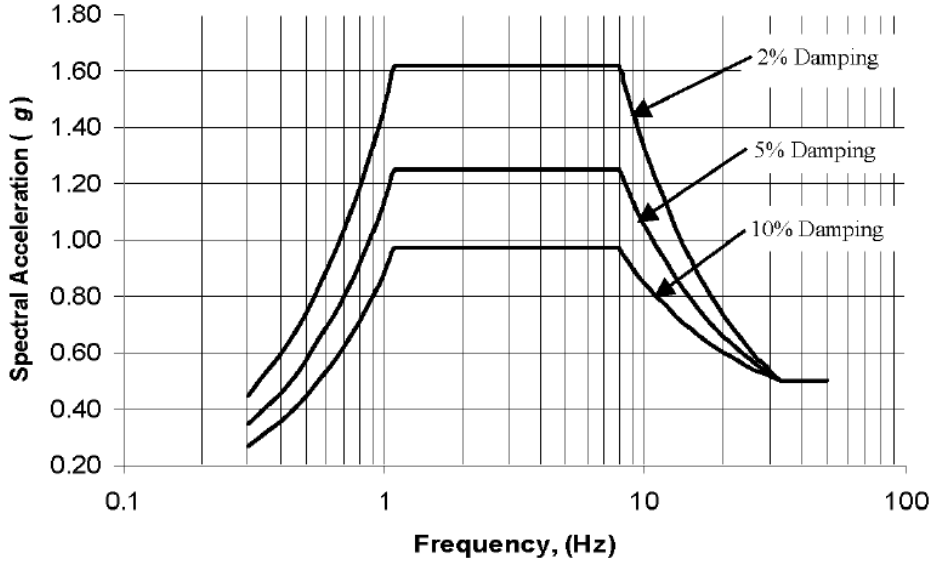

Figure 2: IEEE 693, High Required Response Spectrum, 0.5g PGA

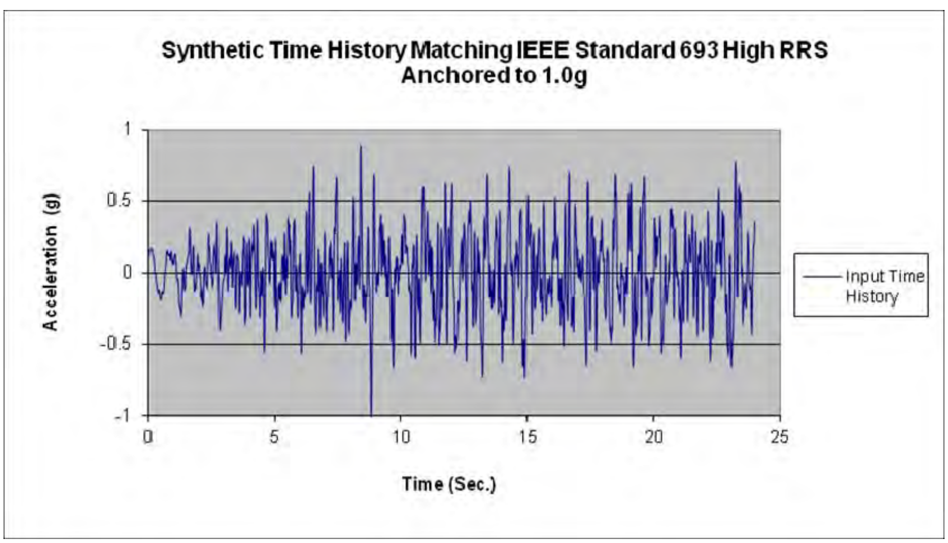

Figure 3: The Synthetic Standard Time History matching IEEE 693 Spectral Shape (1.0g PGA)

RESULTS

The results showed that only 4 out of 80 cases studied, resulted in actual amplification factor greater than 2.5, however the maximum amplification ratio for these 4 cases was 2.76 which is only 10% higher than the prescribed amplification factor of 2.5 by the Standard. The distribution of the results for all 80 cases, are presented below:

- 76 out of 80 (95%) analyses cases, showed amplification factor of 2.5 is conservative.

