COMPDYN 2015
5th ECCOMAS Thematic Conference on
Computational Methods in Structural Dynamics and Earthquake Engineering
M. Papadrakakis, V. Papadopoulos, V. Plevris (eds.)
Crete Island, Greece, 25–27 May 2015

ANALYSIS OF COUPLED SYSTEMS CONSISTING OF SUPPORT STRUCTURE AND HIGH VOLTAGE SUBSTATION EQUIPMENT WITH VERIFICATION VIA FULL-SCALE SHAKING TABLE TESTS

Shakhzod M. Takhirov[1], Amir S.J. Gilani[2], Frank Blalock[3], and Cary Ahrano[3]

[1] Structures Laboratory, Civil and Environmental Engineering Department, University of California, Berkeley and PEER – UC Berkeley
337 Davis Hall, UC Berkeley, Berkeley, CA 94720-1710, USA
e-mail: takhirov@berkeley.edu

[2] Miyamoto International, Inc.
1450 Halyard Dr, West Sacramento, CA 95691, USA
agilani@miyamotointernational.com

[3] Southern States, LLC.
30 Georgia Avenue, Hampton, GA 30228, USA
f.blalock@SouthernStatesLLC.Com and cahrano@bellsouth.net

Keywords: Seismic qualification, full-scale shaking table testing, sub-structuring, finite element analysis, electrical substation equipment, support structure effect.

Abstract. *According to the current recommended practice for design of substation equipment in seismic regions, high-voltage electrical equipment needs to be tested in a shaking table test. The test is conducted in as-installed configuration that includes a support structure and the electrical equipment mounted on top of the latter. According to the requirement, the equipment has to be re-tested every time a new support structure is introduced. The support structure's design for the same equipment varies from utility to utility and is related to the utility's-specific needs, design practice, and constraints. Therefore, every time a utility company requires a new support structure, a complete assembly of the new support structure and its equipment, needs to be re-tested in a shaking table test which is time consuming and expensive. The main objective of this paper is to study numerically such coupled systems consisting of a support structure and high-voltage substation equipment to provide recommendations on the design of the support structures. Optimization of the support structure design that results in adequate seismic performance of the equipment is studied in this paper. The results of the analysis are verified by full-scale tests of a 500-kV air disconnect switch on the shaking table. The complete assembly of the full-scale switch including the support structure is more than 10 m tall and the equipment is about 5 m tall. The same piece of equipment is seismically tested on different support structures to estimate the effect of the support structure on the overall performance of the coupled system. Moreover, the results of this experimental and analytical research are compared to real-time hybrid simulation results of similar equipment published earlier.*

1 INTRODUCTION

In past and recent earthquakes, high voltage substation components have suffered damage leading to disruption in power distribution [1]. As a result, electric utilities have suffered financial losses and the lag in restoring power delayed the restoration of essential services and post-earthquake recovery. Lengthy power outages may potentially inflict significant economic damage on affected communities or whole regions. The recent earthquakes in New Zealand and Japan serve as representative examples of such failures as well as the challenges of the recovery efforts. The IEEE693 Working Group was formed in part to address the seismic vulnerability of such high voltage equipment and to formulate procedures for seismic qualifications of such equipment in the standard.

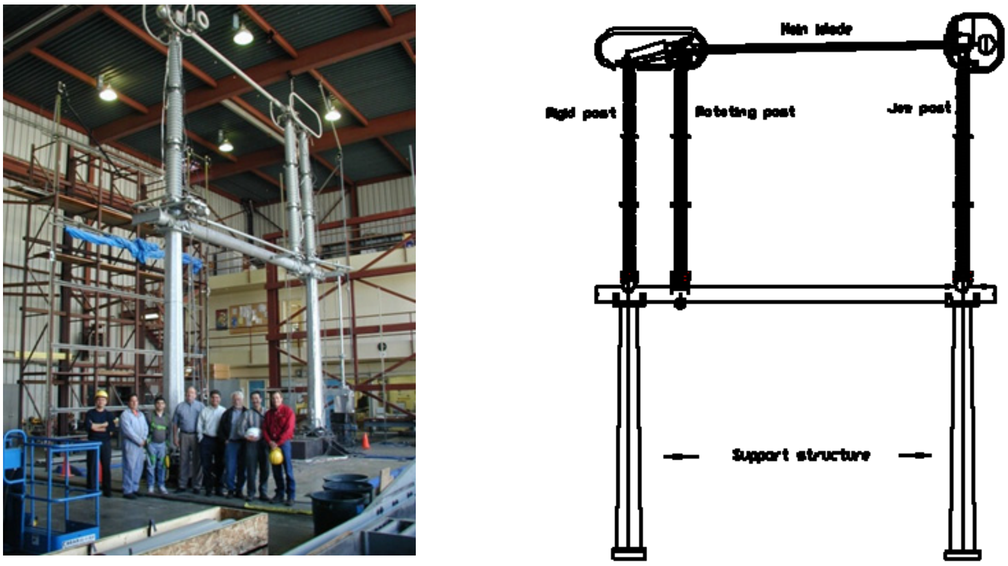
The current version of the IEEE standard covering the seismic qualification of substation equipment was published in 2006 [2]. The standard requires that equipment and components of higher voltage classes must be seismically qualified by multi-axial testing on earthquake simulators (shake tables). In general, equipment requiring shake table testing possesses vulnerable characteristics, such as massive tall insulators or other components that have historically performed poorly in earthquakes.

