ABSTRACT

CHATTERJEE, PAYEL. Qualification of Electrical Substation Equipment subjected to Earthquake Excitation. (Under the direction of Dr. Abhinav Gupta).

Electrical substations have many pieces of critical equipment such as feeder units, transformers, cabinets, relays, and disconnecting switches that need to remain functional during and after an earthquake. The reliability of such a substation in case of an earthquake depends on the seismic response of the individual equipment as well as the effect of interaction between the different components. The current practice for the qualification of electrical substation equipment according to the guidelines of IEEE-693 (2005) is based on voltage classification. The research is an attempt to understand the results from detailed experimental and analytical studies for a gas insulated substation (GIS). The research examines the implementation of IEEE-693 guidelines for a particular case of an actual 115kV gas insulated substation equipment. Reconciliation of the experimental and analytical results is used to identify key aspects in the seismic qualification of such equipment. Wherever possible, limitations observed in the implementation of the IEEE-693 guidelines are discussed. In the absence of appropriate qualification criterion, a methodology is proposed for qualification of GIS unit by finite element analysis. As an illustration, it is shown that the results from typical shake table tests conducted in accordance with IEEE-693 guidelines are not necessarily representative of the behavior of a unit properly installed in its end-use configuration. Consequently, the proposed approach is based on the hybrid utilization of the experimental data from shake table tests of a higher rating unit as well as the analytical results obtained from a detailed finite element analyses.

Qualification of Electrical Substation Equipment subjected to Earthquake Excitation

by
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DEDICATION

To *My Mother*

BIOGRAPHY

Payel Chatterjee was born and brought up in the city of Kolkata in India. She joined the undergraduate program in Civil Engineering at Bengal Engineering and Science University, Shibpur, West Bengal, India in 2005 and received the Bachelors of Engineering (with honors) degree in February 2010. She has been awarded the merit scholarship twice during her undergraduate studies. Upon completion of her undergraduate studies, she joined Indian Oil Corporation Limited, a public sector unit in India, as an Engineering Officer. She worked there till June 2011 and joined North Carolina State University in August 2011 to pursue her Master of Science in Civil Engineering.

Payel is a member of two honor societies, Phi Kappa Phi and Tau Beta Pi at NC State University. Apart from doing her research work, she is also working as a Teaching Assistant for both undergraduate and graduate courses in Structural Engineering and Mechanics in NC State University.

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PART I: INTRODUCTION

1. General

Electrical substations can be air-insulated (AIS) or gas-insulated (GIS) depending on the insulating medium recommended by the manufacturers. A typical substation has many critical pieces of equipment such as feeder units, transformers, cabinets, relays, and disconnecting switches that need to remain functional during and after an earthquake. Figs. 1 and 2 show a typical air-insulated substation and a gas-insulated substation, respectively, to understand the structural difference between the two. In case of a Gas Insulated Switchgear (GIS) substation, the feeder units are mounted inside the substation building and connected to the bushings outside through bus ducts, whereas in an air insulated substation, the entire equipment and bushings are exposed outside.

The reliability of a substation in case of an earthquake depends on the seismic response of the individual component as well as the effect of interaction between the different components. Unlike an air insulated substation, the equipment is mounted inside a building for a gas insulated substation. Hence, it is also important to study the interaction between the building and equipment to understand the operability of such a substation during an earthquake. IEEE-693 (2005) is a comprehensive document that prescribes guidelines for the seismic qualification of substation equipment, substation buildings, structures, and supports. The qualification requirements are characterized by three qualification levels: high (for peak accelerations up to 1.0g), moderate (peak ground accelerations up to 0.5g) and low (peak ground accelerations up to 0.1g). The equipment can be qualified by tests or by a finite element analysis. The different analysis methods involved in equipment qualification include seismic coefficient analysis and finite element analysis using response spectrum or time history. Depending on the voltage requirement specified in IEEE 693 (2005), a part or the complete equipment may be required to be qualified by a shake table test.

2. Literature Review

Many different studies (Stafford, 1975; Llambias et al., 1989; Djordjevic, 1992; Djordjevic and O'Sullivan, 1990; Lee and Abou-Jaoude, 1992; Katona et al., 1995; Ersoy et. al, 2004; Whittaker et. al, 2007, Paolacci et. al., 2009) have focused on understanding the dynamic characteristics of electrical cabinets, disconnect switches, and transformer bushing systems. Simplified methods have been proposed by Djordjevic (1992) and Djordjevic and O'Sullivan (1990) for the evaluation of incabinet response spectra for seismic qualification of different safety related equipment in nuclear power plants based on the maximum amplification inside the cabinet. However, these methods have been found to be excessively conservative (Lee et al., 1990, 1991; Llambias et al., 1989; Gupta et al., 1999 and Gupta and Yang, 2002) and are not directly applicable to the substation equipment.

Most of the literature available on the dynamic behavior of electrical substation equipment describe the seismic interaction between the interconnected units and flexible conductors, mainly for air insulated substations (Filiatrault et al., 2000; Ghalibafian et al., 2005). In recent years, an increased number of GIS units have been used to replace their air-insulated counterparts, due to both space restrictions and cost effectiveness with respect to long term maintenance. Therefore, it is critical to understand the dynamic behavior and characteristics of these GIS units. Existing literature contains very little information on the earthquake behavior of feeder units and support structures for the GIS units. Bargigia et al.

(1993) compare and contrast the various approaches that can be used in the seismic qualification of standardized GIS units. Their work emphasizes the need for evaluating the effect of interaction between the different components (bushings, switchgears, power transformers etc.) and the influence of soil foundation interaction on the dynamic behavior. The current practice of seismically qualifying GIS equipment is centered around the guidelines prescribed in IEEE-693 (2005). According to these guidelines:

- Equipment classified as 169kV or higher is required to be qualified by a time history shake table testing;
- Equipment classified between 121kV and 169kV can be qualified by a finite element analysis;
- Equipment classified between 35kV-121 kV can be qualified by a static coefficient analysis;
- There is no seismic qualification requirement for equipment rated below 35 kV.

IEEE guidelines also recommend shake table tests of only the GIS sub-assemblies particularly in cases where the equipment is too large to fit on the shake table. Typically, a sub-assembly test conducted in accordance with IEEE-693 (2005) guidelines is considered to be sufficient for the qualification of the entire GIS unit. Such sub-assembly tests do not account for interaction between multiple units or the dynamic interaction between the GIS equipment, the associated cable conduits and the connected building support structures. Ideally, a finite element model of the sub-assembly reconciled with the test data could be used to create a larger model of the entire GIS unit and the bushing support structure. Such a reconciled model could then be used to identify the key aspects of the dynamic behavior of the GIS substation equipment.

3. Objective

A study of the existing literature illustrates the lack of a comprehensive methodology for qualification of equipment irrespective of their voltage classification. Shake table tests provide a measure of qualification based on both strength and functionality. However, a finite element analysis can only qualify equipment for strength. The objective of the present study is, therefore, to develop a comprehensive methodology for the seismic qualification of substation equipment that would incorporate both strength and functionality assessment. The key tasks of the proposed research can be outlined as follows.

- Study the data from a shake table test conducted on a subassembly of a higher voltage piece of equipment.
- Utilize the results obtained from a sine sweep test to understand the dynamic characteristics of the equipment.
- Develop a finite element model of the equipment that is validated by a reconciliation of the finite element analysis results with the sine sweep test results.
- Identify the structural and/or material parameters that might be a source of differences between the analysis and test results.
- Identify and outline the structural differences that might exist between the shake table test assembly and the actual in-situ GIS unit. Evaluate the changes in dynamic characteristics due to these structural differences.

- Update the finite element model to incorporate these changes as well as include the multiple interconnected GIS units which are otherwise not present in a shake table test. Evaluate the effect of interaction between multiple units on the dynamic characteristics of the in-situ GIS unit.
- Include the building-model to consider the building-equipment interaction. Evaluate the significance of the building-equipment interaction for the particular case.
- The detailed finite element analysis of the building-equipment model can be used to qualify the GIS equipment but only for strength requirements. Finite element analysis cannot be used to evaluate the functionality of equipment as IEEE 693 (2005) does not specify any functionality criterion. Therefore, develop a methodology to utilize the data from high level shake table test of sub-assembly in conjunction with the results from a finite element analysis for functionality assessment.

4. Organization

The thesis has been divided into three main parts. The first part gives an introduction to the problem being considered for the current study followed by a discussion of the main objectives of the research. The second part is a manuscript which will be submitted for possible publication in peer reviewed journals. A new approach has been proposed in the second part for the qualification of substation equipment of any voltage classification. The proposed approach has been developed from reconciliation of existing shake table test results for a 145 kV unit with those from a finite element model. The effect of various in-situ conditions have also been studied to incorporate those modifications when qualifying a unit of higher or lower voltage rating.

The third part presents a summary and conclusion of the work that has been discussed in detail in the second part. It also proposes tasks for future study in this area of research.

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Figure 1: Air Insulted Switchyard

Figure 2: Gas Insulated Switchyard

PART II: QUALIFICATION OF ELECTRICAL SUBSTATION EQUIPMENT SUBJECTED TO EARTHQUAKE EXCITATION

1. Introduction

Electrical substations have many critical pieces of equipment such as feeder units, transformers, cabinets, relays, and disconnecting switches that need to remain functional during and after an earthquake. In the case of a Gas Insulated Switchgear (GIS) substation, the feeder units are mounted inside the substation building and connected to the bushings outside the building through bus ducts. The reliability of such a substation in case of an earthquake depends on the seismic response of the individual equipment as well as the effect of interaction between the different components. IEEE-693 (2005) prescribes the minimum requirements for the seismic qualification of substation equipment, substation buildings, structures and supports. Depending on the voltage requirement specified in IEEE-693 (2005), a part or the complete equipment can be seismically qualified either by a shake table test or a finite element analysis. Many different studies (Stafford, 1975; Llambias et al., 1989; Djordjevic, 1992; Djordjevic and O'Sullivan, 1990; Lee and Abou-Jaoude, 1992; Katona et al., 1995; Ersoy et. al, 2004; Whittaker et. al, 2007, Paolacci et. al., 2009) have focused on understanding the dynamic characteristics of electrical cabinets, disconnect switches and transformer bushing systems. Simplified methods have been proposed by Djordjevic (1992) and Djordjevic and O'Sullivan (1990) for the evaluation of incabinet response spectra for seismic qualification of different safety related equipment in nuclear power plants based on the maximum amplification inside the cabinet. However, these methods have been found to be excessively conservative (Lee et al., 1990, 1991; Llambias et al., 1989; Gupta et al., 1999 and Gupta and Yang, 2002) and are not directly applicable to the substation equipment.

In recent years, an increased number of GIS units have been being used to replace their air-insulated counterparts, due to both space restrictions and cost effectiveness with respect to long term maintenance. Therefore, it is critical to understand the dynamic characteristics of these GIS units. Existing literature contains very little information on the earthquake behavior of feeder units and support structures for the GIS units. Bargigia et al. (1993) compares and contrasts the various approaches that can be used in the seismic qualification of standardized GIS. It emphasizes the need for evaluating the effect of interaction between the different components (bushings, switchgears, power transformers etc.) and the influence of soil foundation interaction on the dynamic behavior. The current practice of seismically qualifying the GIS equipment is centered around the guidelines prescribed in IEEE-693 (2005). According to these guidelines:

- Equipment classified as 169kV or higher is required to be qualified by a time history shake table testing;
- Equipment classified between 121kV and 169kV can be qualified by a finite element analysis;
- Equipment classified between 35kV-121 kV can be qualified by a static coefficient analysis;
- There is no seismic qualification requirement for equipment rated below 35 kV.

IEEE guidelines also recommend shake table tests of only the GIS sub-assemblies particularly in cases where the equipment is too large to fit on the shake table. Typically, a sub-assembly test conducted in accordance with IEEE-693 (2005) guidelines is considered to be sufficient for the qualification of the entire GIS unit. Such sub-assembly tests do not account for interaction between multiple units as well as dynamic interaction between the GIS equipment, the associated cable conduits and the connected building support structures. It appears that the implementation of IEEE-693 (2005) to an actual GIS unit has several limitations which render it difficult to qualify the necessary equipment without additional information.

This paper is an attempt to discuss the results from detailed experimental and analytical studies for the GIS. The paper examines the implementation of IEEE-693 guidelines for a particular case of an actual 115kV GIS. Reconciliation of the experimental and analytical results is used to identify key aspects in seismic qualification of such equipment. Wherever possible, limitations observed in the implementation of the IEEE-693 guidelines are discussed. In the absence of appropriate qualification criterion, a methodology is proposed for qualification of GIS unit by finite element analysis. It is illustrated that the results from typical shake table test conducted in accordance with IEEE-693 guidelines are not necessarily representative of true behavior of an actually mounted unit. Consequently, the proposed approach is based on the hybrid utilization of the experimental data from shake table tests of a higher rating unit as well as the analytical results obtained from a detailed finite element analyses. The comparative study is used to provide suggestions for specific structural aspects in modeling the GIS unit in a finite element analysis.

2. Description of GIS equipment

A typical 115 kV GIS equipment consists of a circuit breaker, two bus bar modules with integrated combined disconnector earthing switches, a fast acting earthing switch, an integrated current transformer, a cable end unit and a local control cabinet. These components must continue to operate during and after an earthquake. Fig. 1 shows the different components of a typical GIS unit.

The complete GIS substation under discussion consists of ten bays of individual GIS units that are interconnected to each other and to the bushing outside the building through bus ducts. The switchgear and the bus ducts are insulated using toxic SF6 (Sulfur hexafluoride) gas, therefore the name, Gas Insulated Switchgear. Fig.2 shows the layout of a typical GIS substation with the GIS unit, bus ducts, bushings and support structures.

