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Effect of Frequency Content of Earthquake on the Seismic Response of Interconnected Electrical Equipment

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Abstract: To ensure the stable operation of safety-related nuclear power plant (NPP) equipment, they are tested by following the seismic qualification procedures. The in-cabinet response spectrum (ICRS) is used to test the mounted components. However, the ICRS varies significantly with the number of uncertainties that include (1) loaded and unloaded condition of the cabinets, (2) the number of connected cabinets (grouping effects), and (3) higher frequency contents in the seismic inputs. This study focuses on the ICRS generation and alteration induced due to the listed uncertainties. A prototype of an electrical cabinet was experimentally examined. Followed by the numerical modeling of the cabinet, the seismic analysis for the group of cabinets was performed using artificial ground motion compatible with the standard design spectrum and the real accelerograms of high and low frequency contents. The seismic response using finite element (FE) analysis manifests (1) natural frequency of loaded cabinets reduced due to the in-cabinet components while for the unloaded cabinets it increased significantly, (2) a consistent reduction in ICRS due to the grouping effect was recorded when excited by the lower-frequency motion, while it was amplified dramatically due to high-frequency pulses. Interconnected cabinets under the low-frequency input motions have a significant reduction of 50% in the ICRS that corresponds to the higher stiffness of the cabinets, while a 100% increase under the high frequency of ground motion was obtained. High frequency of ground motion, usually above 10 Hz, can cause the interconnected cabinets to resonate as the natural frequency of these equipment lies in this range.

Keywords: seismic qualification; in-cabinet response spectrum (ICRS); electrical cabinets; grouping effect; high frequency pulses

1. Introduction

The seismic evaluation of sensitive equipment is an essential requirement in the nuclear power plant (NPP) industry. The qualification process for this cause generally consists of three steps: (1) modal identification by testing or analysis, (2) demonstration of functional and safety condition, and (3) verification using expert opinions that comprise empirical data, which are often used to evaluate the nonstructural components. NPPs have many types of equipment that are required to be seismically qualified. Most of them are electrical cabinets that are responsible for the safe operation of the plant. Under the seismic loading, they are required to remain functional to safely shut down the NPP. The seismic analysis of electrical cabinet is more significant mainly for two reasons: (1) the number of electrical equipment are greater as compared to other equipment, and (2) electrical cabinets are highly sensitive to the seismic excitation as the natural frequency of the cabinet ranges from 10 to 30 Hz. A pioneer in the seismic assessment and testing of these components is the Electric Power Research Institute (EPRI) [1] which provides state-of-the-art seismic evaluation guidelines based on deterministic and probabilistic assessment.

The electrical cabinet is a non-structural component that carries instruments and controllers responsible for the power distribution in the plant. To ensure the stable operation of the safety-related electrical equipment, in-cabinet response spectrum (ICRS) is generated to test the mounted components. Under the seismic loading condition, the cabinets are required to be seismically qualified for both operational conditions that correspond to the safe operation of mounted components like switches and relays and also the structural safety/stability of the cabinets that corresponds to the cabinet frame, anchorage, sliding, and panel safety. Goodno et al. [2] compiled the percentage of the observed damage to the number of electrical cabinets, in which sliding of the cabinets participate 50%, anchorage 30%, overturning 11.5%, panel failure 7.7%, bracing 7.7%, and concrete pedestal 3.8%. Following the seismic analysis, Tran et al. [3] and Hur [4] studied the effect of the cabinet anchorage on the seismic demand capacity.

According to Salman et al. [5,6] electrical cabinets have distant seismic behavior. A cabinet is a light steel structure consists of several structural members. Different frames and plates members, which are joined using different connection details. Due to this variety of the members, the cabinet has global and local modes effects that correspond to the main-frame and panel excitation. For generating the maximum ICRS, [7–10] have conducted significant research on the seismic analysis of this equipment using the simplified modeling techniques, namely linear and non-linear analysis. Sarno et al. [11] used the simplified FE models to assess the dynamic behavior of single and double door cabinets that are used in hospital buildings. Cho et al. [12] studied the amplification of the ICRS in the cabinet using in-situ testing.

Among the important aspects of this equipment, the mounting of the internal components, and the grouping effects are prominent. The present literature, however, deals with the generation of maximum ICRS using an empty and single cabinet that cannot be extrapolated to the number of cabinets. Most of the available research focuses purely on the dynamic characteristics of the cabinet itself and cares little about the load inside the cabinet, [3,5,6,10,13,14] considering the seismic performance evaluation without the in-cabinet equipment.

The ICRS generated using a single and unloaded cabinet has the possible inconsistency of representing the effective ICRS that can eventually affect the overall seismic qualification of the equipment itself as well as the mounted components. According to IEEE-693 [15], the qualification of a single cabinet or a few connected cabinets, may not be extrapolated to qualify a larger number of cabinets connected in a lineup without adequate justification. This is because (a) individual cabinets in the array may have different mass loading or mass distribution, or different structural stiffness, or both, and (b) the connected cabinets may exhibit different dynamic response, such as different torsional modes compared to the smaller number originally qualified. Moreover, (c) the response of subcomponents mounted in different locations may be affected. As IEEE-693 [15] states that the grouping effect for the electrical cabinets should be considered, this grouping effect for the mechanical equipment need not to be considered as the mechanical equipment includes diesel generator, water pumps, piping system, tanks, etc. Likewise, the mass effect considered for the electrical cabinet is due to the internal (switches and relay) mass that cannot be addressed for the heavy mechanical components. The grouping effect may cause a change in the natural frequency of the cabinets that are already qualified by test. Therefore, the change of dynamic characteristics should be checked after the grouping.

In this regard, this research investigates the effect of component mass on a single cabinet comparatively to the multi-cabinet assembly. Under the same seismic loading condition, the loaded and unloaded cabinets have distant behavior, which is important for the cabinets dynamics and has not been addressed explicitly in the present literature. Grouping of the cabinets without the internal components reduce the ICRS [5,6], however, in the case of the loaded cabinets the ICRS manifesting no potential difference for a single cabinet, but a noticeable alteration for the number of cabinets.

Another aspect is the seismic behavior of the cabinets that are highly influenced by the input ground motion, to evaluate this cause a set of ground motion was selected ranging from low- to high-frequency contents, including the Gyeongju 2016 earthquake and artificial motions compatible to the standard response spectrum of RG 1.60 [16]. Generalizing and extrapolating the seismic response of a single cabinet that may be loaded with or without the internal components have different dynamic characteristics compared to the group of cabinets. This different dynamic behavior under the influence of the ground motions with the high- and low-frequency pulses is investigated in this study.

2. Analytical Model for Cabinet Assembly

2.1. Development Steps

The ICRS is generated prior to the seismic qualification of the components that are installed in the cabinets. Some of the uncertainties that can possibly affect the ICRS includes the loading of the internal components and the grouping effect of the cabinets under the seismic excitation. To the end, this study uses a systematic approach as shown in Figure 1. A three-step procedure was considered to make the grouping effect more profound. A single cabinet behavior was investigated under the seismic excitation comparatively to the number of cabinets connected considering the loading and unloading condition and dynamic characteristic of the input excitation. Step 1 includes the modal analysis of the prototype using the numerical and experimental procedures, followed by step 2 that considers the effect of the high frequency of the ground motion comparatively with the design response spectrum of RG 1.60, and lastly, step 3 addresses the grouping effect on the overall seismic performance of the cabinets.