- Out of the 80 analyses cases studied, only 4 cases (5% of population) showed amplification factor in excess of 2.5. The highest amplification factor was 2.76 and corresponded to case 37 (Stand-alone support frequency of 10 Hz., frequency ratio = 2, and mass ratio = 0.5). This value exceeds the value of 2.5 specified by the IEEE 693 Standard by only 10%.

- Out of the 80 analyses cases studied, 10 cases (12.5% of population) showed amplification factors greater than 2.0 but less than 2.5.

- Out of the 80 analyses cases studied, 10 cases (12.5% of population) showed amplification factors greater than 1.5 but less than 2.0.

- Out of the 80 analyses cases studied, 56 cases (70% of population) showed amplification factors that were less than 1.5.

In order to see the variation of these results in graphical form, a series of plots of normalized amplification ratios were plotted vs. a varying parameter, whilst keeping all other varying parameters constant. For example Figure 4 plots the variation of normalized amplification ratio vs. frequency ratio for support frequency of 5 Hz. On this plot, the variation of mass ratios is shown by different lines having different colors. Figure 5 plots the variation of normalized amplification ratio vs. mass ratio for support frequency of 5 Hz. On this plot, the variation of frequency ratios is shown by different lines having different colors. Figure 6 plots the variation of normalized amplification ratio vs. support frequency for a frequency ratio of 1.0. On this plot, the variation of mass ratios is shown by different lines having different colors. In these plots normalized amplification ratio is the ratio of amplification factor normalized to 2.5 (divided by 2.5), thus a normalized amplification ratio of 1.0 corresponds to an amplification factor of 2.5. Not all such plots can be shown in this paper, as such, the reader is referred to Reference 2 for a complete set of charts showing such variations of support amplification factors vs. frequency and mass ratio for the 4 categories of support stand-alone frequencies examined in this research.

In addition, Figures 7 and 8 show the plots of amplified response spectra at the top of the support structure, superimposed on the ground spectra, for analysis cases 37 and 33. Analysis case 37 corresponds to the support frequency of 10 Hz. with frequency ratio of 2.0 and mass ratio of 0.5 which resulted in the highest amplification factor of 2.76. Analysis case 33 corresponds to the support frequency of 10 Hz. with frequency ratio of 1.0 and mass ratio of 1.0 which resulted in a moderate amplification factor of 1.48. The top portion of these figures shows the comparison of spectra at top of the structure (base of equipment) vs. the input ground spectra. The bottom portion of these plots shows the same amplification factors normalized and plotted as a function of frequency (Transfer function). Again, not all such plots can be shown in this paper, as such, refer to Reference 2 for a complete set of such plots for all 80 analysis cases.

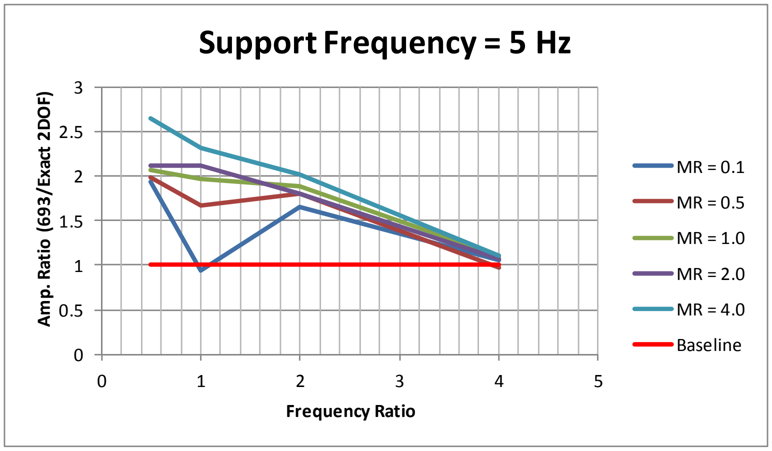

Figure 4: Normalized Amp. Ratio vs. Frequency Ratio (FR)
For Support Frequency (SF) = 5 Hz.