Each of these bays consists of the circuit breaker, disconnector switches, earthing switches and bus bar modules as shown in Fig. 1. The GIS units and the bus ducts are supported by steel frame supports throughout. The sectional properties and height of these frames change as per the site and supporting requirement. Typically these frames are constructed of square tube steel columns, beams, and braces. The beam and brace connections are fully welded to the tube steel columns. The feeder units with the bus ducts and supporting structures are mounted on the concrete floor of the two story building as shown in Fig. 3.

The upper story of this 2 story building is a prefabricated metal building and the lower floor is a concrete structure. The concrete floor is approximately 4m (14 feet) above grade. For the equipment under discussion, the ten bays of the GIS equipment as shown in Fig. 2, measure about 47m long and 5m wide. Typically, a single bay of GIS equipment in a substation is an assemblage of three individual GIS equipment. The individual unit has components similar to Fig. 1. Each of these assemblages is mounted on a pair of square tubular steel supports that are welded to embedded steel channels in the concrete floor slab. Fig. 4 shows the plan of a single bay of GIS equipment.

A typical elevation for one bay with all the pipe assemblages, supports and mounting arrangements has been shown in Fig. 3. The tubular steel section, on which the pipes and other frame supports are mounted, is elevated from the floor slab about an inch and is bolted and grouted to the floor slab at two points. This has been shown schematically in Fig. 5.

Typically a single bay measures about 5m long and 5m wide. Hence, it is not practical to accommodate a complete single bay on a typical shake table. A common practice is to conduct a shake table test on only a part of the typical GIS assemblage, just like the one shown in Fig. 1.

The following section gives a brief description on the requirements for earthquake input as per the IEEE-693 (2005) qualification guidelines.

3. Earthquake input requirements of IEEE-693 (2005)

IEEE-693 (2005) gives the minimum requirements for the seismic qualification of substations, with emphasis on the electrical equipment, substation buildings, structures and their supports. Three qualification levels, high (for peak ground accelerations up to 1.0g), moderate (peak ground accelerations up to 0.5g) and low (peak ground accelerations up to 0.1g), are used to characterize qualification requirements. The equipment can be qualified by tests or through analysis. The different analysis methods include seismic coefficient analysis and finite element analysis using response spectrum or time history.

The shake table testing shall be conducted in five stages (IEEE-693, 2005): (a) Resonant frequency search, (b) Time history test, (c) Time history operational test, (d) Sine beat test, (e) Final resonant frequency search.

In the resonant frequency search, a sine sweep test is conducted over the resonant frequency range for the equipment, from a lower bound frequency of 1 Hz to an upper bound frequency of 33Hz. Two different frequency searches are recommended – one prior to and the other after the completion of the high level time history test. The purpose is to understand the structural changes and the significance of these changes due to high level seismic input. Such changes are likely to occur due to non-linear behavior and permanent deformations such as those due to yielding or tearing of structural elements in the mounting arrangement. It is recommended that the change in frequency after the high level time history test be less than 20%, else the reasons for a larger change be examined and address appropriately.

In the time history based shake table test, IEEE-693 (2005) specifies the input spectra for the high and moderate qualification levels. Fig. 6 shows the IEEE recommended high level response spectra which is anchored at 0.5g.

These spectra are characterized by the following equations when anchored to 0.5g (Fig. 6):

Spectral Accelerations, S_a (g), for Frequencies, f(Hz):

$$
\begin{aligned}
S_a &= 1.44\beta f && 0.0 \le f \le 1.1 \\
&= 1.25\beta && 1.1 \le f \le 8.0 \\
&= (13.2\beta - 5.28) / f - 0.4\beta + 0.66 && 8.0 \le f \le 33 \\
&= 0.5 && f > 33 \qquad (1)
\end{aligned}
$$

$\beta = \frac{3.21 - 0.68\ln(d)}{2.1156}$, where d is the percent damping (2,5, 10 etc) and $d \leq 20\%$.

The following equations can be used for spectra anchored at 0.25g.

Spectral Accelerations, S_a (g), for Frequencies, f(Hz):

$$
\begin{aligned}
S_a &= 0.572\beta f && 0.0 \leq f \leq 1.1 \\
&= 0.625\beta && 1.1 \leq f \leq 8.0 \\
&= (6.6\beta - 2.64) / f - 0.2\beta + 0.33 && 8.0 \leq f \leq 33 \\
&= 0.25 && f > 33 \qquad (2)
\end{aligned}
$$

$\beta = \frac{3.21 - 0.68\ln(d)}{2.1156}$, where d is the percent damping (2,5, 10 etc) and $d \leq 20\%$.

It must be noted that the specifications mentioned above are intended to be used in the qualification of the equipment that is located at the ground level. Consequently, these spectra cannot be used directly for the qualification of the GIS units being considered in this study as all the ten bays of the GIS units are located at an elevation of about 4 m (14 feet) above the ground, i.e., the concrete slab of the first story in the two story building shown in Fig. 3. In fact, this situation presents an inconsistency in the seismic design requirements. It is important to note that the 2-story concrete-steel building design is governed by the appropriate building code which is typically the International Building Code (IBC (2009)). The earthquake input at the base of the building is characterized by the corresponding spectra specified in these codes which are very different from that specified by IEEE-693 in their frequency content. Figure 7 shows the response spectrum for IBC (2009) and it is compared with respect to the required response spectrum for IEEE-693, as given in Equation (1). The IEEE-693 design spectrum is scaled appropriately to have the same anchoring PGA as the

IBC design spectrum for the comparison. Consequently, a seismic analysis of the building is needed to generate the floor motion. The resulting floor spectra should then be compared to IEEE-693 specified spectra anchored to appropriate PGA values. If the IBC (2009) spectra are used as the input for generating the floor spectra, it is very likely that the resulting floor spectra do not envelope the IEEE recommended spectra due to the narrow banded nature of the IBC (2009) spectra even if the corresponding peak floor accelerations are much larger than that recommended by IEEE-693.

4. Proposed approach to seismic qualification of GIS equipment

As discussed earlier, IEEE-693 (2005) prescribes different qualification methods depending on the voltage classification of the equipment under consideration. The flowchart in Fig. 8 describes the qualification process currently in practice.

As discussed in the flowchart, IEEE-693 (2005) has separate recommendation for different voltage rating of equipment. The high rating equipment that are qualified by shake table testing are therefore evaluated for both functionality as well as their structural strength. Functionality is established if all the instruments and the entire GIS test setup remains functional during and after the test. However, in case of equipment lower than 169 kV voltage rating, the qualification using finite element analysis can only ascertain an evaluation based on strength. The functionality of instruments cannot be evaluated due to lack of any available functionality criterion. An analysis methodology that incorporates both of these evaluations can be an important tool for seismic qualification of equipment. We propose such a hybrid approach in which the test data from a similar but higher voltage rating GIS unit can be used to develop an experimentally validated finite element model. The modified/updated model can then be qualified for strength as well as functionality. The flowchart in Fig. 9 illustrates the proposed approach.

The flowchart discusses a process where we consider a subassembly or the complete equipment of higher voltage rating. The equipment is then tested on a shake table for both sine sweep input as well as the IEEE recommended time histories. Unlike sine sweep tests, the time history tests have high acceleration inputs and the corresponding behavior of the equipment can be nonlinear. Such tests can be used to evaluate the functionality of the equipment. The sine sweep tests, on the other hand, have low acceleration inputs and the equipment behaves linearly for the magnitude of input accelerations in these tests. The acceleration responses are recorded at certain reference points where the accelerometers are mounted. The transfer functions obtained in the sine sweep test can be used to identify the dynamic characteristics of the equipment as discussed later in this paper.

The results from the sine sweep test can be used to create a finite element model that reconciles well with the test data. It must be noted that this finite element model corresponds to the higher voltage rating equipment. The input motion for high level shake table tests of this equipment is likely to be different from that of lower rating equipment based on the location. Furthermore, the lower voltage rating equipment is likely to be different from the higher rating equipment in its structural characteristics due to differences in mounting arrangement, or different cross sections of pipes and other structural members. The structural differences between the tested equipment and the actually installed equipment can be identified and the finite element model can be accordingly modified to represent the actual in situ conditions. A finite element analysis of this updated model would be expected to give the corresponding dynamic characteristics of the lower voltage rating equipment. Such a reconciliation is necessary to establish a confidence in the finite element model and also to evaluate the corresponding changes in the dynamic behavior of the lower voltage rating equipment due to changes in structural members or mounting arrangements. A time history analysis of this updated finite element model can be used to evaluate the acceleration responses at the corresponding reference points in the equipment. Functionality of electrical instruments is highly sensitive to acceleration during an earthquake (Stafford, 1975; Llambias et al., 1989; Djordjevic, 1992; Djordjevic and O'Sullivan, 1990; Lee and Abou-Jaoude, 1992; Katona et al., 1995; Ersoy et. al, 2004; Whittaker et. al, 2007, Paolacci et. al., 2009). The instruments are considered to be qualified in a shake table test if they remain functional during and after the test. Consequently, the equipment can be considered to be qualified if the maximum acceleration responses from the finite element analysis are less than the test values. However, if the accelerations are found to be higher than the test values, the finite element model can be used to evaluate structural modifications for reducing the accelerations. Subsequently, the corresponding modifications will have to be incorporated in the actually installed equipment.

We apply the proposed approach to study the qualification of a 115 kV GIS unit using the results from the shake table test of a 145 kV GIS equipment. The following sections provide a description of the test setup, finite element model and a reconciliation of the test data with the analysis results for this case study.

5. Description of test setup

Fig 10 shows the elevation of a typical 145kV unit. The equipment has electrical instruments as those in the 115 kV unit shown in Figure 1. The only difference pertains to structural members and mounting arrangements. The feeder units are supported by steel frames. The entire assemblage of feeder unit and frame supports are mounted on square tubular sections. These square tubular sections are in turn bolted at five points to the shake table as shown in Fig. 11.

The mounting arrangement of the test setup is, therefore, different from the in-situ arrangement as shown in Fig. 5. Another major difference between the test setup and the actual equipment at site is the location of the control cabinets. The local control cabinet in the test setup is bolted to the two bus bar modules at four points and is not supported directly on the floor. The approximate weight of each such cabinet is about 450kg (1000 lbs). Fig. 12 shows the control cabinet attached to the equipment. In the actual site, the control cabinets are not attached to the equipment structurally. Multiple control cabinets are located on the floor slab away from the equipment as shown schematically in Fig. 13. The GIS equipment is connected to the cabinets only through long flexible cables which do not impart any structural interactions between the two.

The GIS unit is fitted with accelerometers at six points, namely, A, B, C, D, F, and H. Point A is located at the top of the control cabinet, points B and C are at the top of each of the horizontal bus bars, points D and H are located at the top of the middle and end vertical units. The point F is at the bottommost part of the end vertical GIS unit. The data obtained from the shake table tests is discussed in detail in the following section. Fig. 14 shows the different reference points and the connectivity of the cabinet to the bus bar modules schematically.

6. Discussion of test results

The plots of transfer functions at various accelerometer locations as evaluated from sine sweep tests with input in X direction are shown in Fig 15. The corresponding plots for the transfer functions with input in Y direction are shown in Fig. 16.

As can be seen in these plots, the accelerometers at points A and H experience significant amplifications in the low frequency region, i.e. below 20 Hz or so. The amplifications at all other acceleration locations are relatively much smaller. A careful examination of these plots can be used to outline the following characteristics

- Accelerometer location A experiences significant amplification in both X and Y directions in the vicinity of 7.5 Hz. However, there is no amplification for all practical purposes at all other accelerometers in the vicinity of 7.5 Hz. Therefore, this is a local mode of the cabinet which experiences significant vibration in both X and Y directions but does not influence the response at other accelerometer locations.
- Significant amplification is observed for input in the X-direction at accelerometers H and A in the vicinity of 15 Hz. The amplification at locations B and D is about half or less than that at locations A and H and the amplification at other locations is relatively nonexistent. This pattern is representative of a global rocking mode in

which large amplifications are observed at extreme left and right corner elevations (points A and H) and the amplification at locations B and D are relatively much less.

- For an input in the Y-direction, accelerometer location H experiences significant amplification in the vicinity of 10 Hz with negligible amplifications at all other locations. Therefore, it appears to be a local mode of vertical end unit in the GIS that has accelerometer H located on top of it.
- Amplifications in the high frequency region above 20 Hz, mostly at accelerometer location A, are not necessarily critical from the perspective of an earthquake input because the spectral values are almost equal to peak ground or floor accelerations as seen in Fig. 6 which gives the IEEE-693 recommended spectra.

The subsequent sections give a brief description of the finite element model and a comparison and reconciliation of the test and analysis results.

7. Finite Element Analysis

7.1 Description of Model

Evaluation of the most accurate behavior of the GIS unit would require a detailed model particularly of the pressurized horizontal and vertical pipe units as well as the instruments and control boards inside these units. The internal instruments together with bolted flange connections at the joints of the conduits can exhibit localized nonlinearities which can be critical in evaluating accurate amplifications. However, such a detailed model is, in many cases, not only difficult to create due to lack of appropriate details but also impractical from the perspective of qualification.

A simpler approach is to capture the general overall behavior in a finite element model by using a relatively simple model. The localized complexities can then be introduced in the model for improved reconciliation with the test data. We use frame elements to create a simple model of the entire system as shown in Fig. 17. The horizontal bus bar modules, circuit breaker, cable end unit, local control cabinet, connecting bus bars and the supports are all modeled as frame elements with dimensions consistent with the test setup.

The vertical units are modeled as 900 mm x 10 mm circular frame members and the horizontal bus bar modules are modeled as 430 mm x 5 mm circular frame members. The control cabinet and the circuit breaker are modeled as a 500 mm x 500 mm hollow rectangular frame section of thickness 16mm. The mass of the cabinet is lumped at four points along the length of the frame element. The total weight of the cabinet has been taken as 450kg (1000lbs).