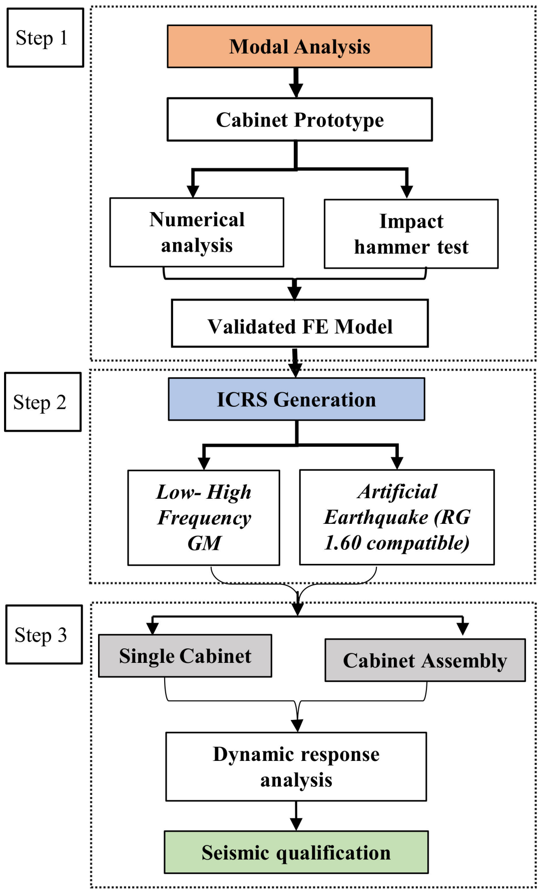

Figure 1. Schematic procedure for the seismic qualification of interconnected cabinets.

2.2. Modal Testing

An impact hammer test was carried out to determine the inherent dynamic characteristics of the cabinet under the influence of the in-cabinet components load. The prototype was excited in both front to back and side to side direction. Seven accelerometers were installed to record the response at different locations of the cabinet as shown in Figure 2. Specifications of the tested cabinet and material are given in Table 1. Based on the loading condition, three different cases of cabinets were analyzed as given in Figure 3. Figure 3a represents the case without the internal component while (b) considers the mass of the internal component at the top, where the loads were mounted at two floors and each floor carries 50 kg, and (c) for the fully loaded condition of the cabinet, a total mass of 200 kg was used at four floors. The mass was assigned using thick steel plates, each having mass of 50 kg as shown in Figure 4.

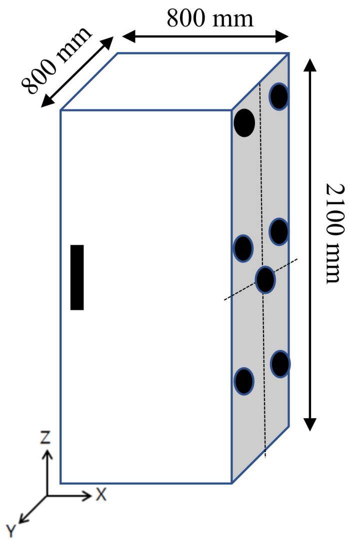

Figure 2. Installed accelerometers on the cabinet specimen.

Table 1. Cabinet Specification.

Size	2100 (H) × 800 (W) × 800 (D) mm
Weight	290 kg
Internal Dead Load (Assumed)	200 kg per cabinet
Elastic Modulus, Density (ρ), and Poisson's Ratio (ν)	200 GPa, 7850 kg/m^3, and 0.3
Bolt Size	M14 × 80

(**a**) (**b**) (**c**)

Figure 3. Cabinets prototype under different loading condition: (**a**) Empty cabinet; (**b**) Loaded at the top; (**c**) Fully loaded.

Figure 4. Assumed load for the internal components.

2.3. Numerical Modeling

The cabinet prototype was modeled in SAP2000 [17]. A cabinet member like main-frame, front and back door panels, side panels, column frame, and base subframe, etc. are connected using bolts or threaded connections. All the degrees of translation are restrained as per the experimental test setup. Following the experimental analysis, three different cases for the loading condition were analyzed: (1) empty cabinet, (2) loaded at the top floors (100 kg), and (3) fully loaded cabinet (200 kg).

The load as mentioned in Table 1 was assigned as a uniformly distributed load at each floor level. Figure 5 depicts the numerical model of the cabinet. Using the eigen analysis, the natural frequencies of the cabinet considering the maximum mass participation ratio (MMPR) for the governing modes were obtained.

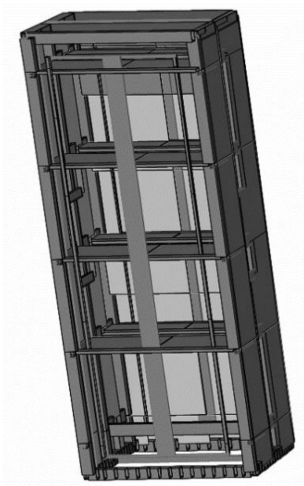

Figure 5. FEM model of Cabinet.

2.4. Validation of FE Models

Verification of the dynamic characteristics of the FEM model is required before its use for further analysis. For this cause, the numerical analysis was examined to meet the dynamic characteristics obtained using an experimental analysis. The outcomes from the experimental modal test are studied and the polynomial curve fitting method was used to extract the natural frequency of the cabinet. Figure 6 represents the comparative results from the experimental and numerical analysis making a good agreement. The figure shows the frequency response for the side to side direction as the front to back direction has no significant effect. Using the maximum modal mass participation ratio (MMPR), the 1st global mode of the cabinet having the mass participation of 77% was selected.