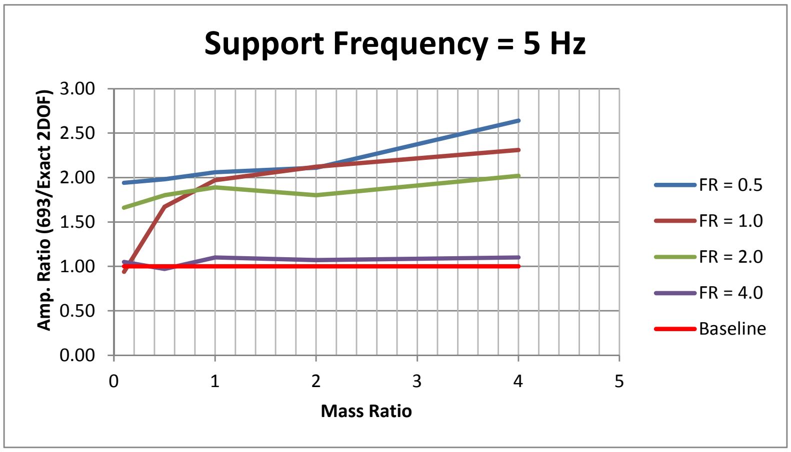

Figure 5: Normalized Amp. Ratio vs. Mass Ratio (MR)
For Support Frequency (SF) = 5 Hz

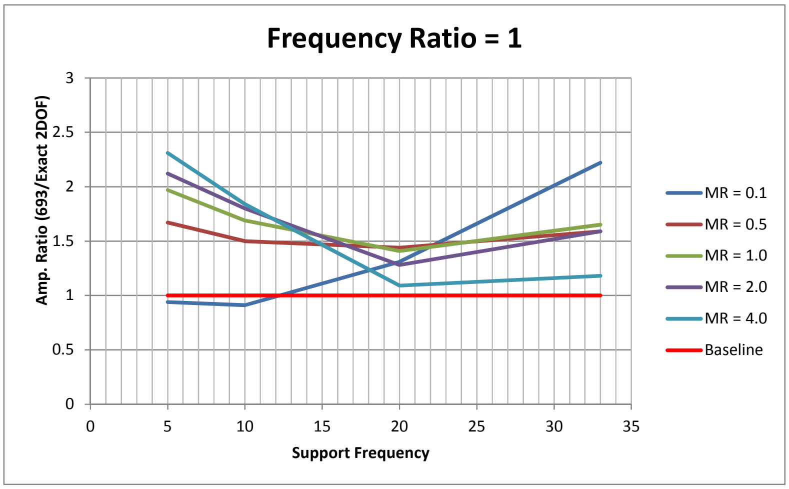

Figure 6: Normalized Amp. Ratio vs. Support Frequency (SF)
For Frequency Ratio (FR) = 1