The supports are modeled as hollow rectangular sections. The vertical frames are rectangular tubes of 4mm thickness and the base supporting tubes are 10mm thick. The frame elements used to represent the tubular base support are fixed at five points as shown in Fig. 17, to represent the test setup. The end portion of the base support is provided with incompressible links that will simulate the test condition as closely as possible.

The connection between the control cabinet and the horizontal bus bar modules has been modeled using frame elements of 36mm (1.4 inch) diameter. This is similar to the bolts used in the test setup to connect the cabinet with the equipment as shown in Fig. 14. In the test setup, the horizontal bus bar modules pipes are connected to each other and to the supports through small supporting channels. Also, the middle vertical unit is bolted to the tubular steel sections and the end vertical unit is connected to the supporting frame structure. The connectivity between these structural members may not necessarily be completely rigid. However, in the absence of adequate information, the corresponding degrees of freedom in the two adjoining members are considered to be constrained, thereby making the connectivity between them as rigid. The corresponding accelerometer locations (A, B, C, D, F and H) for the test setup and the finite element model have been shown in Figs. 14 and 17.

The finite element model can be used to evaluate not only the dynamic characteristics but also to conduct a detailed time history analysis. In the proposed approach, the first step is to evaluate the dynamic characteristics and compare them with the corresponding data obtained from the shake table test. The dynamic characteristics such as the frequencies, mode shapes and participation factor evaluated from the finite element analysis of the model described above cannot be compared directly with the test data as the test data are expressed in terms of transfer functions and not the mode shapes or participation factors. The next section describes the theoretical formulation for the transfer function so that the mode shapes and participation factors can be used to calculate the transfer functions at desired locations for comparison with test data.

7.2 Formulation for Transfer Function

The equation of motion for a multi degree of freedom system can be written as follows:

$$[M]\{\ddot{u}\} + [C]\{\dot{u}\} + [K]\{u\} = -[M]\{u_b\}\ddot{u}_{g_0}\mathrm{e}^{\mathrm{i}\Omega\mathrm{t}} \tag{3}$$

where [M], [C] and [K] are the mass, damping and stiffness matrices, $\{u_b\}$ is the influence force vector at the base of the system, $\ddot{u}_g(t)$ is the ground acceleration function at the base with frequency Ω, and {u} is the relative displacement response vector.

Let, $\{\mathrm{u}\} = \{u_0\}\mathrm{e}^{\mathrm{i}\Omega \mathrm{t}}$

Using superposition of modes,

$$\{\mathrm{u}\} = [\Phi]\{\mathrm{z}\} = [\Phi]\{z_0\}\mathrm{e}^{\mathrm{i}\Omega \mathrm{t}}$$

where, [Φ] is the mode shape matrix . (4)

Substituting derivatives of Equation 4 into the equation of motion (3) and pre-multiplying by $[\Phi]^T$, we can use the orthogonality of mode shapes. This gives a set of equations of motion for equivalent single degree of freedom systems having the same frequencies as the frequency of the system for the different modes. The equation of motion for the k^th mode is given by:

$$(-\Omega^2 + i\Omega 2\xi_k\omega_k + \omega_k^2)z_{0k}e^{i\Omega t} = -\Upsilon_k\ddot{u}_{g_0}\mathrm{e}^{\mathrm{i}\Omega \mathrm{t}} \tag{5}$$

where, Υ_k is the participation factor in the k^th mode, and ω_k is the frequency of vibration in the k^th mode. The solution of the differential equation gives the following magnitude for the steady-state amplitude of displacement response for the k^th mode:

$$z_{0k} = -\frac{\gamma_k\ddot{u}_{g_o}}{-\Omega^2 + 2i\Omega\xi_k\omega_k + \omega_k^2} \tag{6}$$

Therefore, the steady state response for any degree of freedom s, for N number of modes is given by:

$$u_s = \sum_{k=1}^{N} \Phi_{sk} z_{0k} e^{i\Omega t}$$

(7)

Substituting (12) into (13) and rearranging we get:

$$\frac{\ddot{u}_{s_{max}}}{\ddot{u}_{g0}} = \sum_{k=1}^{N} \frac{\Phi_{sk}\gamma_k\Omega^2}{-\Omega^2 + 2i\Omega\xi_k\omega_k + \omega_k^2}$$

(8)

Again,

$$\ddot{u}_s^{total} = \ddot{u}_s(t) + \ddot{u}_g(t)$$

(9)

Therefore,

$$\frac{\ddot{u}_{s_{max}}^{total}}{\ddot{u}_{g0}} = \sum_{k=1}^{N} \frac{\Phi_{sk}\gamma_k\Omega^2}{-\Omega^2 + 2i\Omega\xi_k\omega_k + \omega_k^2} + 1$$

(10)

The above expression is the definition of transfer function (H(ω)) for any degree of freedom s,

$$H_s(\omega)_g = \sum_{k=1}^{N} \frac{\Phi_{sk}\gamma_k\Omega^2}{-\Omega^2 + 2i\Omega\xi_k\omega_k + \omega_k^2} + 1$$

(11)

At the peak, for small damping ratios, $\Omega = \omega$, for that particular mode k,

$$H_s(\omega)_g = \frac{\Phi_{sk}\gamma_k}{2i\xi_k} + 1 \tag{12}$$

The finite element analysis gives the modal participation factors (γ) for each mode and the corresponding modal shapes (Φ) at the reference points. The magnitude of transfer function in the above equation can be calculated as $|H(\omega)|$.

The values of the product of γ and Φ at each of the accelerometer locations in the model for the different modes can be substituted into the analytical expression for the transfer function. Equation 12 can be used to plot the magnitude of the transfer functions over a frequency domain. Such plots can be compared between the test results and the finite element analysis results for reconciliation of the two. It must be noted that calculation of the product of participation ratio and the mode shape ordinate at a particular location as well as damping of the system in each mode by an inverse solution of the Equation 12 using the experimentally obtained values of $|H(\omega)|$ is not trivial. The accuracy of the inverse solution is highly dependent upon the availability of the data at appropriate multiple locations. In this particular case, the number of accelerometer locations is not sufficient to perform an inverse solution with sufficient accuracy. Furthermore, the peak values of the transfer functions are very sensitive to the damping values as discussed in detail in the next section.

7.3 Discussion of Finite Element Analysis Results

The plots of transfer functions for the corresponding accelerometer locations in the finite element model as evaluated from substituting the values of γ and Φ values into the equation for transfer function (11) are shown in Fig. 18 for an input in the X-direction. The corresponding plots for the transfer functions for the input in the Y direction are shown in Fig. 19.

A comparison of these plots with the plots in Figs. 15 and 16 shows that they exhibit similar behavior. As can be seen in Figs. 18 and 19, similar to the test results, accelerometer locations A and H exhibit significant amplifications in the low frequency regions, i.e. below 20 Hz or so. The amplifications at all other accelerometer locations are relatively smaller. A careful study of these plots shows the following similarities with the test results.

- Accelerometer location A experiences significant amplification in both X and Y directions in the vicinity of 7 Hz. However, similar to test data, there is no amplification at all other accelerometer locations in the vicinity of 7 Hz. Therefore, the finite element mode has been able to accurately represent the local mode of the cabinet.
- Significant amplification is observed for the plots in X direction at accelerometer locations A and H in the vicinity of 19 Hz. The amplification at locations B and D is about half in order of magnitude, similar to the test observations. Therefore, the typical global rocking mode that has been observed in the test data matches well with the finite element model with large amplifications at the extreme left and right corner elevations and relatively lower amplifications at the intermediate points B and D.

- Accelerometer location H experiences signification amplification in the vicinity of 11 Hz with negligible amplifications at all other points in the Y direction. This resembles closely the local mode of the vertical end unit in the GIS test setup on which the accelerometer H has been mounted.

The above discussion provides significant confidence in the finite element model for its reconciliation with the test setup. Figs. 20 through 22 show the comparison of the plots of transfer function for individual accelerometer locations for the test setup for input in X direction and the finite element model. The corresponding plots for input in Y directions are shown in Figs. 23 through 25 for the accelerometers A, D and H. The transfer functions for the test accelerometer locations have been plotted by substituting the corresponding values of the product of γ and Φ into Equation 11. The values of the product of γ and Φ can be obtained from using the peak values from the test data and substituting into Equation 12 for a given damping ratio. The transfer functions for the finite element has been plotted for a damping ratio of 4% for the X direction and 3% for Y direction.

As can be observed from these plots, there are differences in peak values between the test data and finite element analysis. This difference in the magnitude can be attributed to the lack of adequate data that enables a closer simulation of the test setup. A better reconciliation would require a more detailed model so that we get better values of γ and Φ which would then give us closer peak values with the test data. For the present case study, the different components of the equipment have been modeled as simple frame elements. Also, in absence of detailed information, it has not been possible to model the control cabinet accurately and also the different connections between the various components. Therefore, an exact reconciliation with test setup to capture the exact behavior of the equipment has not been possible. Another important factor that affects the estimation of the peak values of the transfer function is the damping of the equipment. Damping has a significant effect in increasing or lowering the peak value of the transfer function, as will be discussed in the next section.

8. Significance of Damping

The damping coefficient has a significant influence on the values of the transfer function. Figs 26 and 27 show the effect of damping on the transfer functions for the point H in X and Y directions.

As can be seen in Figs. 26 and 27, with the increase in damping, the peak value of the transfer function approaches the test value. Hence, damping is a very important criterion to be considered for the reconciliation of test and finite element analysis results.

9. Structural modifications for in-situ conditions

The shake table test has been conducted on a 145 kV subassembly of the equipment. However, at the actual site a 115 kV equipment is to be installed where multiple units are interconnected to each other. Therefore, it is important to describe the major differences between the tested equipment and the in-situ conditions. A careful study of the equipment to be actually installed gives the following observations.

- The mounting arrangement of the equipment tested in the shake table is different from the in-situ mounting arrangement. As has been shown in Fig. 10, the tested assembly is bolted to the shake table at five points. The actual equipment is supported on the tubular steel sections that are elevated by about 12mm (half an inch) from the floor level and fixed at two points by channel sections that are in turn grouted to the floor, as shown schematically in Fig 5.

- The local control cabinet, on top of which the accelerometer A is mounted, is not connected to the equipment at the actual installation site. Therefore, the effect of the cabinet can be overlooked for all practical purposes of studying the dynamic characteristics of the equipment to be actually installed.
- The equipment to be installed has multiple units interconnected to each other and also to the supporting structures and bushings outside. Therefore, interaction between multiple units can have an important effect on the dynamic characteristics of the equipment.
- The actual mass of the equipment depends on the cross sectional properties of the vertical and horizontal bus bar modules. Therefore, changing the diameter and mass of these modules can cause substantial changes in the dynamic behavior of the equipment actually installed.

The differences listed above are some of the major modifications that have to incorporated into the reconciled finite element model for the 145 kV equipment so that we can use the single unit to develop the finite element model for the entire 115 kV equipment that will be installed at the site.

9.1 Significance of mounting condition

The effect of the mounting arrangement can be illustrated if we change the mounting conditions for the finite element model of the tested 145 kV subassembly and evaluate the change in frequencies. The mounting arrangement of the finite element model for the tested 145 kV equipment has been changed from fixed at multiple locations to fixed and pinned conditions at two locations for illustration purposes. As has been shown in Fig. 28, the frequency of the model is around 6.16 Hz when the supporting tubular section is fixed at multiple locations to simulate the condition of the shake table test. However, the fundamental frequency drops to 5.94 Hz when it is fixed only at two locations. This condition is similar to the in-situ mounting arrangement. The frequency drops further to 5.9 Hz if instead of fixed boundary condition, the mounting arrangement is pinned at two points.

9.2 Significance of the interaction between multiple units of the equipment

As has been discussed before, the entire equipment cannot be tested on the shake table because of its size. So, the reconciliation of the test setup with the finite element model is for a subassembly of the entire equipment. At the actual site ten units of equipment are interconnected to each other and also to the bushings outside the building. The interaction between the multiple units of the equipment can also lead to a change in dynamic characteristics of the equipment. Figs. 29 and 30 show the plots of transfer functions for the reference point H in the X and Y directions for the single unit modeled in finite element analysis to simulate the test setup and the finite element model for the actually installed equipment where ten bays are interconnected to each other and also to the bushings outside.

As can be seen, the transfer function peaks for the location H for both X and Y directions have lower peak values for the actually installed equipment configuration. The units are connected to each other in the Y direction of the analysis. A study of Fig. 30 shows that due to the interaction between the multiple units, the equipment behaves more rigidly in the Y direction.

10. Interaction between building and Equipment

At the actual site, the entire equipment is mounted inside a building. In the present case study, the building is a two story concrete-steel building in which the equipment is housed on the first floor. Therefore, the dynamic characteristics of the equipment will be affected by the interaction between the building and equipment. The mass of the equipment is about ten percent of the total mass of the building. In order to understand the effect of interaction between the building and the system we can consider the building as the primary system and the equipment as the secondary system. If the GIS equipment is rigid, similar to the conditions of the shake table test, there is no interaction between the building and the equipment. However, if the equipment has flexible mounting arrangement, as the actual in-situ conditions, then there can be significant mass interaction between the equipment and the building.

As the equipment is mounted on the floor slab in the building, the floor spectrum generated from a finite element analysis of the building can be used for understanding the dynamic characteristics of the equipment and qualify it for strength and functionality. The floor spectrum can be generated by analyzing the building and the equipment separately (uncoupled system) or by a single step analysis of the building and the equipment as together (coupled system). The uncoupled analysis does not consider mass interaction, whereas a couple analysis accounts for mass interaction between the primary and secondary system.

The following section shows a case study for a simple single degree of freedom (sdof) – single degree of freedom (sdof) primary-secondary system to illustrate the effect of mass interaction on the response spectra for a coupled analysis.