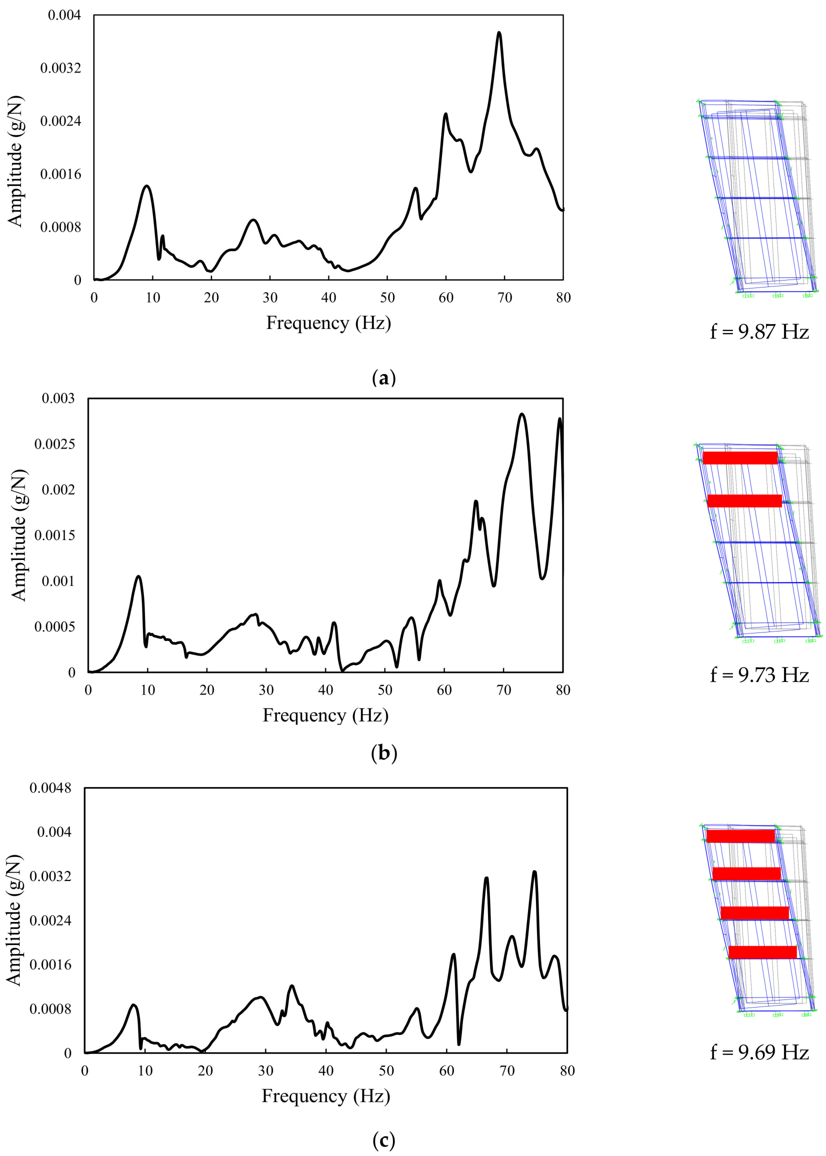

Figure 6. Natural frequencies from Experimental and Numerical modal analysis: (**a**) Empty Cabinet; (**b**) Loaded Cabinet at the top; (**c**) Fully loaded Cabinet.

3. Mathematical Model for Interconnected Cabinets

Figure 7 depicts the typical assembly of two cabinets connected with a link member. Figure 8 is the mathematical model as two single degree of freedom (SDOF) system with the masses m_a and m_b with springs k_1, k_2 and a connecting member k_3. As the cabinets are assumed to have the same dynamic characteristics in such case, $m_a = m_b$ *and* $k_1 = k_2$. The undamped equations of motion are given as under:

$$m_a\ddot{x}_1 + (k_1 + k_3)x_1 - k_3x_2 = 0 \quad (1)$$

$$m_b\ddot{x}_2 + k_2x_2 + k_3(x_2 - x_1) = 0 \quad (2)$$

$$-\frac{k_1 + k_3}{m_a}x_1 + \frac{k_3}{m_a}x_2 = \ddot{x}_1$$

$$\frac{k_3}{m_b}x_1 - \frac{k_2 + k_3}{m_b}x_2 = \ddot{x}_2$$

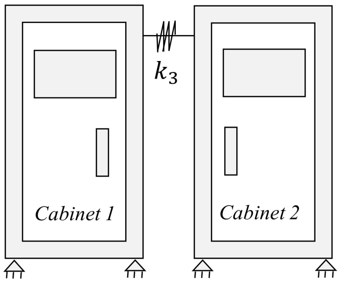

Figure 7. Typical assembly of two cabinets.

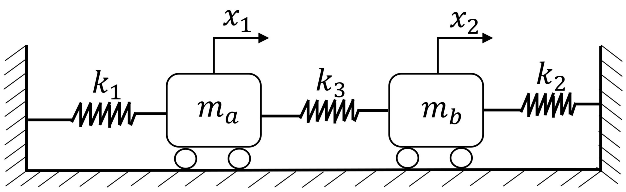

Figure 8. Mass-spring model of two interconnected cabinets.

Rearranging these quantities into a matrix as $m_a = m_b = m$, where k_3 is the effective stiffness between the two cabinets and given as $k_3 = \frac{k_1 \cdot k_2}{k_1 + k_2}$

$$\begin{bmatrix} -\frac{k_1+k_3}{m} & \frac{k_3}{m} \\ \frac{k_3}{m} & -\frac{k_2+k_3}{m} \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} = \begin{bmatrix} \ddot{x}_1 \\ \ddot{x}_2 \end{bmatrix} \tag{3}$$

When the effect of the connecting spring k_3 is neglected, i.e., $k_3 = 0$, the matrix in such case is given as:

$$\begin{bmatrix} -\frac{k_1}{m} & 0 \\ 0 & -\frac{k_2}{m} \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} = \begin{bmatrix} \ddot{x}_1 \\ \ddot{x}_2 \end{bmatrix} \tag{4}$$

The above equation becomes two independent degrees of freedoms. Meanwhile, in the case of the rigid link, i.e., $k_3 = \infty$, the system of Figure 8 becomes a one-degree system having the mass of $2m$ and the stiffness of $k_1 + k_2$. If the cabinets have the same stiffness, i.e., $k_1 = k_2 = k$, the Equation (3) becomes as:

$$\begin{bmatrix} -\beta & \alpha \\ \alpha & -\beta \end{bmatrix} x = \ddot{x} \tag{5}$$

where $\beta = \frac{k+k_3}{m}$, $\alpha = \frac{k_3}{m} =$, $x = \begin{bmatrix} x_1 \\ x_2 \end{bmatrix}$

Using the eigen value analysis the corresponding natural frequencies were calculated by

$$\begin{bmatrix} -\beta & \alpha \\ \alpha & -\beta \end{bmatrix} x = -\omega^2 x \tag{6}$$

$Ax = \lambda x$ where $\lambda = -\omega^2$

Figure 7 represents the two cabinets which are analyzed for the different parametric trials. The natural frequency of each cabinet is 10 Hz, following the effect of k_3, mass and stiffness of the cabinet the following cases were analyzed.

Case 1. Neglecting the effect of k_3 in the case of $k_3 = 0$

Case 2. Neglecting the effect of k_3 in the case of $k_3 = \infty$

Case 3. Connecting by the flexible spring, in the case of $k_3 \neq 0$

Figure 9 is obtained using Equation (3). As in Case 1, the k_3 is ineffective and the two SDOFs are oscillating independently. Case 2 also behaves as a one degree system having $2m$ and $k_e = k_1 + k_2$

while Case 3 represents the coupled condition in which k_3 is the effective stiffness. This effective stiffness k_3 may be from the integral stiffness of the cabinet and boundary condition or both. The mass and stiffness ratio for the two coupled cabinets manifests an obvious effect on the overall performance of the cabinet assembly. This effect is further addressed in the numerical modeling for the series of connected cabinets in Section 4.