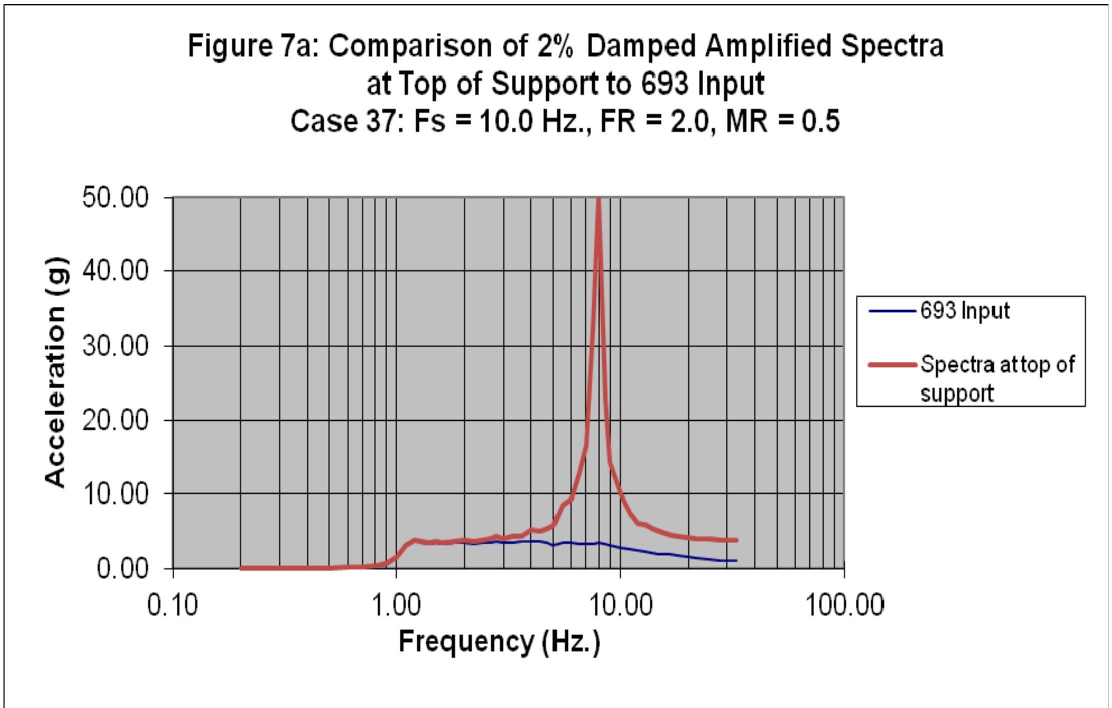
Figure 7a: Comparison of 2% Damped Amplified Spectra
at Top of Support to 693 Input
Case 37: Fs = 10.0 Hz., FR = 2.0, MR = 0.5
Acceleration (g)
50.00
40.00
30.00
20.00
10.00
0.00
0.10
1.00
10.00
100.00
Frequency (Hz.)
693 Input
Spectra at top of support

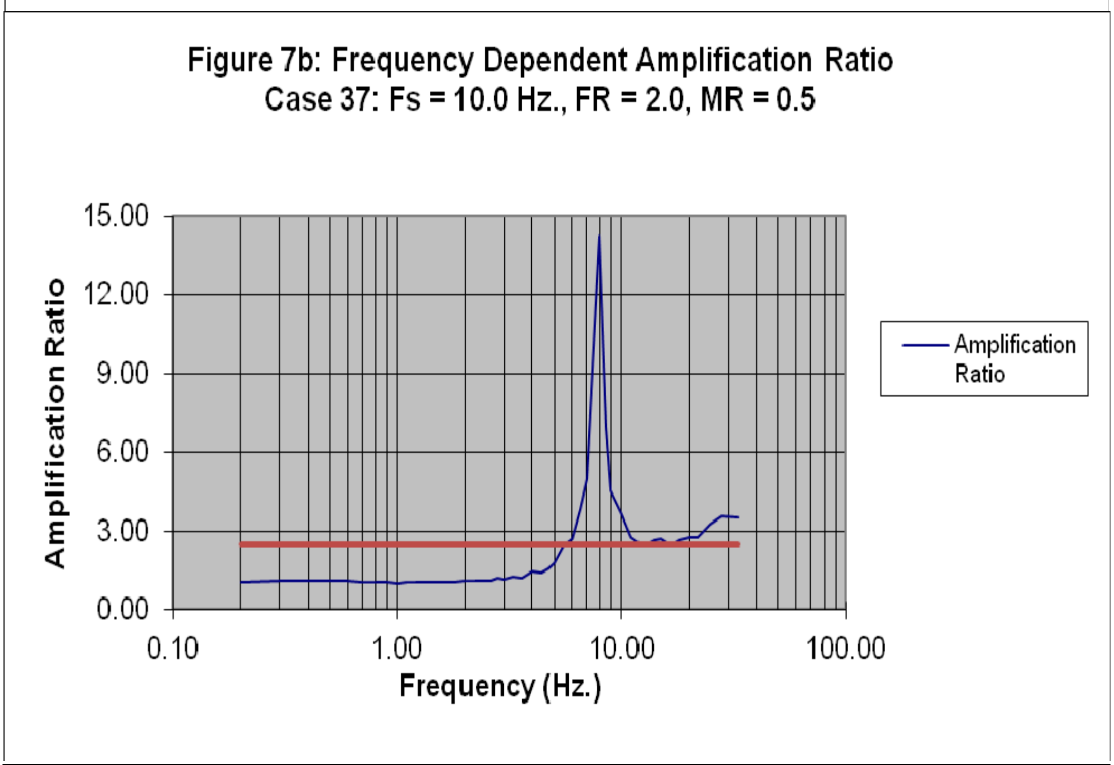
Figure 7b: Frequency Dependent Amplification Ratio
Case 37: Fs = 10.0 Hz., FR = 2.0, MR = 0.5
Amplification Ratio
15.00
12.00
9.00
6.00
3.00
0.00
0.10
1.00
10.00
100.00
Frequency (Hz.)
Amplification Ratio