10.1 Coupled System: Effect of Mass Interaction

The equation of motion for a sdof primary – sdof secondary (2-dof coupled) system is:

$$\begin{bmatrix} m_p & 0 \\ 0 & m_s \end{bmatrix} \begin{Bmatrix} \ddot{u}_p \\ \ddot{u}_s \end{Bmatrix} + \begin{bmatrix} C_p + C_s & -C_s \\ -C_s & C_s \end{bmatrix} \begin{Bmatrix} \dot{u}_p \\ \dot{u}_s \end{Bmatrix} + \begin{bmatrix} K_p + K_s & -K_s \\ -K_s & K_s \end{bmatrix} \begin{Bmatrix} u_p \\ u_s \end{Bmatrix} = -\begin{bmatrix} m_p & 0 \\ 0 & m_s \end{bmatrix} \begin{Bmatrix} 1 \\ 1 \end{Bmatrix} \ddot{u}_g(t)$$

Or,

$$[M]\{\ddot{u}\} + [C]\{\dot{u}\} + [K]\{u\} = -[M]\{u_b\}\ddot{u}_g(t) \tag{13}$$

where, m_p is the mass of the primary system, m_s is the mass of the secondary system, C_p and C_s are the damping constants for the primary and secondary systems, K_p and K_s are the stiffness for the primary and secondary systems, respectively.

$\ddot{u}_g(t)$ is the input ground motion and $\{u\}$ is the displacement response vector for the system.

The first equation becomes:

$$\ddot{u}_p + \left(2\xi_p\omega_p + 2\xi_s\omega_s r\right)\dot{u}_p - 2\xi_s\omega_s r\dot{u}_s + \left(\omega_p^2 + \omega_s^2 r\right)u_p - \omega_s^2 r u_s = -\ddot{u}_g(t)$$

(14)

$$r = \frac{m_s}{m_p}$$

(15)

where, r is the mass ratio.

The second equation can be written as:

$$\ddot{u}_s + 2\xi_s\omega_s\dot{u}_s + \omega_s^2 u_s - 2\xi_s\omega_s\dot{u}_p - \omega_s^2 u_p = -\ddot{u}_g(t)$$

(16)

On the other hand, if we do an uncoupled analysis, the equation of motion for the secondary system is:

$$\ddot{u}_s + 2\xi_s\omega_s\dot{u}_s + \omega_s^2 u_s = -\ddot{u}_p^T(t)$$

(17)

where, $\ddot{u}_p^T(t) = \ddot{u}_p(t) + \ddot{u}_g(t)$ is the total acceleration at the primary system degree of freedom.

A comparison between Equations (16) and (17) shows that the response of the secondary system in the case of a coupled analysis is influenced by the behavior of the primary system and the interaction between the two cannot be captured by an uncoupled analysis in the complete sense as seen in Equation (17).

Figs. 31 and 32 show the plots of floor spectra for a sdof-sdof primary-secondary system. In case of the uncoupled analysis, the floor time history generated from a finite element analysis of the primary system is used to generate the floor spectrum for the secondary system. The coupled analysis has been conducted for mass ratios of 0.1, 0.01 and 0.001 between the primary and the secondary system. The primary system is assumed to have a natural frequency of 4 Hz. As can be seen from the plots, the effect of mass interaction is quite significant for mass ratios of 0.1 and 0.01. It causes a reduction in the peak values for frequencies around 4 Hz. The two systems are said to be tuned when their fundamental frequencies are closer to each other. Therefore, the effect of mass interaction on the response is most prominent for tuned systems. However, as we decrease the mass ratio further to 0.001, effect of mass interaction is almost negligible and the response is similar to an uncoupled analysis.

For the equipment building system under discussion, the mass of the equipment is about ten percent the floor mass of the building. Therefore, the effect of mass interaction can be significant for dynamic response of the equipment. However, in this case the building has a fundamental frequency of 1 Hz and the first predominant mode of the equipment is around 16 Hz. Therefore, the two systems are detuned with respect to their fundamental mode. However, both the building and the equipment are multi-degree of freedom systems. The most interaction would occur between the building modes closest to the fundamental mode of the equipment. The building has a mode around 15 Hz which corresponds to higher order modes. At this frequency, the building and the equipment are nearly tuned. Therefore, it will be essential to consider the effect of mass interaction between the equipment and the building on the dynamic characteristics and response of the equipment. The above discussion illustrates the significance of different in-situ conditions on the dynamic characteristics of the equipment. It further implies the importance of modifying the reconciled finite element model of higher voltage classification to account for the various actual conditions at the installed site for the lower voltage equipment that has to be qualified in the present study. As discussed in our proposed approach in Fig. 8, the modified finite element model can be used further to conduct a time history analysis to estimate the maximum accelerations for its qualification.

11. Conclusion

A new methodology is proposed for qualification of electrical substation equipment for both strength and functionality assessment. For this purpose, we have studied the earthquake behavior of a GIS equipment using the shake table test results of a 145 kV subassembly of the equipment. The test provides data from a sine sweep test which can be used to understand the dynamic characteristics of the equipment. The test data can be further used to develop a reconciled finite element model of the equipment. Such a finite element model can be updated to represent the equipment that is actually installed on the site. The key observations can be summarized as:

- The proposed methodology can effectively utilize the shake table test data for a higher voltage rating equipment in the qualification of the actually installed lower voltage rating equipment.
- The dynamic behavior of the equipment at an actual site can be significantly different from an equipment tested on shake table due to following reasons:
    1. Mounting arrangement;

2. Structural differences between the test setup and the actual setup at the site;
3. Interaction between multiple units;
4. Interaction between the equipment and the building.

- The data available from the shake table test is not sufficient to accurately develop a finite element model that would simulate the test results exactly.
- The complete information on the damping characteristics of the equipment is important to reconcile the test data with the finite element analysis.

The present study makes an attempt to reconcile the shake table test data with a finite element model within the restrictions of incomplete data available. This gives us some validation of the finite element model. The high voltage equipment was tested for functionality during the shake table test. The reconciled finite element model has been modified according to the actual site conditions and qualified for its strength by a subsequent finite element analysis. We conclude that this approach qualifies the lower voltage equipment both from strength and operability aspects. We further discuss the effect of different in-situ conditions and emphasizes the incorporation of those changes while qualifying the equipment at the actual site.

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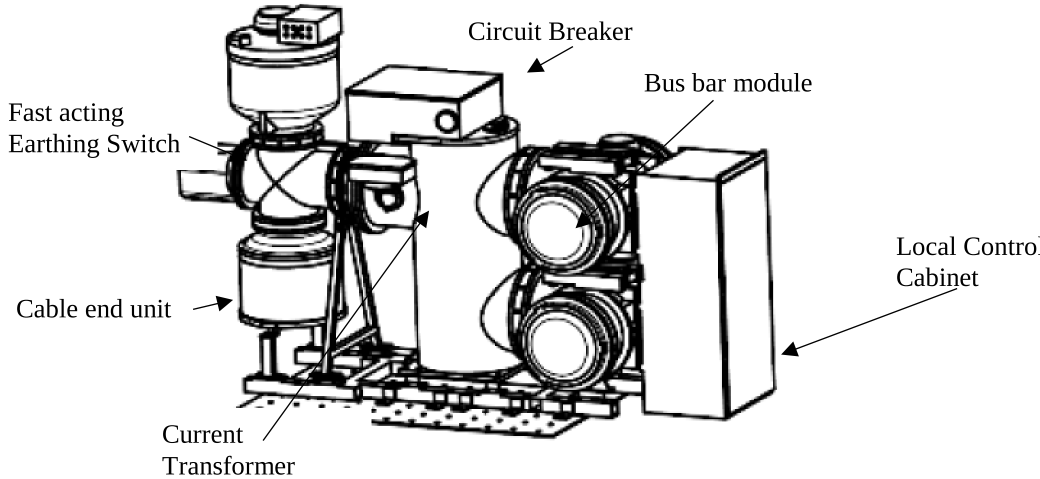