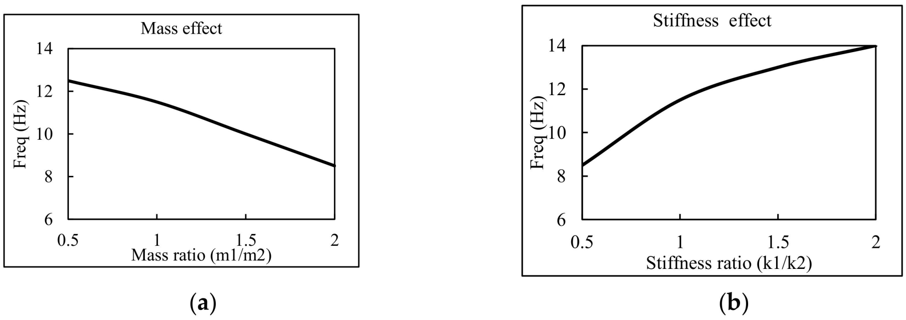

Figure 9. Effect on the natural frequencies of cabinets considering k_3; (**a**) Effect of mass ratio; (**b**) Effect of stiffness ratio.

4. Uncertainties in In-Cabinet Response Generation

4.1. Grouping Effects of the Cabinet

As investigated by [5], the seismic response is significantly reduced as the number of cabinets increased, additionally, the acceleration threshold for a single cabinet varies with the number of cabinets. However, the analyzed cabinets were empty. Cabinets in the available literature are mostly single with no consideration of in-cabinet components. In this regard, this study included the effect of the in-cabinet component on the ICRS for a standalone cabinet comparatively with the number of interconnected cabinets. An experimentally validated cabinet model was used to study the grouping effect, and in FE models, a rigid link was considered as the cabinets are connected by a bolted connection. For the parametric investigation, six cabinets were used to study the effect of the grouping effect. Figure 10 represents the six comparative cases for the cabinets.

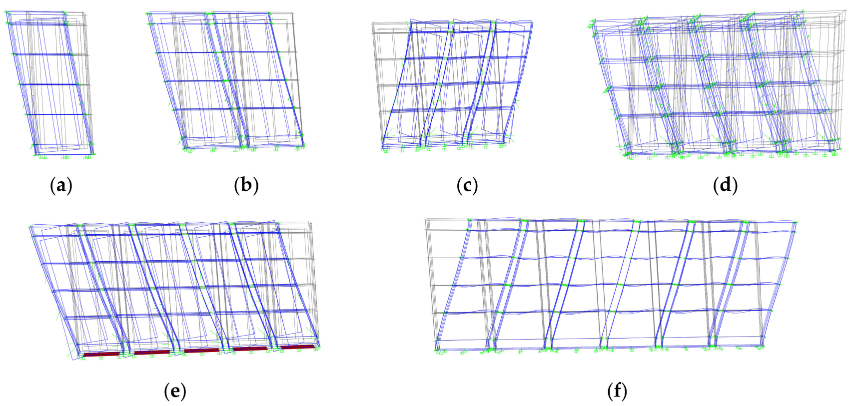

Figure 10. Numerical models for the grouping effect of the cabinets; (**a**) Single Cabinet; (**b**) Two cabinet assembly; (**c**) Three cabinet assembly; (**d**) Four cabinet assembly; (**e**) Five cabinet assembly (**f**) Six cabinet assembly.

4.2. Effect of the In-Cabinet Component Load

Available research using the analytical methods for the linear and nonlinear analysis can cause inconsistency that includes: (1) a beam stick model cannot represent the grouping effect of the cabinet, and the local behavior of the plates. (2) ICRS for an empty cabinet and a group of loaded cabinets vary significantly, which can eventually alter the seismic analysis as suggested by the (IEEE-344, 2005), and the response of a single cabinet cannot be extrapolated to the number of cabinets. Referred to the above concern a 3D FEM model was generated for single and interconnected cabinets to investigate the effect of the internal component. The distribution of the components (switches and rely) mass in the cabinets has a substantial effect on the dynamic characteristic of the cabinets. Lin et al. [18] used the horizontal and vertical load distribution of the in-cabinet equipment in a single cabinet to investigate the ICRS, however in this study, the horizontal distribution with the grouping effect was considered.

4.3. Influence on ICRS due to Input Protocol

High-frequency pulses are potentially sensitive to NPP safety-related components. The sensitivity analysis of these safety components was conducted by [19] using shake table testing and it was found that these components are potentially high-frequency sensitive. The components include relay and other control devices, which are subject to change of state, contact chatter, signal change/drift, and other intermittent electrical functionality failure modes. Gupta et al. [20] used the high-frequency content of the Gyeongju earthquake for a single cabinet that results in the ICRS amplification.

However, in this study, the grouping effect of the cabinet was investigated with the assumption that the grouping effect of the cabinet may be highly influenced by the high frequency of the ground motions. As the phenomenon of incoherence is important for high-frequency ground motions and high-frequency response of structures (primarily greater than 10 Hz) stated by [21]. In this regard, a set of ground motion was selected based on the low to the high-frequency range. The data set was scaled to the (RG 1.60) spectrum. Additionally, a set of artificial ground motions compatible to (RG 1.60) was generated to investigate a comparative seismic response of the interconnected cabinets. Figure 11 represents the seismic inputs used in the analysis, the bold line represents the mean frequency of the input motions (a) represents the low frequency of earthquakes (below 10 Hz) (b) represents the higher frequency ground motion (above 10 Hz) (c) is the scaled acceleration spectra of 12 artificial and recorded earthquakes with (RG 1.60). Table 2 lists the characteristics of the selected ground motions which were scaled to 1 g of ground motion.

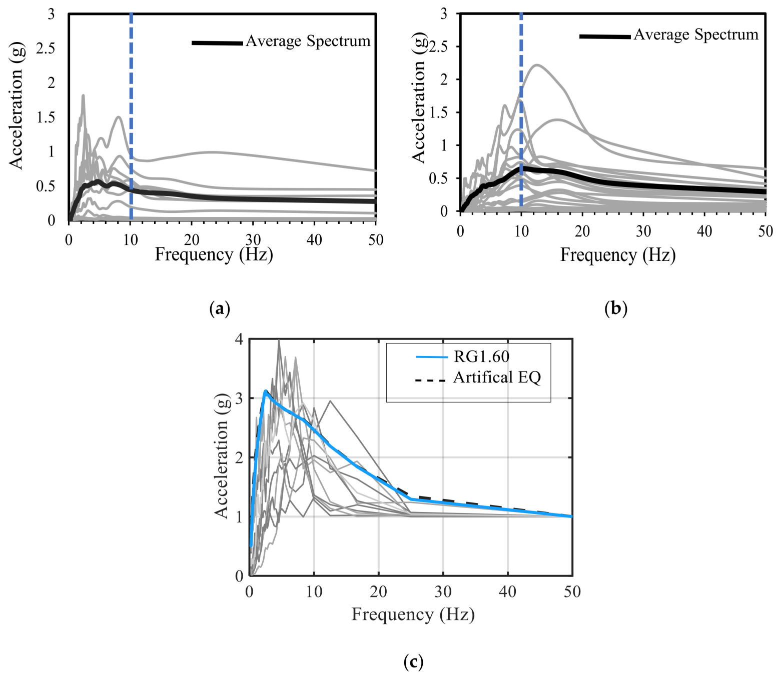

Figure 11. Seismic inputs for the ICRS generation: (**a**) Low frequency earthquakes (below 10 Hz); (**b**) High frequency earthquakes (above 10 Hz); (**c**) Scaled ground motions with artificial ground motions compatible with RG 1.60.