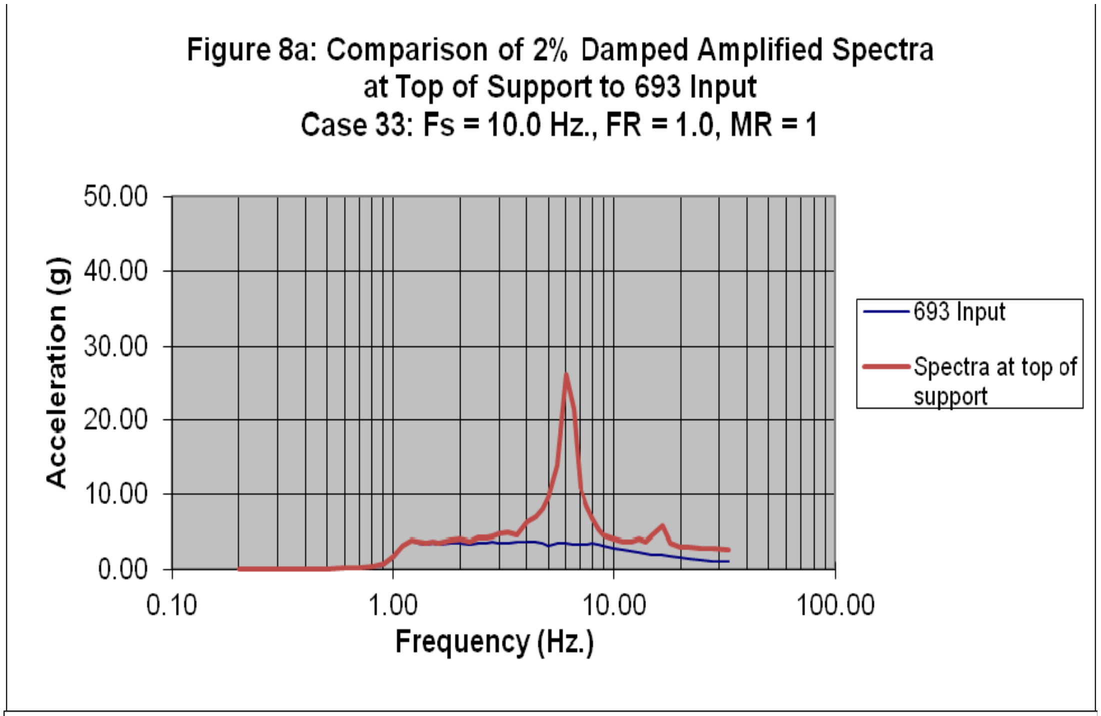
Figure 8a: Comparison of 2% Damped Amplified Spectra
at Top of Support to 693 Input
Case 33: Fs = 10.0 Hz., FR = 1.0, MR = 1
Acceleration (g)
50.00
40.00
30.00
20.00
10.00
0.00
0.10
1.00
10.00
100.00
Frequency (Hz.)
693 Input
Spectra at top of support