Figure 1: A typical GIS subassembly

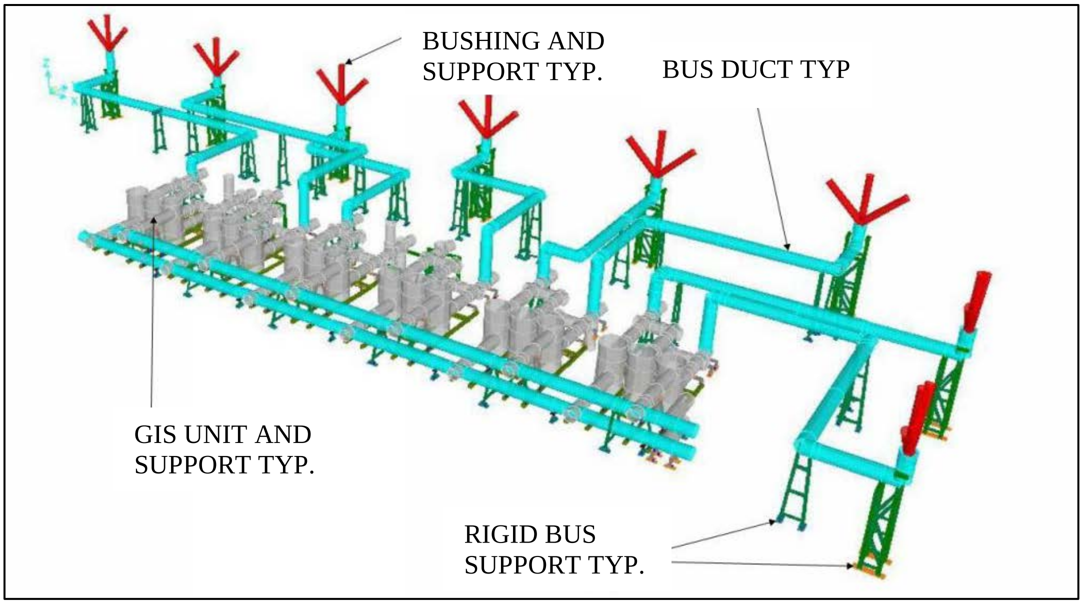


Figure 2: A typical layout of an entire GIS equipment

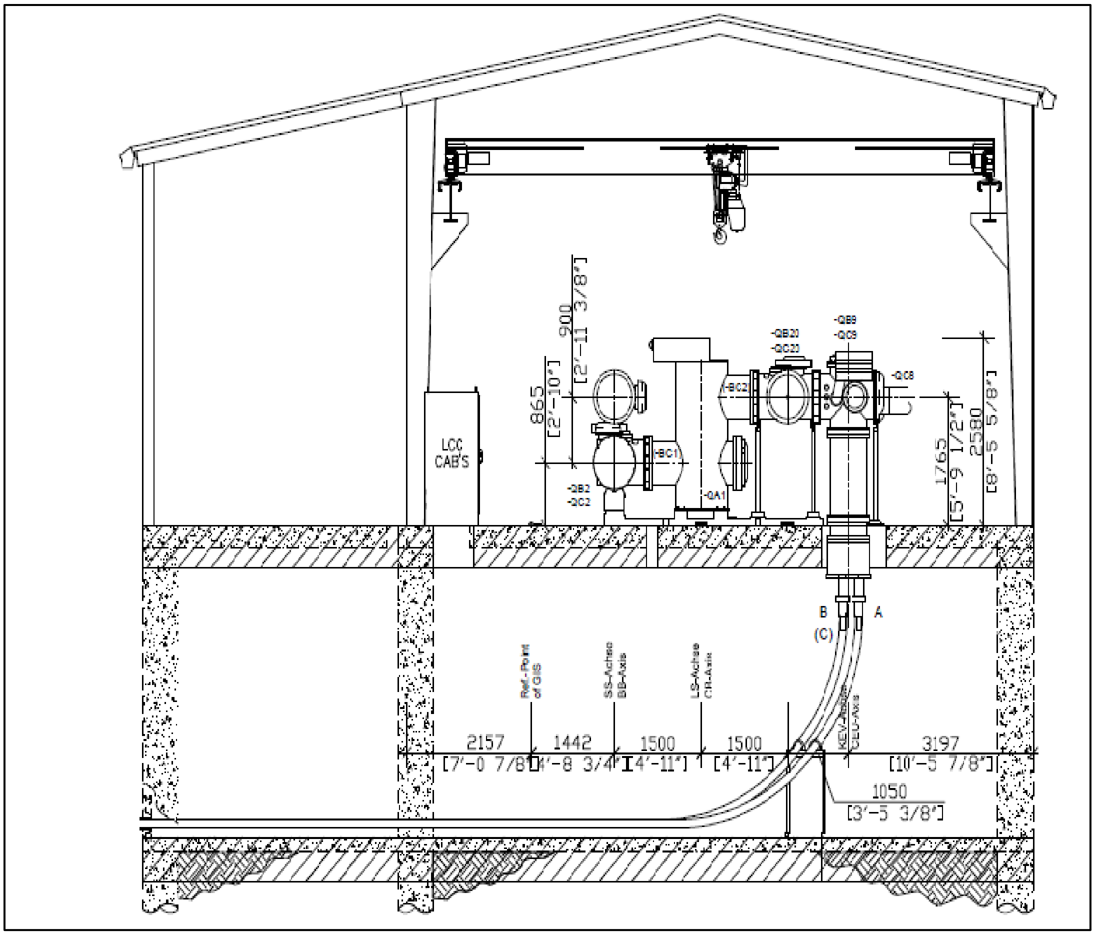


Figure 3: A typical elevation of a GIS substation

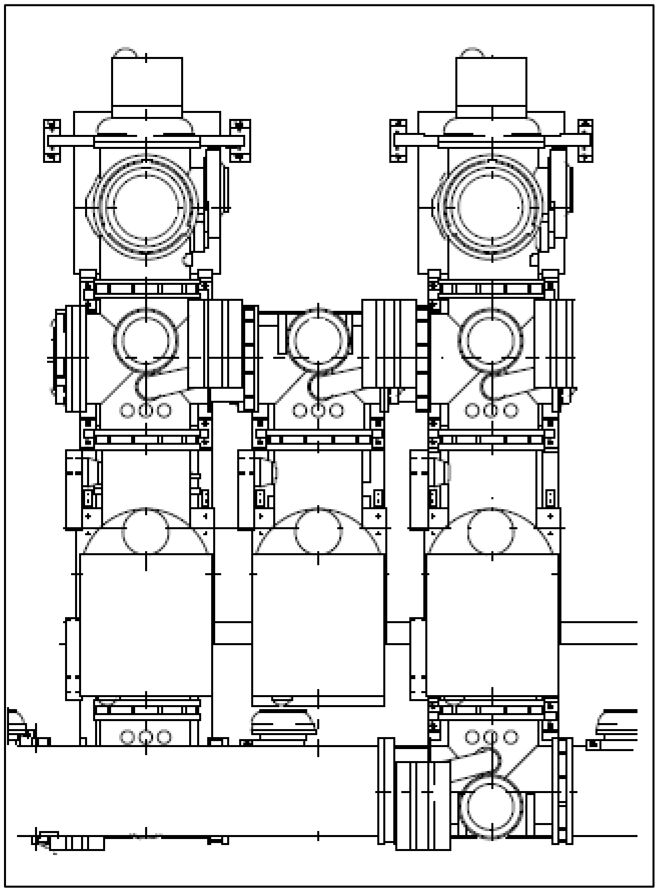


Figure 4: A typical plan of a single bay of GIS equipment

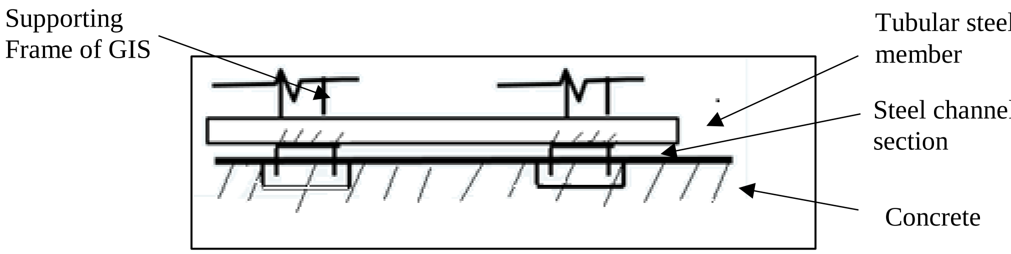


Figure 5: Mounting arrangement of a GIS unit

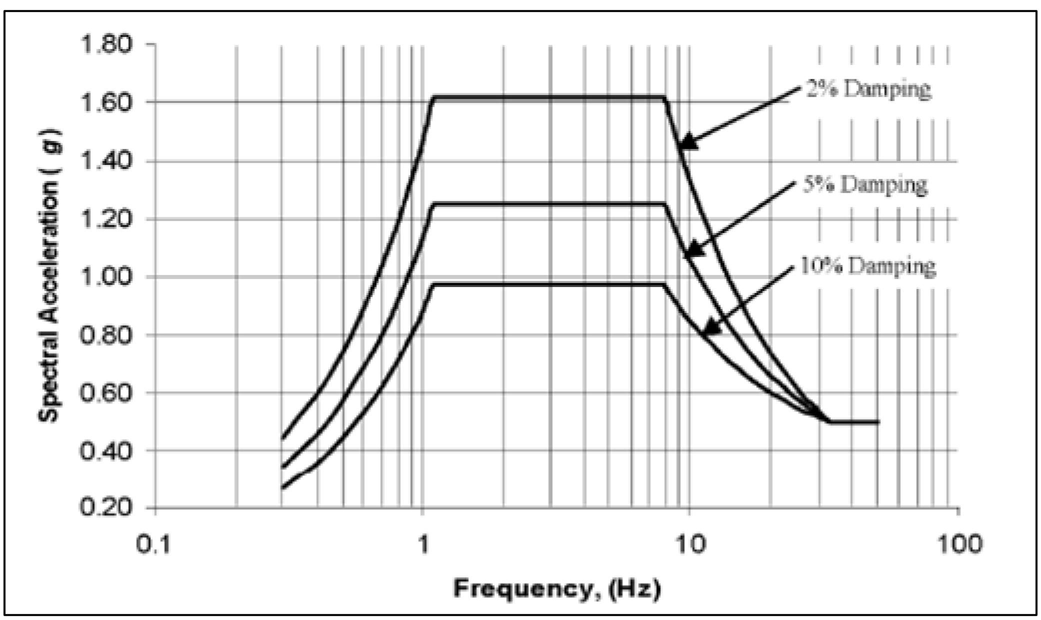


Figure 6: Required response spectrum anchored to 0.5g, IEEE-693 (2005)

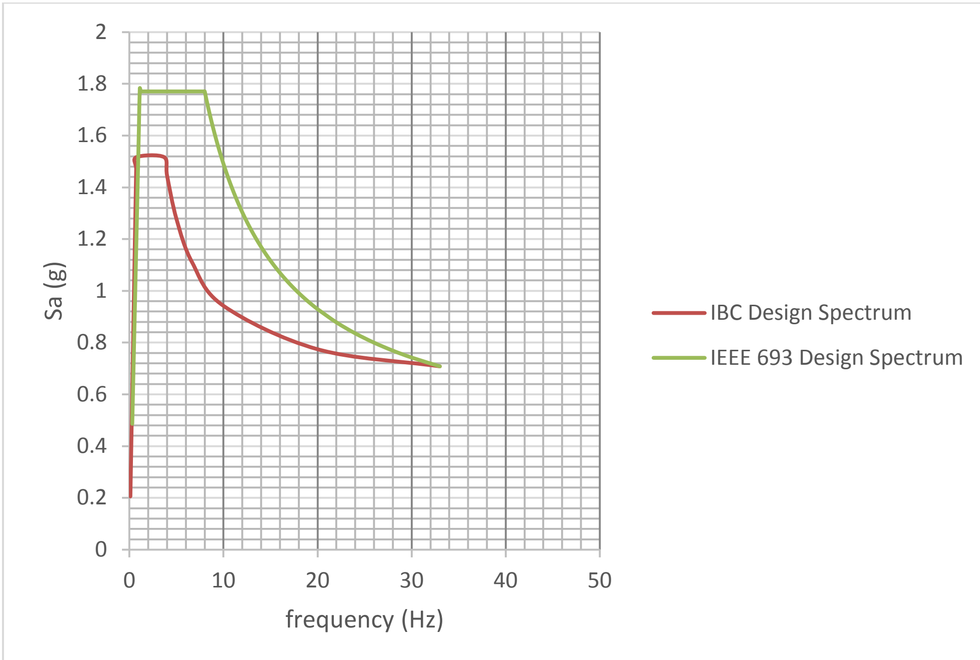


Figure 7: Comparison of IBC 2009 response spectrum with IEEE-693 required response spectra

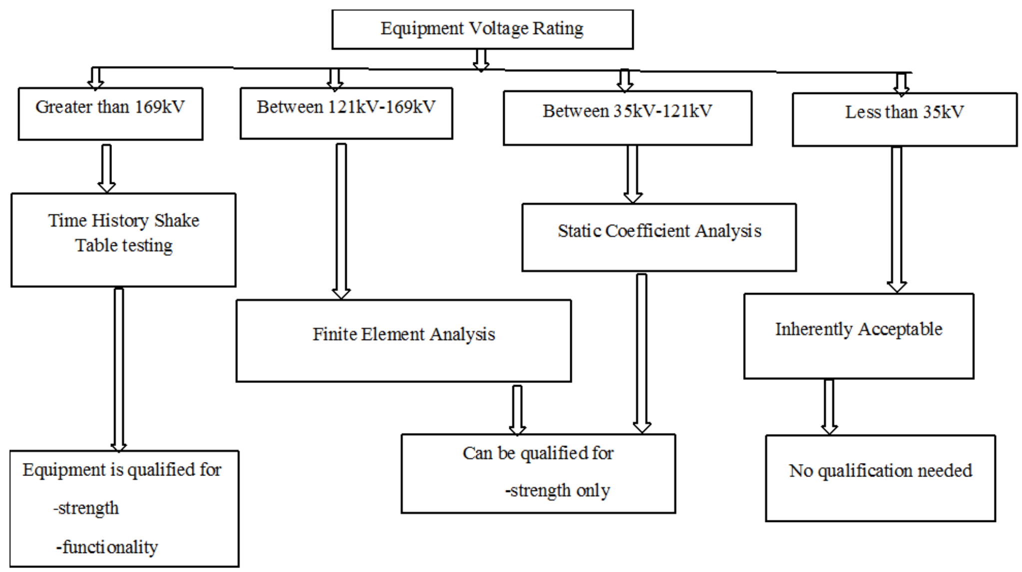


Figure 8: Recommended qualification process for GIS equipment as per IEEE 693 (2005)