Table 2. Characteristics of selected ground motion (PEER NGA).

No	Earthquake Name	Year	Magnitude	R_{RUP}(km)	$V_{s,30}$ (m/sec)
1	Victoria_Mexico	1980	6.33	14.37	471.53
2	Nahanni_Canada	1985	6.76	9.6	605.04
3	Cape Mendocino	1992	7.01	6.96	567.78
4	Landers	1992	7.28	69.21	382.93
5	Northridge-01	1994	6.69	68.93	501.75
6	Northridge-01	1994	6.69	47.98	544.68
7	Hector Mine	1999	7.13	43.05	382.93
8	El Mayor-Cucapah_Mexico	2010	7.2	45.47	523.99
9	Goungju_South Korea	2016	5.7	14	550.60

* R_{RUP} (km), $V_{s,30}$ (m/sec) are radius of rapture and shear wave velocity.

5. Result and Discussion

5.1. In-Cabinet Components and Grouping Effect of the Cabinets

The dynamic characteristic of the interconnected cabinets considering the internal components was studied. The internal component can considerably change the natural frequency of the cabinets and it is important to consider as in the present literature mostly the cabinets are analyzed without this effect [3,5–8,12,20]. Table 3 presents the dynamic properties of the cabinet under the internal component load.

Table 3. Natural frequencies of the cabinets.

Number of Cabinets		1	2	3	4	5	6
Frequency (Hz)	Empty Cabinet	9.87	13.60	15.46	15.87	15.90	16.02
	Loaded Cabinet	9.69	11.95	12.55	12.83	12.96	12.98

Table 3 enlists the reduction in the natural frequency corresponding to the mass of the internal component, while an increase due to the additional stiffness provided by the number of cabinets. This alteration in the natural frequency was further investigated due to the mass and stiffness ratio of the cabinets. Two cabinets were considered, and a relative change in the mass and stiffness ratio was investigated that eventually affect the seismic response. For mass ratio, the mass of the internal component was adjusted while stiffness was kept constant, and for stiffness ratio, the modulus of elasticity was changed, respectively. For mass ratio $\frac{m_1}{m_2} = (0.25\ldots..2)\&\frac{k_1}{k_2} = 1$ and stiffness ratio $\frac{k_1}{k_2} = (0.25\ldots..2)$ while $\frac{m_1}{m_2} = 1$.

Figure 12 represents the effect due to the change in the dynamic characteristics. A consistent change in the natural frequency occurs due to the mass and stiffness ratio, as in case of mass ratio the increment results in lowering the natural frequency while in case of stiffness ratio the natural frequency is shifted higher, both these phenomena can be explained with the principle behavior of a structure, $f = \frac{1}{2\pi}\sqrt{\frac{k}{m}}$. Figure 12 also represents the effect, when the two different cabinets are connected, and the relative stiffness and mass may vary affecting the frequency of the cabinet units. For the loaded cabinets, the modal characteristics due to the additional mass and stiffness are provided in Table 4. It is noteworthy that the increment in the stiffness of the cabinets is significant between one and two cabinets, but the increment in the mass of the cabinet system is important in each case of the cabinets.

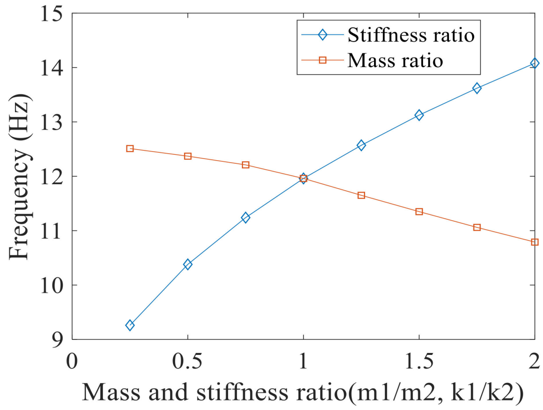

Figure 12. Variation in natural frequencies of two cabinets due to mass and stiffness ratio.

Table 4. Model characteristics of cabinets assemblies.

	Stiffness Ratio		Mass Ratio		Modal Characteristic	
No. of Cabinets	**Modal Stiffness (kN/m)**	**Difference**	**Modal Mass (kg) (Active/Total)**	**Difference**	**Modal Frequency (Hz)**	**Modal Mass Participation %**
1	4403	—	365/480	—	(9.8)	77.11
2	7262	40%	672/960	50%	(11.95)	77.18
3	7851	8%	1008/1440	34%	(12.55)	77.80
4	8294	5.3%	1344/1920	25%	(12.87)	77.84
5	8561	4%	1680/2400	18%	(12.96)	77.88
6	8739	2%	2016/2880	16.65%	(12.98)	77.88

The dynamic characteristic of a single cabinet was used as a benchmark to evaluate the effect of the cabinet assemblies. The modal mass and stiffness were obtained using eigen analysis with the corresponding dominant frequency mode having the participation of 77%. As the mass and stiffness contribution is relative in the case of two cabinets a shift in the frequency was observed that manifest an increase in the stiffness of the cabinets. In contrast, for three, four, five, and six cabinets assembly, the mass to stiffness ratio is distant, which presents a small effect on the frequency. It was found that the further addition of the cabinets will not change the stiffness of the assembly although the effect of the component load can affect the dynamic response. It is understood from Table 4 that the increment induced in the cabinet system due to the mass and stiffness vary significantly and this scenario changes the dynamic characteristic of the cabinets. Furthermore, it was found that a 10% increment in the stiffness can cause a considerable shift in the frequency of the cabinets.

5.2. Seismic Response of the Inter-Connected Cabinet Assemblies

The current practice in the NPP for the seismic qualification of in-cabinet equipment in many cases uses the constant amplification factor which only accounts for the low frequency ground motions, however for the higher frequency of ground motion this idealization may underestimate the ICRS. The design response spectrum (RG 1.60) for this cause is used to evaluate the seismic response of the cabinet considering the grouping effect of the cabinets. Figure 13 represents the response of a single cabinet comparative to two and three interconnected cabinets. The response shown is the average response for the 12 artificial earthquakes compatible with (RG 1.60). The ICRS pattern using (RG 1.60) depicts no potential difference due to the grouping effect of the cabinets. However, based on the modal analysis of the cabinet, it is understood that the addition of the cabinet will improve the dynamic integrity of the cabinets. It was found that (RG1.60) having the peak spectral acceleration in the range of 2–10 Hz, the average response of the cabinets due this reason is not affected as the cabinet frequency may be distant from the peak frequency of the input. Subsequent research has identified that in some cases the ICRS generated by using the constant factors can be very conservative even if the smallest factors are used [20].