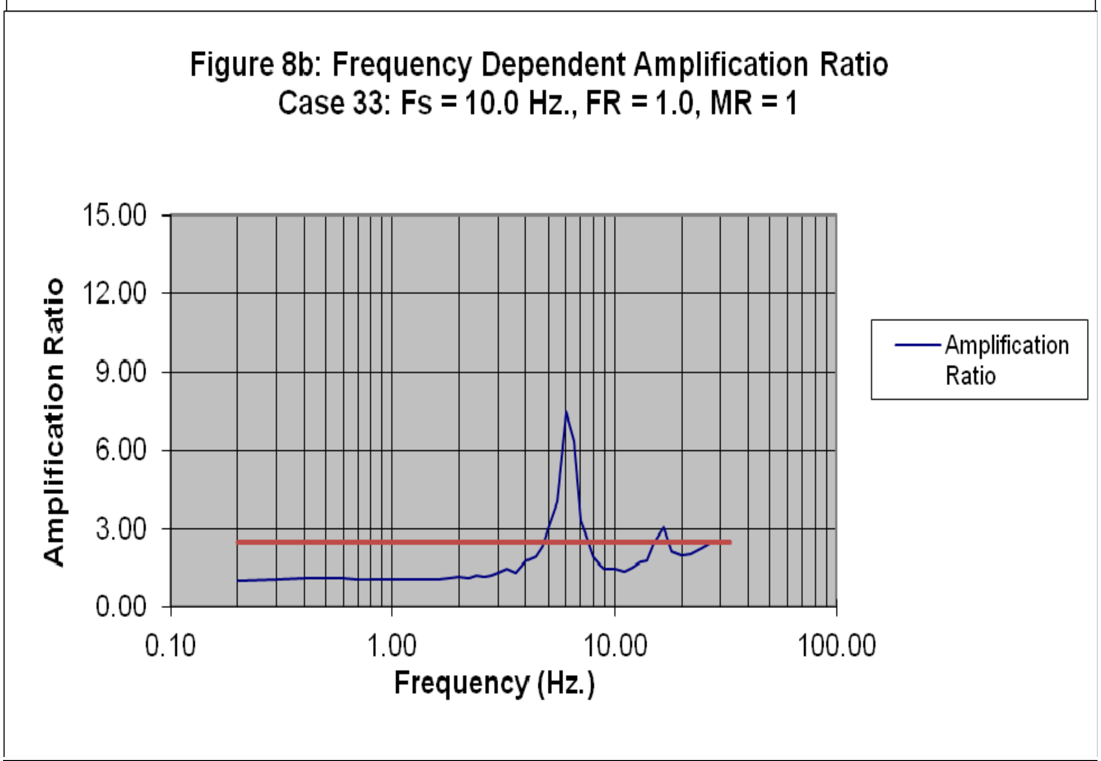
Figure 8b: Frequency Dependent Amplification Ratio
Case 33: Fs = 10.0 Hz., FR = 1.0, MR = 1
Amplification Ratio
15.00
12.00
9.00
6.00
3.00
0.00
0.10
1.00
10.00
100.00
Frequency (Hz.)
Amplification Ratio

CONCLUSIONS

The research concluded that in general the amplification factor of 2.5 as specified by the IEEE 693 Standard is a good conservative factor in the absence of support dynamic data. However, it also concluded that for the majority of the population studied (82.5% of the population), this factor is overly conservative and can be reduced to below 2.0. Various charts are provided in Reference 2.0 that can be used by the equipment vendor to refine this amplification factor if the range of mass and frequency ratios could be pre-defined.

PRACTICAL APPLICATIONS

These charts may be used to guide the equipment designer in selecting the characteristics of a support for a given equipment that is likely to respond with a more favorable amplification factor compared to the 2.5 factor prescribed by IEEE 693. In order to achieve this favorable result, limits on the range of mass and frequency ratios of the equipment to support would be required. Should the equipment supplier choose to qualify the equipment using an amplification factor less than 2.5, the support designer must in turn furnish a support having the appropriate characteristics. Because of the complexities and uncertainties in the dynamic response of equipment and their supports, the designer should use these charts only to guide the selection of design parameters. A detailed analysis of the specific equipment/ support system should be performed as part of the seismic qualification.

REFERENCES

1. IEEE Recommended Practice for Seismic Design of Substations, IEEE 693-2005, May 8, 2006.
2. "Study of Support Amplification Factors for various Frequency and Mass Ratios of Idealized Equipment Mounted on a Support Structure". EPRI, Palo Alto, CA: 2013. 3002000767.