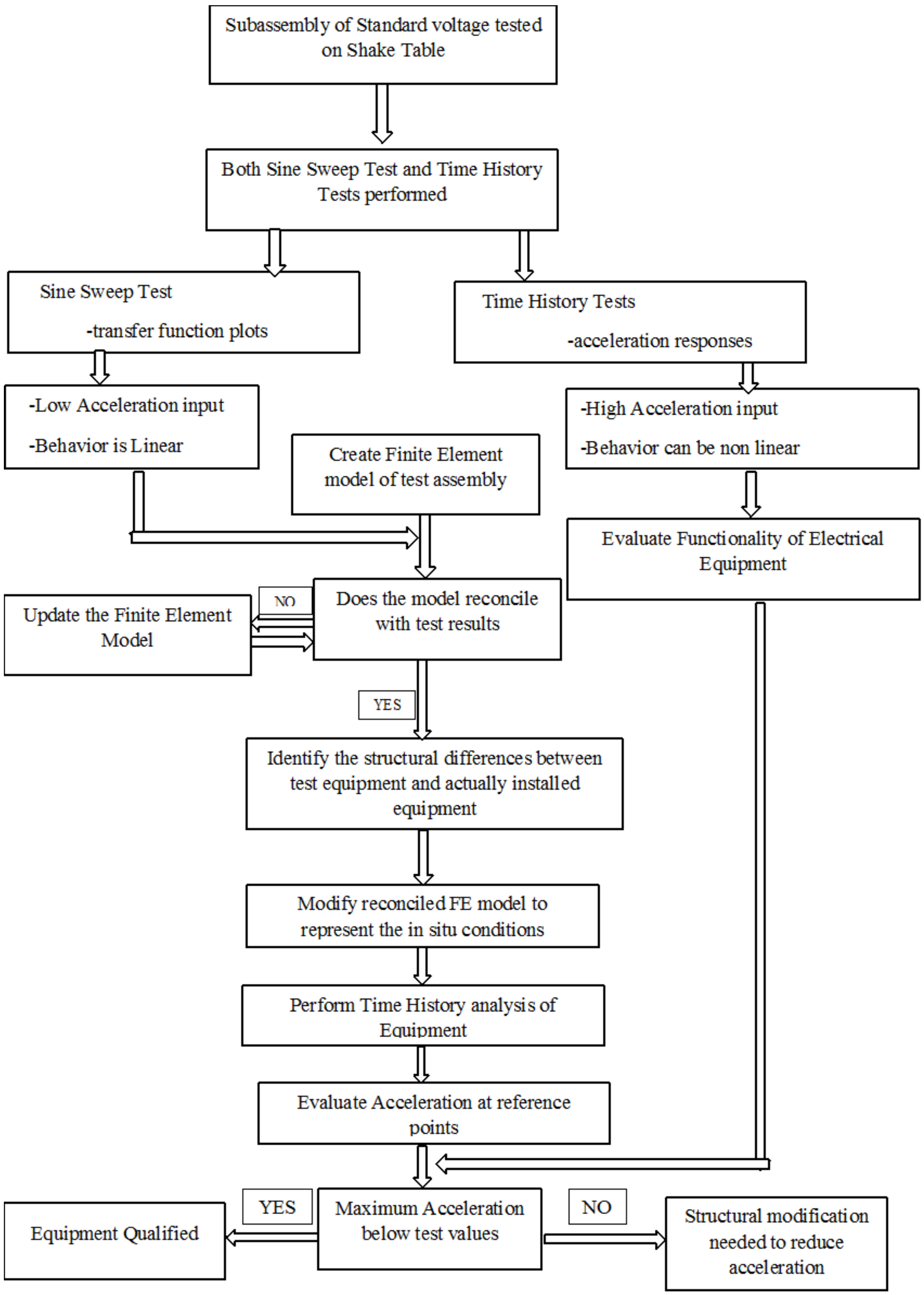


Figure 9: Proposed approach for GIS qualification

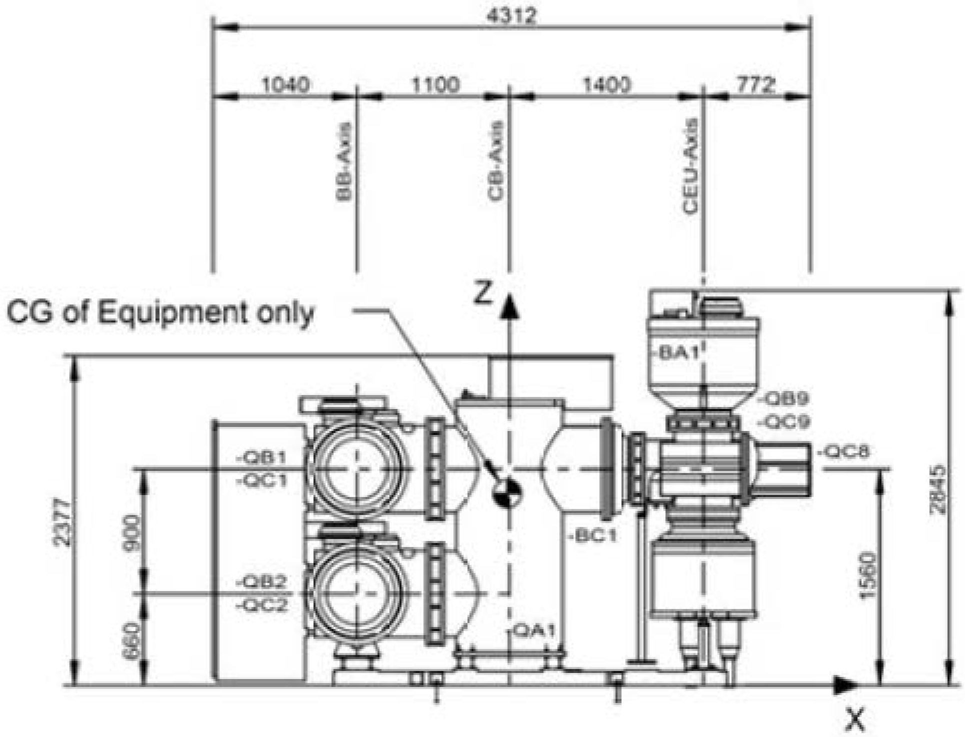


Figure 10: The test setup of a typical 145 kV GIS subassembly

Figure 11: Mounting arrangement of Test setup

Figure 12: Location of control cabinet in the test setup

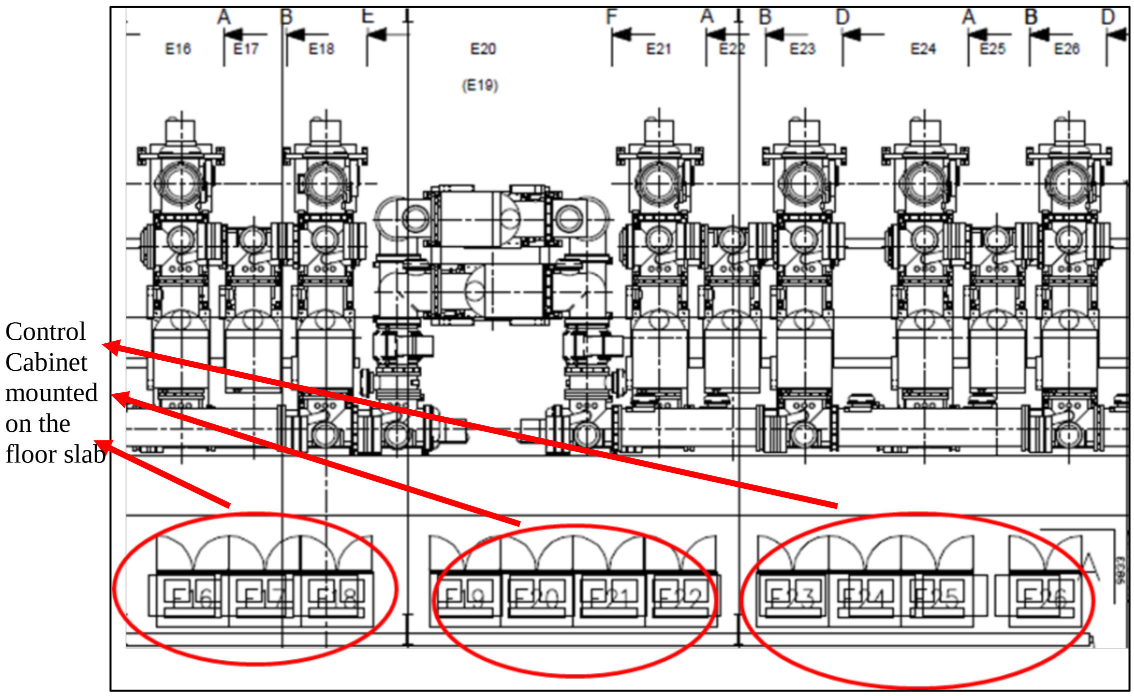


Figure 13: Location of control cabinet at the actual site

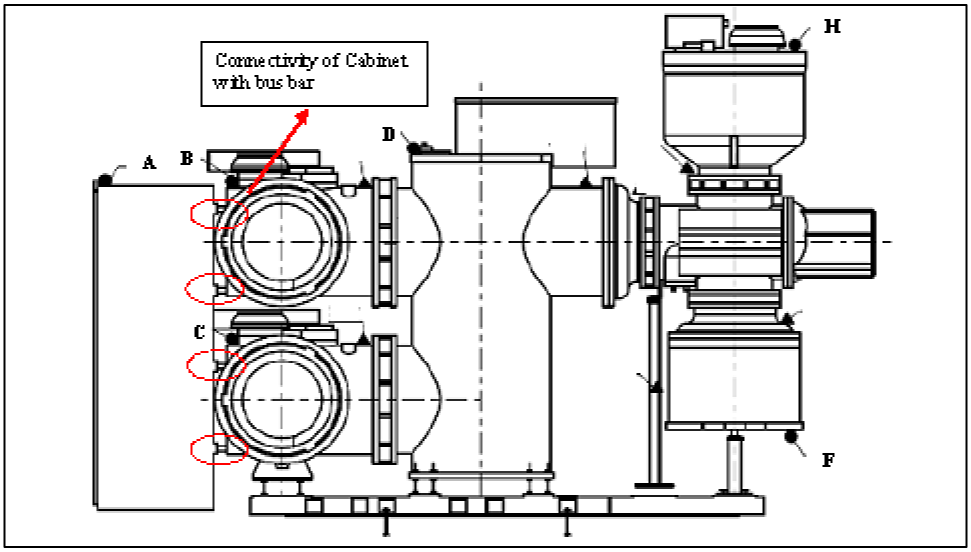


Figure 14: Location of accelerometer locations and the connectivity of local control cabinet for test setup

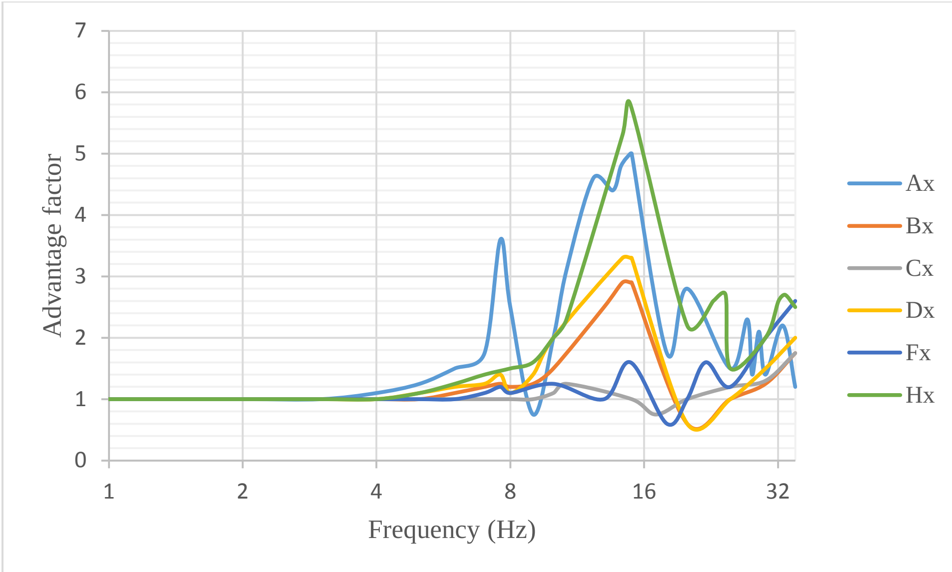


Figure 15: Transfer function in X direction, shake table test

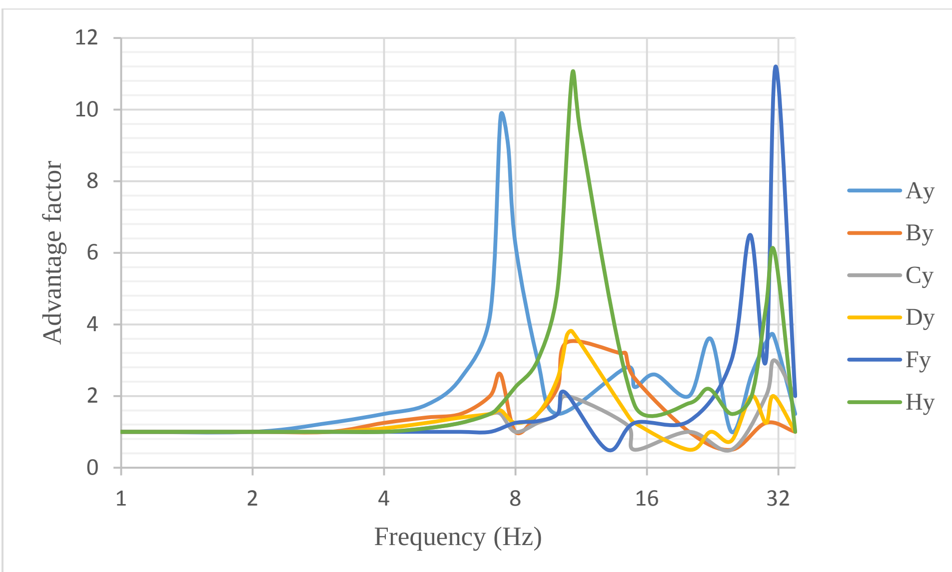


Figure 16: Transfer function in Y direction, shake table test

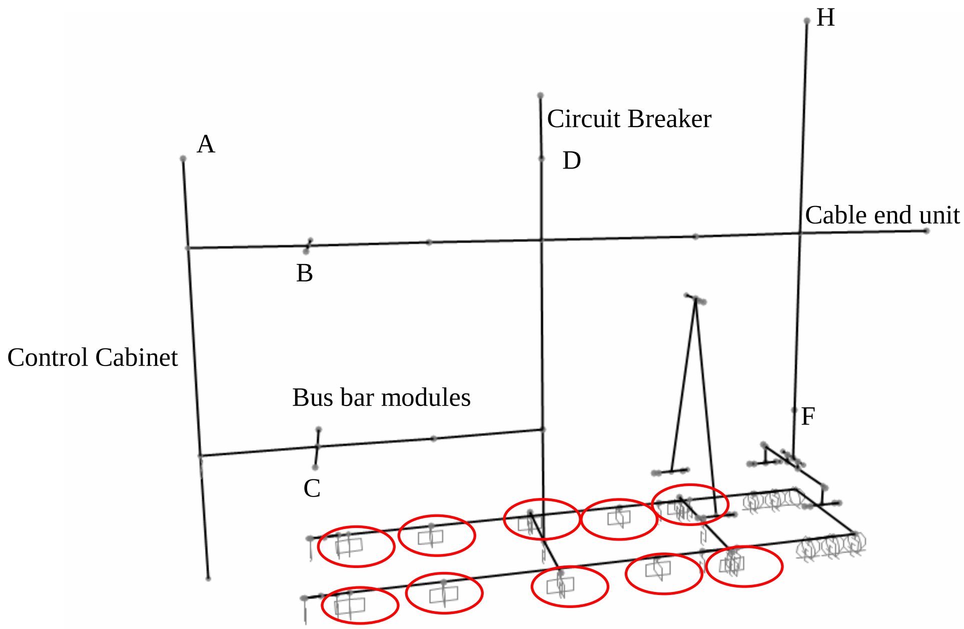


Figure 17: Frame model for the finite element analysis showing accelerometer locations