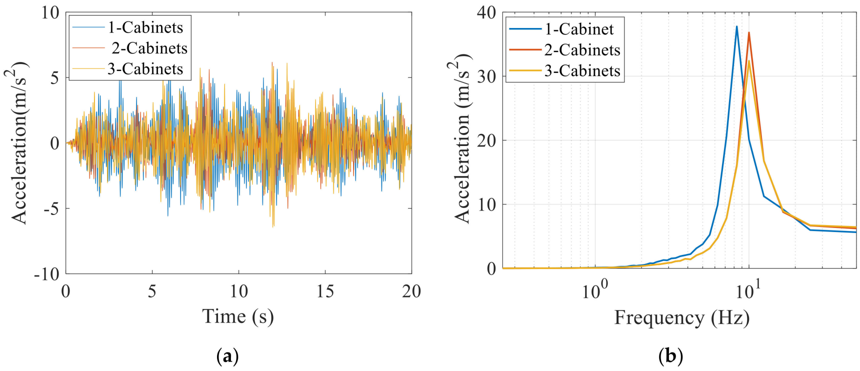

Figure 13. Cabinet response under the Artificial ground motion compatible with RG 1.60; (**a**) Acceleration response; (**b**) Maximum In-Cabinet response.

ICRS under the Low and High Frequency Pluses

The grouping effect of the cabinets under the high frequency of ground motion is presented in Figures 14 and 15. The response shows the peak acceleration response under two earthquakes namely Victoria_ Mexico and Goungju_South Korea. The cabinet cases show a dramatic alteration in the seismic response due to the peak frequency content of the input. As from the modal analysis, it is understood that a single cabinet has considerably low stiffness compared to the two interconnected cabinets, however, the effect of the ground motion parameters can be more effective for the group of cabinets. The very possible reason for this is the resonating frequency of the cabinet corresponds to the frequency of ground motion. Victoria_ Mexico has a peak frequency of 12 Hz, which amplifies the ICRS by 25%. Figure 14b represents the response for the different cabinet's assemblies with amplification in the response.

In the case of Goungju Earthquake, the peak frequency of the motion is 12.5 Hz followed by many predominate frequencies range with significantly larger spectral values than (RG 1.60). The ICRS generated for the three cases of the cabinet is shown in Figure 15. In the case of one cabinet, the S_a is 100 m/sec2 while for two and three cabinets it is almost 200 m/sec2 that accounts for 100 % amplification in the response. Increasing the number of cabinets further will result in the amplification of the ICRS. This manifests that the dynamics characteristics of the ground motion have a significant effect on the ICRS generation than the cabinets itself. Furthermore, the interconnected cabinets result in a higher natural frequency that might be more vulnerable to the high-frequency pulses. Using the constant amplification factor in such a case would be inappropriate.

In the case of low-frequency earthquakes, the grouping effect of the cabinet is highly effective in lowering the seismic response. Figures 16 and 17 represent the seismic response of cabinets under the low frequency of the earthquakes. This reduction is due to the dynamic modification induced due to the number of cabinets that eventually increase the stiffness of the interconnected cabinets. Another possible reason is the difference in the peak frequency of the input and natural frequency of the multi-cabinets that avoid the cabinets to resonate. It was found that the lower frequency of the earthquake causes a more consistent decrement in the ICRS. For instance, the peak frequency of the El Mayor-Cucapah_ Mexico is less than the Nahani Canada results in lowering the ICRS by 30% response. Figure 18 represents the peak acceleration response of the cabinets under the five selected low-frequency earthquakes. The response shows a constant de-amplification due to the grouping effect and lower frequency of the ground motion.

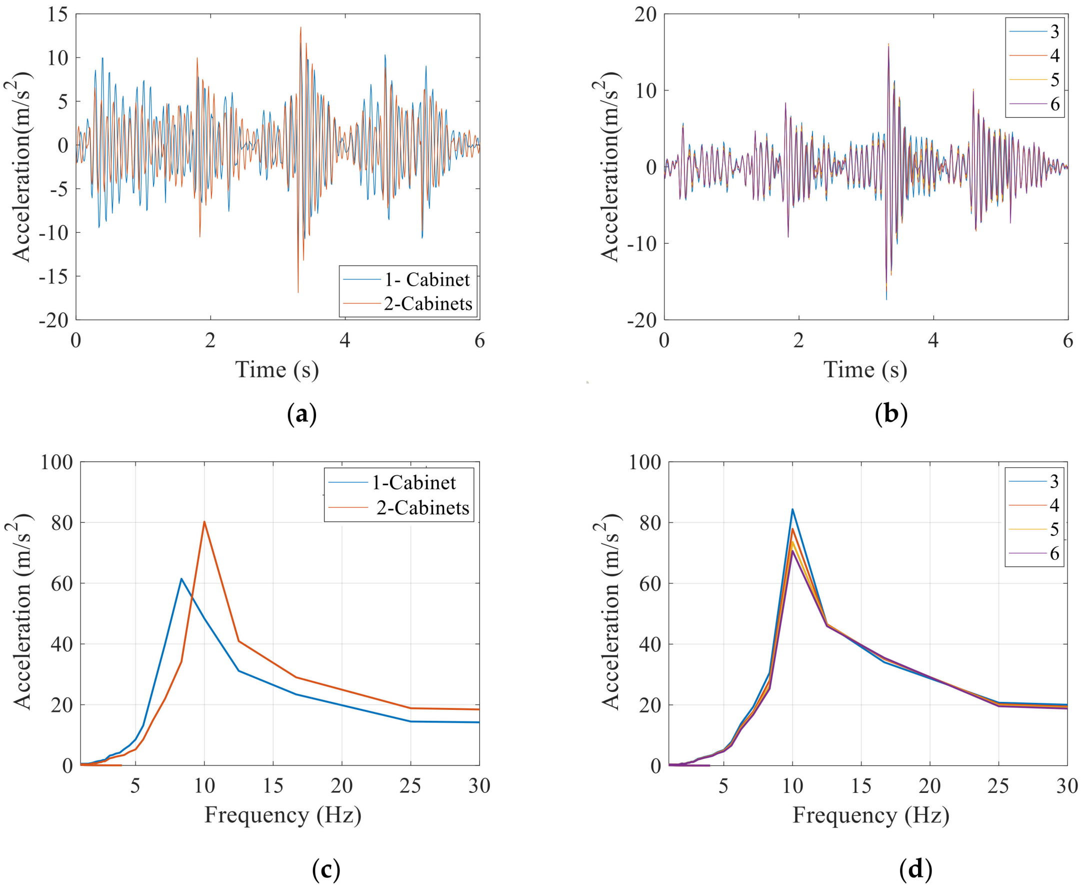

Figure 14. Seismic response of cabinets assemblies under Victoria_ Mexico: (**a**) Acceleration response for one and two cabinets; (**b**) Multi-cabinets acceleration response; (**c**) Maximum ICRS for one and two cabinets; (**d**) Maximum ICRS for multi-cabinets.