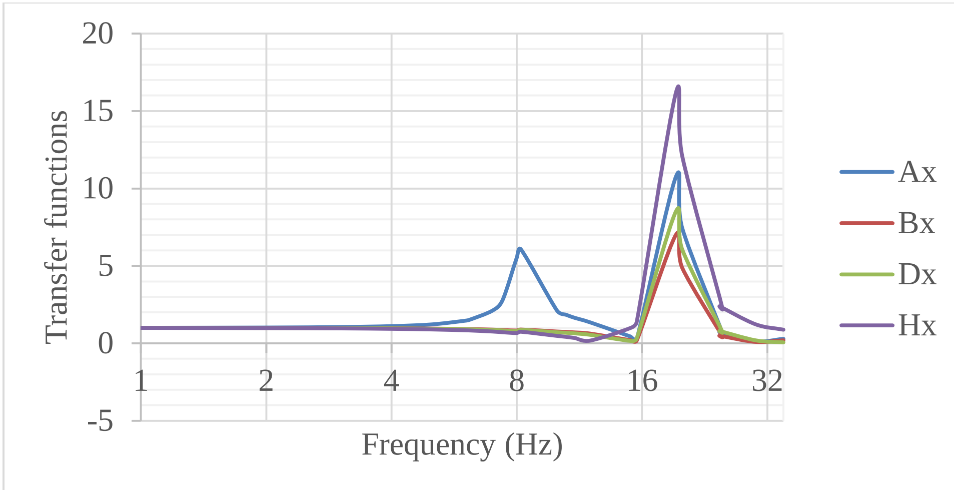


Figure 18: Transfer function in X direction, finite element analysis

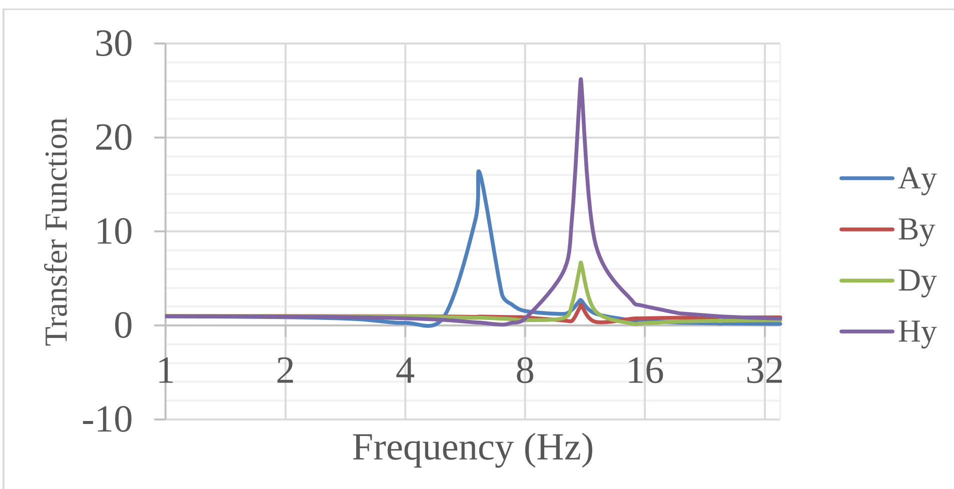


Figure 19: Transfer function in Y direction, finite element analysis

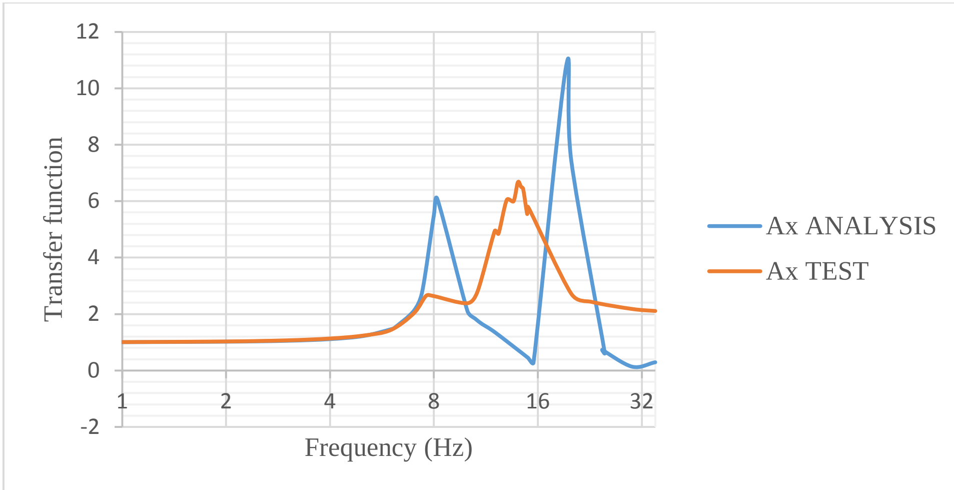


Figure 20: Transfer function for location A in X direction, shake table test and finite element analysis

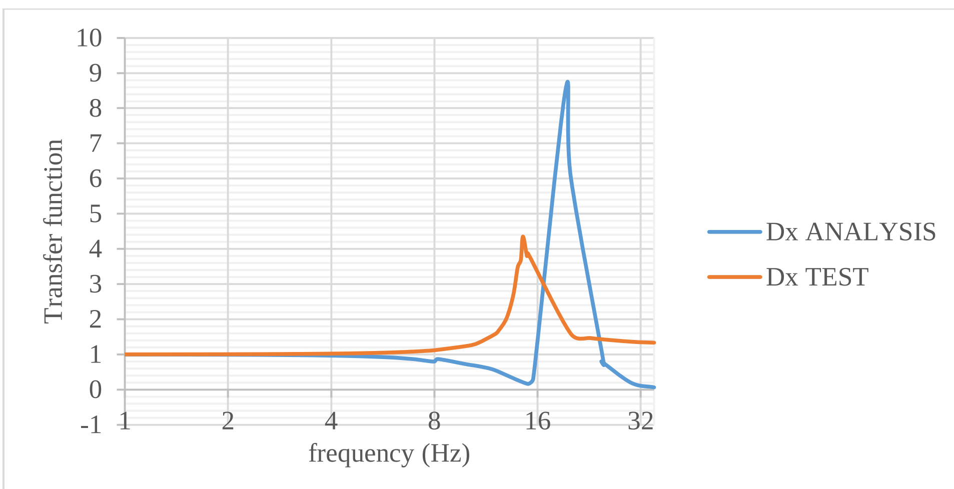


Figure 21: Transfer function for location D in X direction, shake table test and finite element analysis

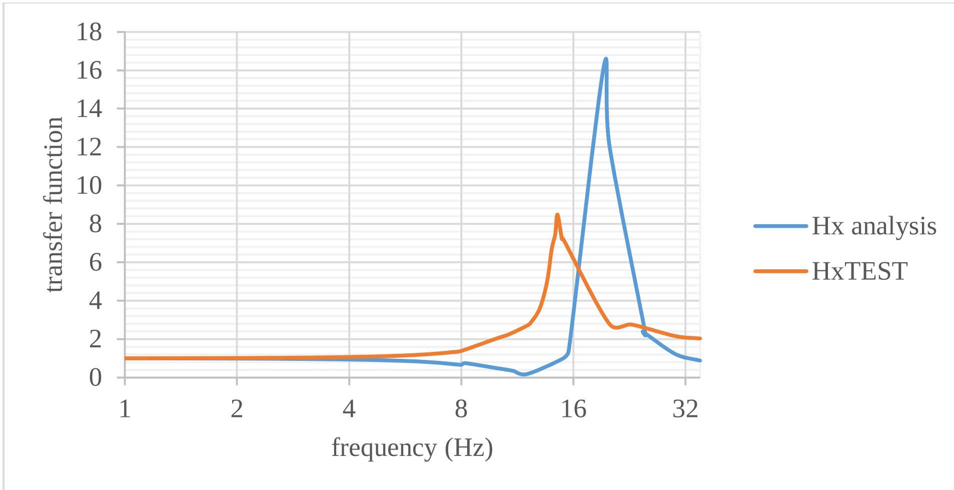


Figure 22: Transfer function for location H in X direction, shake table test and finite element analysis

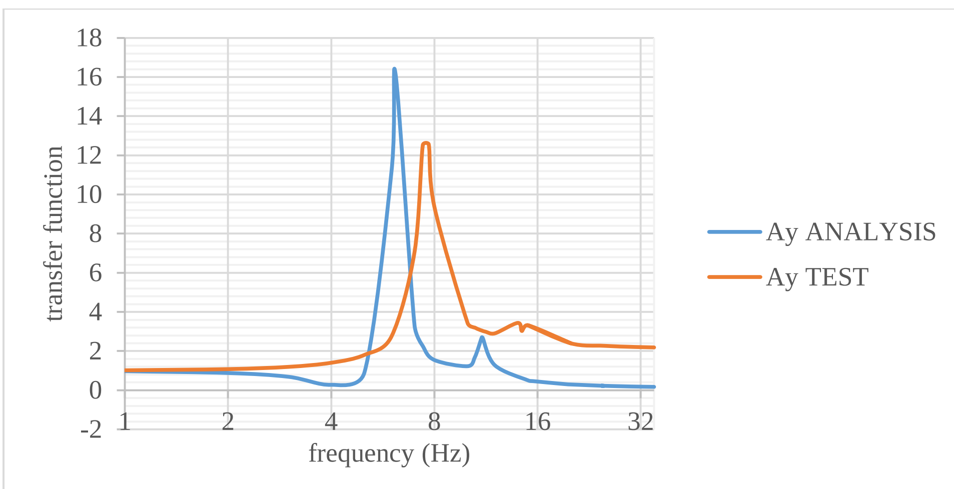


Figure 23: Transfer function for location A in Y direction, shake table test and finite element analysis

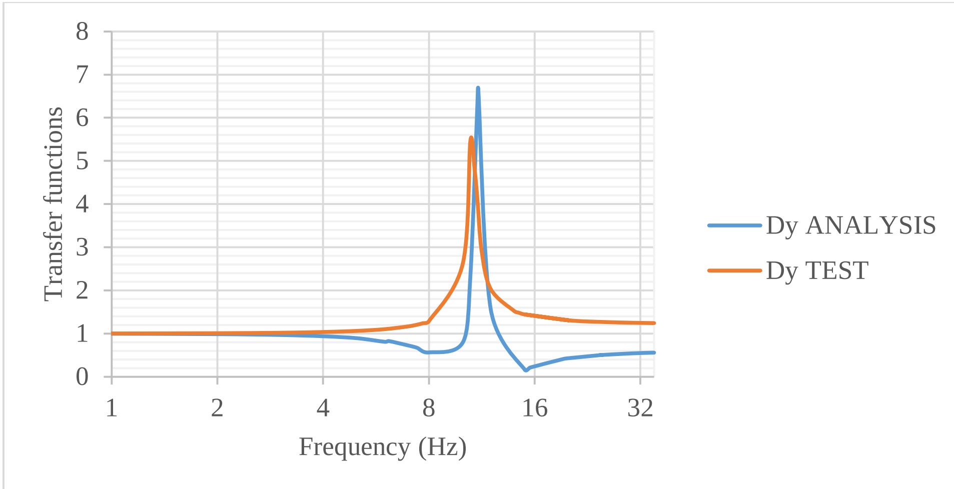


Figure 24: Transfer function for location D in Y direction, shake table test and finite element analysis

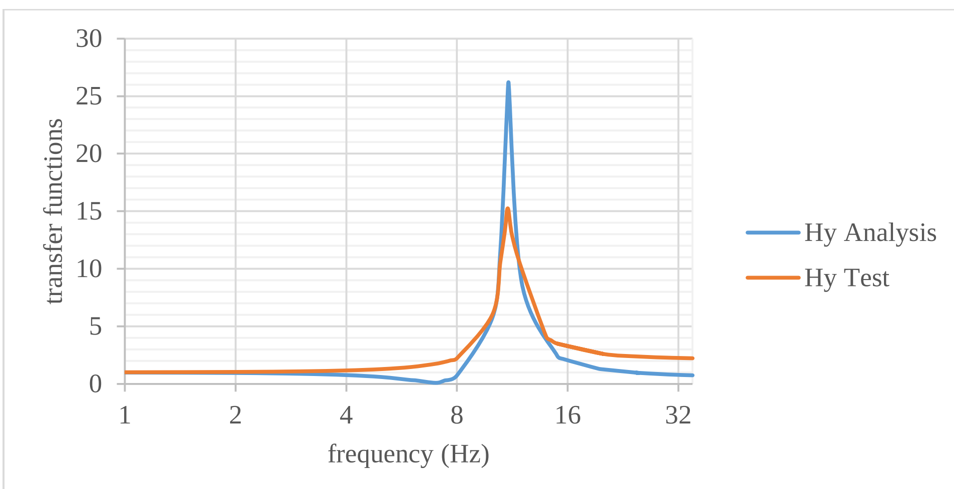


Figure 25: Transfer function for location H in Y direction, shake table test and finite element analysis

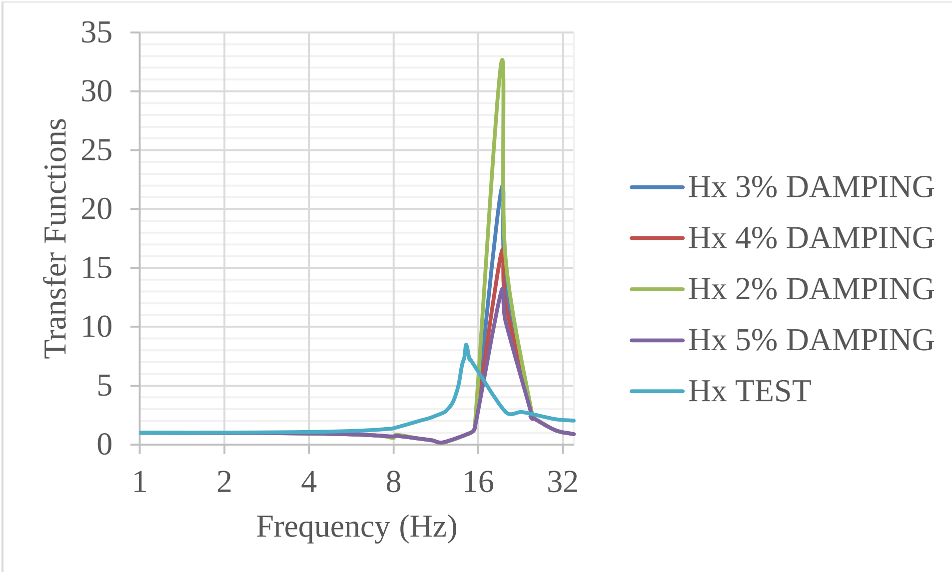


Figure 26: Effect of damping on transfer functions for location H in X direction, finite element analysis

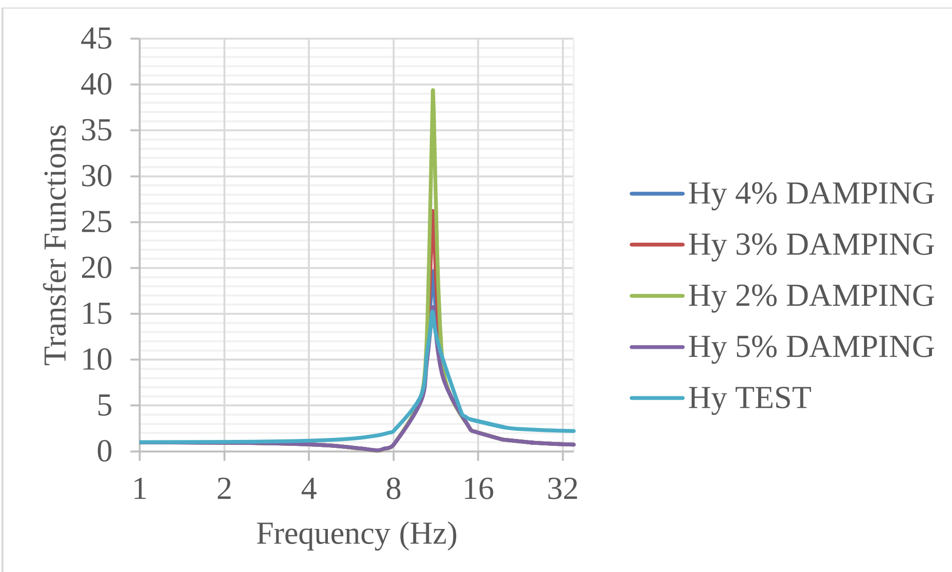
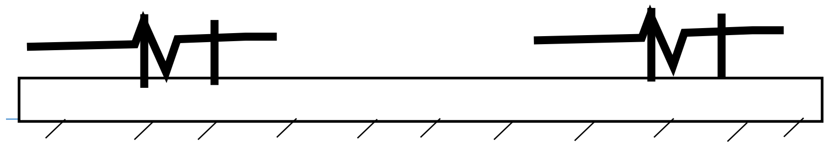
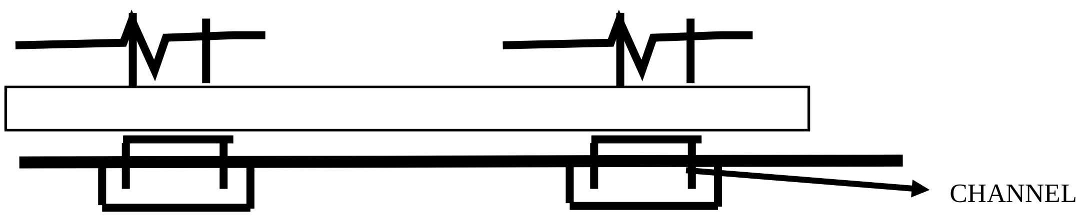


Figure 27: Effect of damping on transfer functions for location H in Y direction, finite element analysis



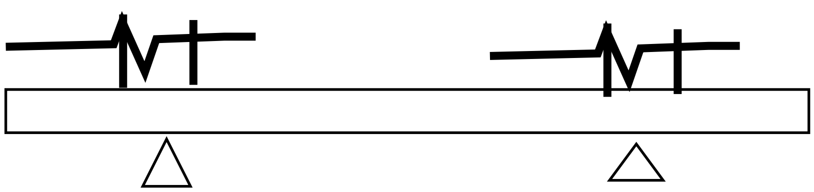
Frequency: 6.16 Hz

(i) Supporting tube fixed along the length



Frequency: 5.94 Hz

(ii) Supporting tube fixed at two points (in-situ condition)



Frequency: 5.9 Hz

(iii) Supporting tube pinned at two points

Figure 28: Effect of boundary condition of mounting arrangement on frequency of equipment

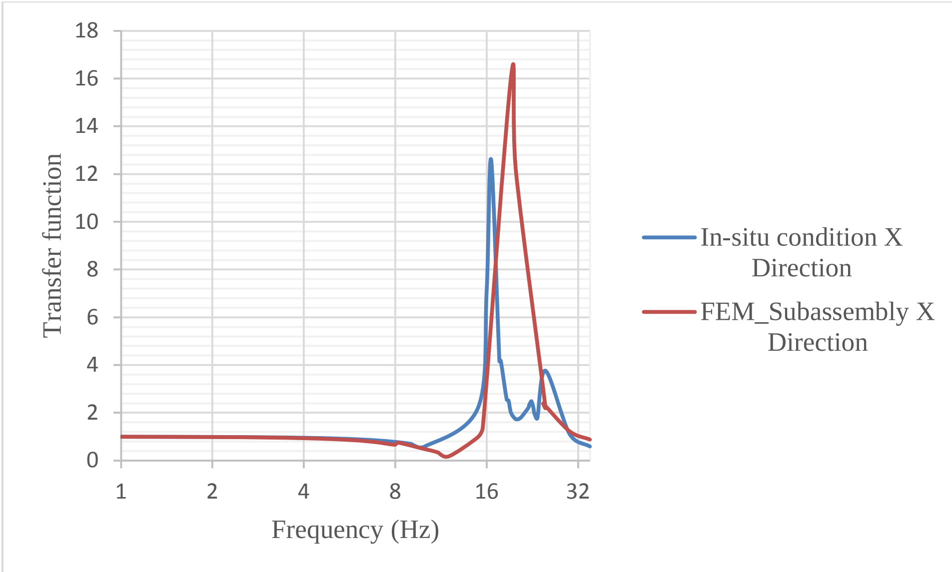


Figure 29: Effect of interaction between the equipment: Transfer function for location H in X direction, finite element analysis

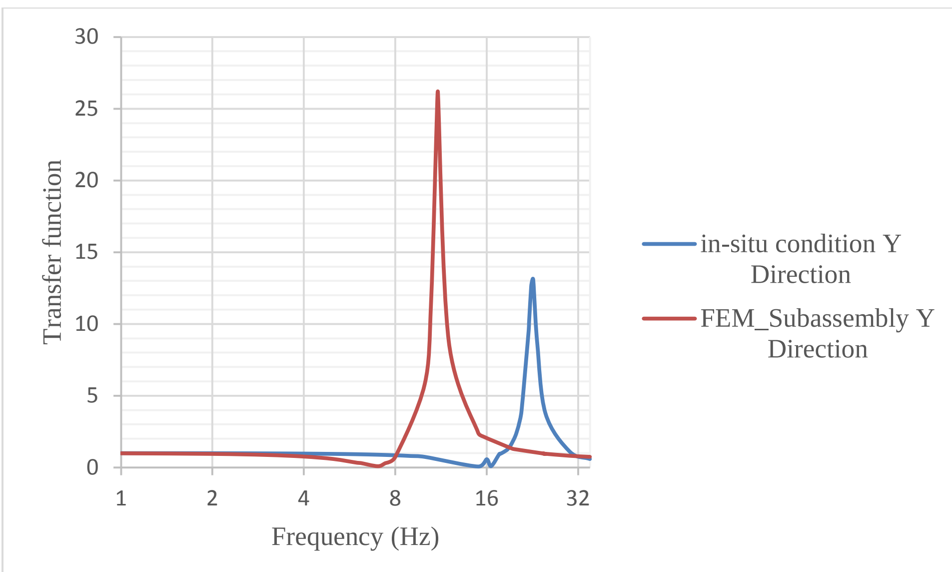


Figure 30: Effect of interaction between the equipment: Transfer function for location H in Y direction, finite element analysis

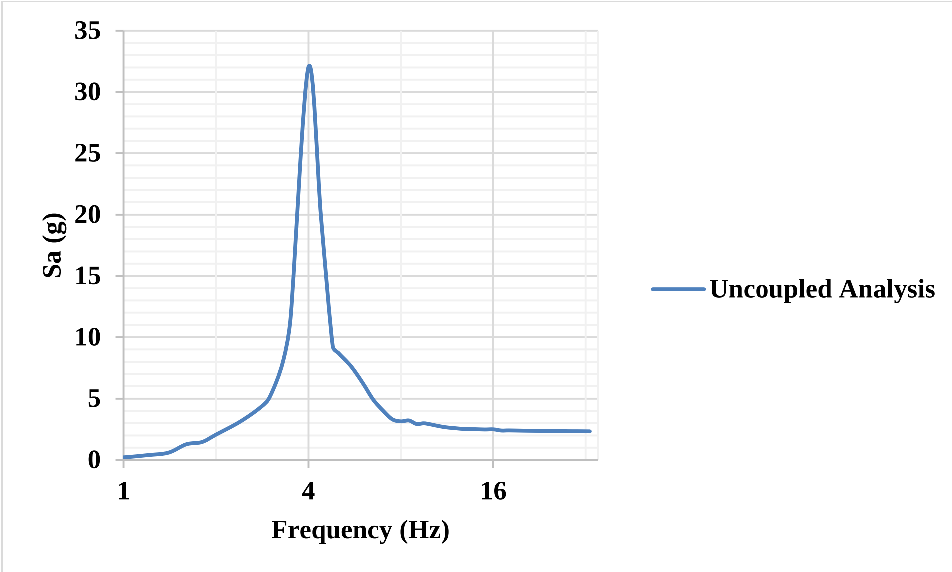


Figure 31: Floor spectrum for an uncoupled primary-secondary system

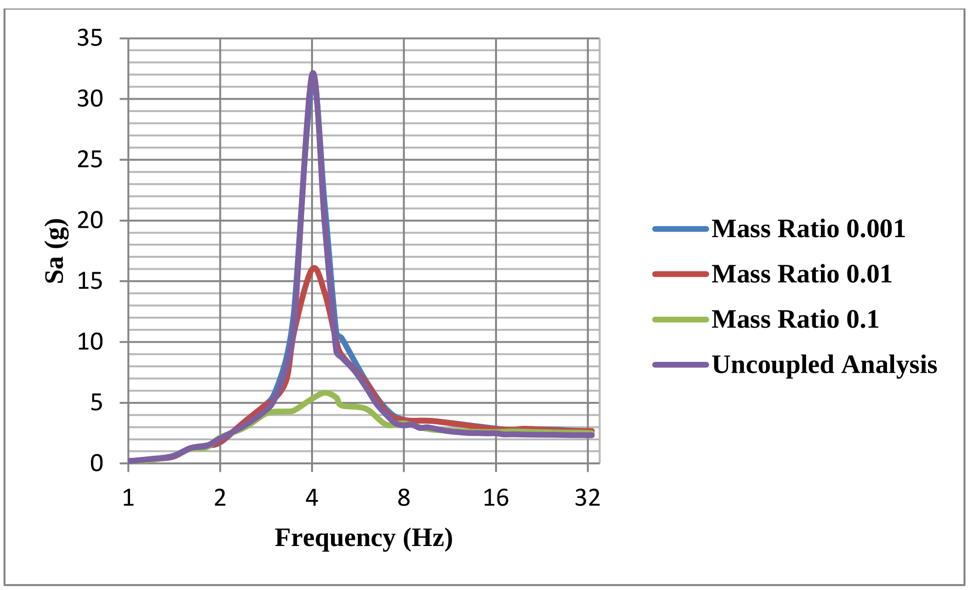


Figure 32: Effect of mass interaction on the floor spectra of a primary-secondary system, coupled analysis

PART III: SUMMARY AND CONCLUSIONS

1. General

The current practice for the qualification of electrical substation equipment is based on voltage classification. The qualification requirements of IEEE 693 (2005) recommends shake table tests to be conducted only for equipment of 169 kV or higher voltage. The seismic qualification of equipment of lower rating is ascertained by a finite element analysis. Such an analysis ensures a qualification based on strength only. This research proposes a new approach of qualification of electrical equipment, irrespective of its voltage classification, that can provide sufficient confidence on the equipment both from strength as well as functionality perspective. The key aspects that lead to the development of this new approach can be summarized in the following sections.

2. Reconciliation of test results with finite element analysis

The shake table test results for a 145 kV GIS equipment has been used to create a finite element model**.** The reconciliation process mainly involved the following iterative steps.

- A basic finite element model is developed from a preliminary study of the test setup.
- The formulation of transfer function for a multi-degree of freedom system subjected to input ground acceleration motion is developed from the solution of the equation of motion.
- The values of mode shapes and modal participation factors obtained from the finite element analysis of the model are used to calculate the values of transfer functions from analysis.

- The finite element model is reconciled with the test setup by a comparison of the transfer function plots of the test results and the finite element analysis.

3. Effect of equipment damping and other in-situ conditions

At the actual site a 115 kV equipment is to be installed where multiple units are interconnected to each other. Therefore, it is important to understand the effect of different in-situ conditions on the dynamic behavior of the equipment and identify the major differences between the test setup and the in-situ equipment. A study of the various parameters that need to be considered for the qualification of the actual 115 kV equipment gives the following observations.

- Damping of the equipment is a very significant factor that can affect the peak values of the transfer functions which in turn are related to mode shapes, modal participation factors and natural frequencies of the equipment. Hence, it is essential to incorporate correct damping values when reconciling the test results with the finite element model.
- The effect of mounting condition also governs the dynamic behavior of the equipment.
- The interaction between the multiple units of the equipment can have a significant effect on the peak values of the transfer functions and the corresponding natural frequencies of the equipment.
- The equipment is housed inside a building at the actual site. The mass interaction between the equipment and the building plays a significant role on the floor spectra.

> A time history analysis of the entire equipment gives us the maximum acceleration responses that are used for the qualification of the equipment. Therefore, a coupled analysis of the equipment and the building would yield more realistic results as compared to an uncoupled analysis of the equipment only.

It is important to incorporate these structural modifications in the reconciled finite element model. This model can be used to generate a complete finite element model of the 115 kV equipment to be installed at site. As discussed before, a time history analysis of this model will qualify the equipment for strength. The confidence on the qualification of the equipment based on functionality is ensured from the shake table test results.

The present work, therefore, makes an attempt to arrive at a new methodology for qualifying electrical equipment and discusses the various parameters that needs to be explored further for a better understanding of the dynamic characteristics of the equipment.

4. Recommendations for future research

The detailed comparison of finite element analysis and shake table test data in this study illustrates that the behavior of GIS equipment can be very sensitive to the mounting arrangement. The actual in-situ mounting arrangement exhibits a nonlinear behavior due to the uplift of the tubular sections at the base. It is recommended that this nonlinear behavior be characterized by its corresponding equation of motion and the corresponding variation in the frequencies be established by a parametric study of such a simple model. Furthermore, it is recommended that any future tests should consider measuring accelerations at more locations that would enable inverse solution of the transfer functions to establish realistic damping characteristics. The accelerometer locations in the test should be selected in a manner that helps the development of the finite element model. Finally, studies are needed to establish a functionality criterion for the electrical instruments so that a finite element analysis alone can be used to qualify the complete equipment.