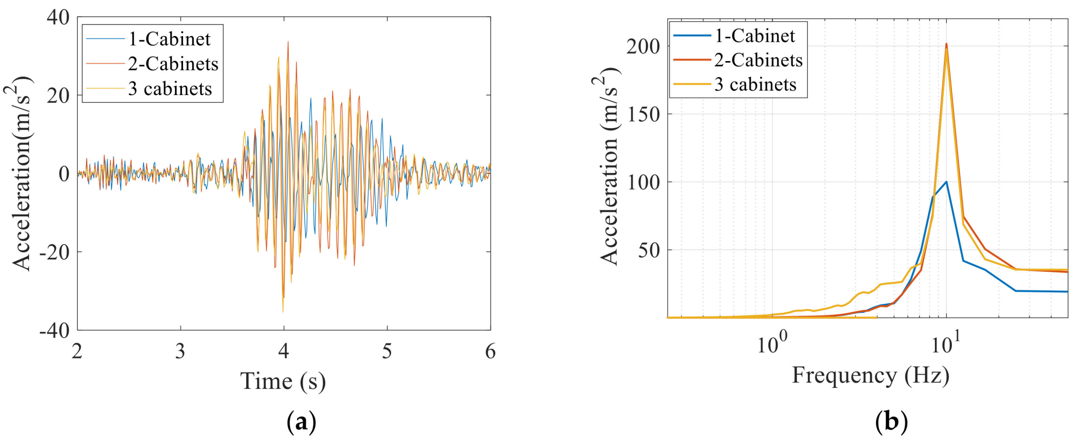

Figure 15. Seismic response of cabinets under the Goungju Earthquake: (**a**) Acceleration response; (**b**) Maximum In-cabinet response spectra.

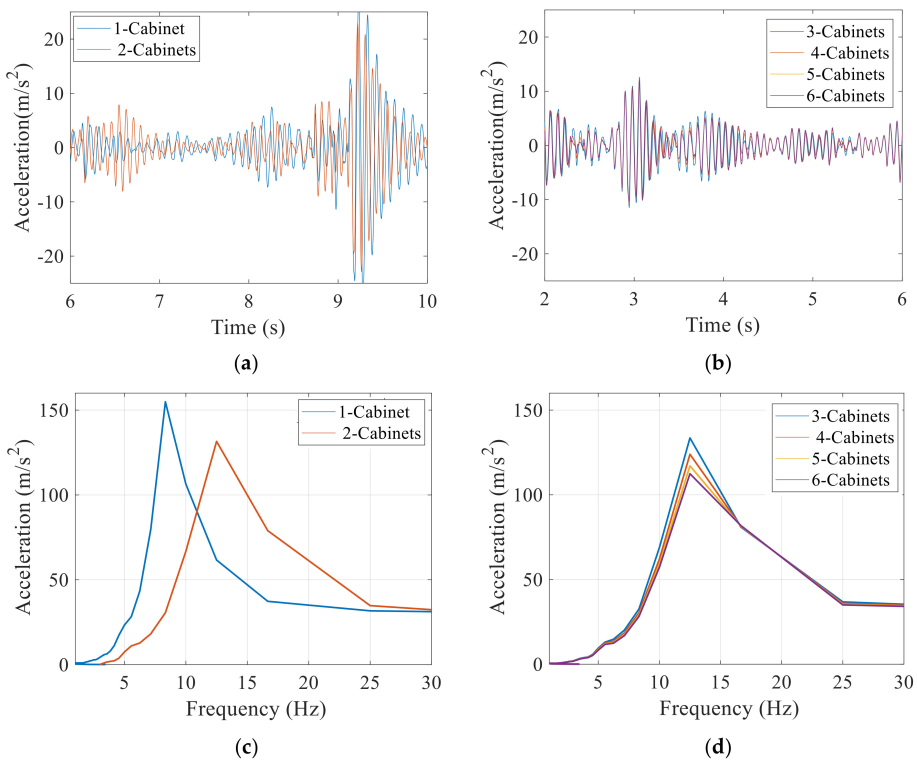

Figure 16. Seismic response of cabinets under Mexico Nahani Canada earthquake: (**a**) Acceleration response for one and two cabinets; (**b**) Acceleration response for multi-cabinets; (**c**) Maximum ICRS for one and two cabinets; (**d**) ICRS for multi-cabinets.

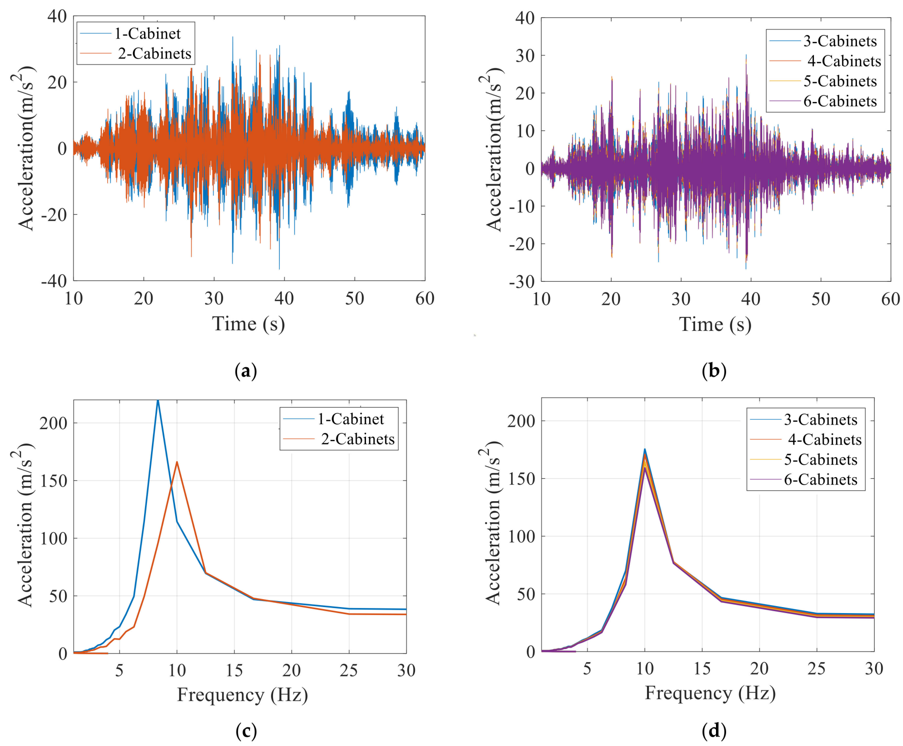

Figure 17. Acceleration response under El Mayor-Cucapah_ Mexico Earthquake: (**a**) Acceleration response for one and two cabinets (**b**) response from multi-cabinet (**c**) Maximum ICRS for one and two cabinets (**d**) Maximum ICRS for multi-cabinets.

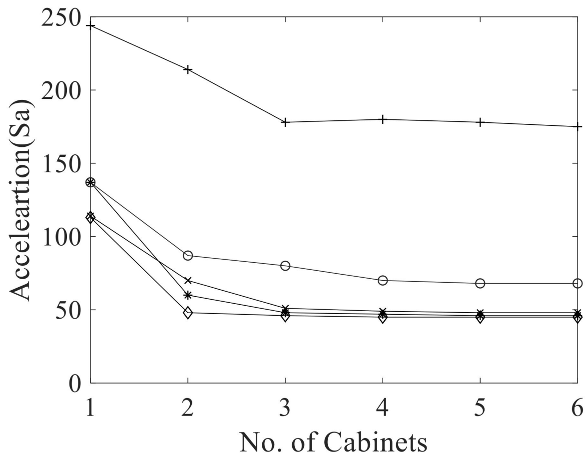

Figure 18. Acceleration response under Low frequency earthquake (below 10 Hz).

The response reduction capacity for the empty cabinets is different from the loaded cabinets. As investigated by the same author in the previous work shown in Figure 19 the response reduction capacity for the two cabinets is up to 50% and this extends to 70 % for three connected cabinets. The reason for this high reduction was the floor response used in the analysis that has the peak frequency of the 4.6 Hz while the cabinet having a high frequency of 14.41 Hz. Another possible reason was the effective stiffness of the cabinets that go on increasing when the cabinets are empty. This alteration in the seismic response due to the loading of the in-cabinet components can be considered as an important aspect of the electrical cabinets. The load arrangement considered in numerical and experimental analysis was inspired by the horizontal distribution and it may vary with the vertical distribution of the internal components.

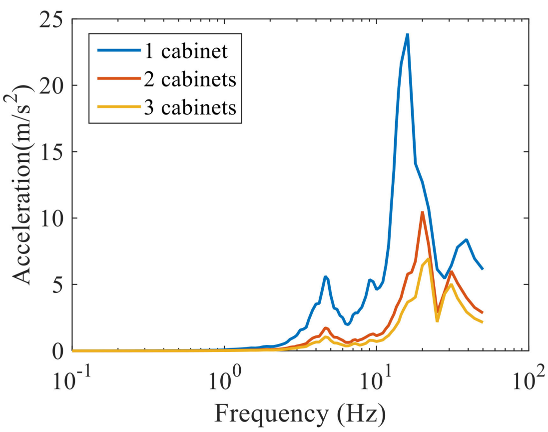

Figure 19. In-Cabinet response generated using empty cabinets (Salman et al., 2019).

The results presented in this research focuses on the high frequency of the ground motion, it should be noted that the high frequency of the ground motion is not the only parameter that amplifies the seismic response but also depends upon the strong motion duration (SMD), predominant frequencies and higher frequencies with high spectral acceleration. For instance, the two recorded earthquakes in South Korea are Pohang and Gyeongju earthquakes. Pohang has a higher frequency of 18 Hz with a strong motion duration of 1.5 sec has a lower impact compared to the 12 Hz of Gyeongju with the (SMD) of 10.60 s. As stated by [22] that ground motions having greater strong motion duration can produce more load reversal as compared to the low duration. Again, the strong motion duration is also not the governing parameter as it depends upon the input excitation intensity range. Investigation by [23] states that there exists a positive correlation between the (SMD) and structural damage however in some peak ground acceleration (PGA) and frequency ranges, input motion with shorter duration may cause more substantial damage than the long duration. Determining the high-frequency content is significant for the type of input ground motion in which the peak and predominate frequencies are significantly different that are generally known as broadband type motions. Further study in this domain is required to address the effect of the input ground motion parameters on the NPP and its components more explicitly.

6. Effect on the Seismic Qualification

One of the important focus of this study is to address the ICRS generation to qualify the performance of the inside components. It was found that in many cases constant amplification factors in the ICRS are used for the design of NPP and its components that are consistent in the case of low-frequency earthquake but in case of high-frequency earthquake it may be not effective. As cabinets are high-frequency equipment and the grouping effect considerably increases the natural frequency, this results in higher ICRS. For instance, Figure 20 represents the (RG 1.60) spectrum with the natural frequency of a typical single cabinet, the ICRS in this case shows no potential difference compared to the number of cabinets as shown in Figure 13. A representative ICRS in this case may underestimate the effect of the high frequency of ground motion on the number of cabinets. An increase in the number of cabinets results in a high natural frequency that may be affected by the high pulses of the ground motion as shown in Figures 14 and 15. This analysis is based on a prototype of a cabinet having natural frequency of 10 Hz while the new available cabinets in the NPP generally have the natural frequency of 15–20 Hz. Considering the grouping effect of these cabinets may be more vulnerable to the future expected earthquake that might bear high-frequency contents. For an accurate ICRS generation, considering the loading of the in-cabinet components, grouping effects, and ground motion parameters is recommended.

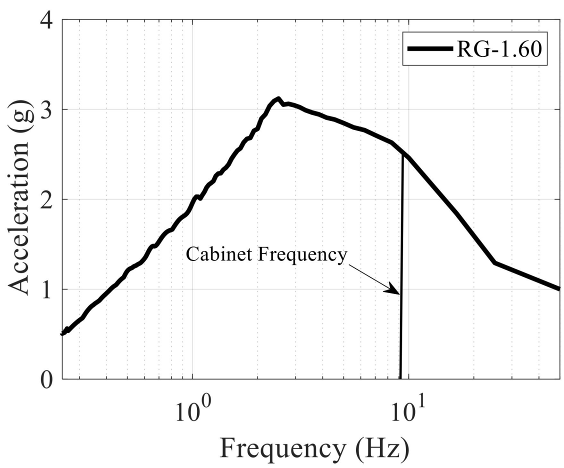

Figure 20. RG 1.60 and corresponding cabinet's frequency.

7. Conclusions

Seismic response of the electrical cabinets was investigated using linear time history analysis considering the in-cabinet components loading, grouping effect of the cabinets, and effect of the ground motion parameters that mainly include the high-frequency pulses. The in-cabinet components and the grouping effect of the cabinets were found to be an important aspect affecting the ICRS. However, the present literature mostly considers empty and standalone cabinets that can possibly lead to underestimation of the seismic qualification of the cabinet itself and the in-cabinet mounted components as well. Some of the key findings from this study are listed below:

- Grouping effect of the cabinets considering the internal equipment reduces the seismic response on one hand, but it can considerably amplify the response due to inherent ground motion parameters.
- Grouping effect under the low-frequency input motion has a constant de-amplification almost (50%) in the in-cabinet response that corresponds to the higher stiffness provided by the number of cabinets as shown in Figure 18. Meanwhile, under the high frequency of ground motion, the response is dramatically amplified. High frequency of ground motion usually above 10 Hz can cause the interconnected cabinets to resonate as the natural frequency of this equipment lies in this range.
- High frequency of the multi-cabinets manifests the higher stiffness, however the energy of the strong motion can amplify the response of the cabinets as compared to a single cabinet.
- Using the standard design spectra (RG 1.60) the comparative response of the cabinets represents no potential difference on the ICRS while it is significantly amplified by the seismic inputs having high frequency pulses.
- Cabinets connected in series may have high integral stiffness, but due to their sensitivity to the input motion parameters, they can be more vulnerable than a stand-alone cabinet. This analysis is based on a cabinet prototype that has less stiffness than the available NPP cabinets, in this regards the grouping effect for the cabinets having higher stiffness can be more effective.
- Future extension in this domain can be considered by investigating the nonlinear dynamic interaction of the cabinets having different dynamic characteristics as in this study the cabinet was considered to have the same dynamic properties.

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