The IEEE693 Working Group is developing the next version of the standard and bases its requirements on the feedback received from open discussions with academia, utility companies, consulting engineers, and equipment manufacturers. The involvement of all interested parties in the development process of the standard has been proven to be very beneficial.

2 EQUIPMENT AND ITS SUPPORT STRUCTURE

Substation components or entire equipment assemblies are often installed on a supporting structure to provide structural integrity as well as achieve electrical clearance from the ground. Examples include: a disconnect switch on a support structure, bushings on top of a transformer, a circuit breaker on a supporting structure and many others. Since all equipment requiring shake table testing must be tested full-scale (preferably in the as-installed configuration), the feasibility of seismic qualification by testing can be limited by the capacity of a test laboratory. These limitations may include the clearance above the shake table, the footprint of the support structure and the equipment itself. The allowed payload of a shake table, displacement and velocity limits are also significant factors to consider. Utilities may often use support structures of their own design, and certain types of equipment may be installed with widely varying support configurations depending on functional needs.

To address these issues, the standard allows the testing of electrical equipment without a support structure under amplified strong motion that accounts for the effects of a support structure. Since no guidance on how that amplification has to be derived, there is some misunderstanding when it comes to testing equipment without a support structure. To some extend this approach is somewhat related to the sub-structuring idea when a system is subdivided into two or many components. These components are interacting with each other ensuring interaction of the components as parts of a coupled system. To achieve this interaction, all six degrees of freedom needed to be imposed at all interfacing nodes between the components. Since the majority of shaking tables can reproduce only three degrees of freedom, this approach is not conservative enough and can miss amplification coming from the remaining degrees of freedom. This shortcoming of this approach is discussed in this paper and is based in part on the extensive research program conducted on the 550-kV vertical break disconnect switch at the University of California, Berkeley as part of the Lifelines Program [3]. The switch was tested using many configurations, including the two major ones: main blade closed and main blade open. The latter configuration was tested with amplified strong motion obtained from the top of the support structure. The switch in closed configuration is presented in Figure 1. Later on, the same equipment was tested on three different support structures to investigate the effect of support structure with stiffer designs.



a) b)

Figure 1: Photo of 500-kV switch installed on shaking table (left) and its schematic drawing (right).

3 PHYSICAL PROPERTIES OF EQUIPMENT AND SUPPORT STRUCTURES

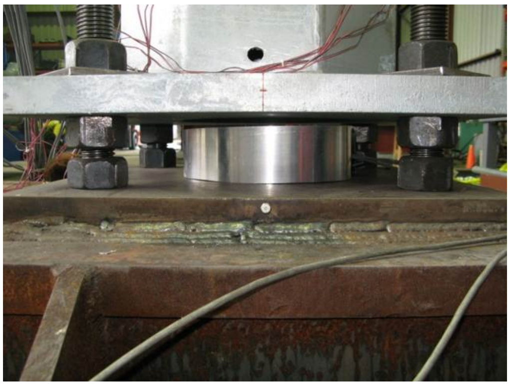
3.1 Support structure

In the recent years following study [3], several support structures were introduced into the investigation and the 500-kV switch was tested on three more support structures. All the support structures had a similar overall design and they consisted of two identical steel columns with octagonal cross sections. The columns were fabricated from 4.76 mm and 7.94 mm thick steel and were tapered as summarized in Table 1. As presented in the table, the distance between opposite flats of column, *D*, measured at its top and bottom, varied from column to column. This distance was incrementally increased to increase the stiffness of the support columns. Here, in *D*, also called AF (Across Flats) distance.

Support	*D* at base, m	*D* at top, m	Wall thickness, mm	Length, m	Reference
SA	0.445	0.305	4.76	4.29	[3]
SB	0.457	0.305	7.94	4.64	[5]
SC	0.508	0.406	7.94	4.64	[6]
SD	0.660	0.406	7.94	4.64	[7]

Table 1: Design details for each support column studied.

As a general practice, a support structure is installed on several anchors embedded into a concrete foundation. An exposed portion of the anchors is long enough to accommodate leveling nuts under the bottom plate of the support column as presented in Figure 2a. In some cases this space is packed with grout or left exposed as presented in Figure 2b. An earlier study [4] showed that the presence of grout under the support structure has a negligible effect on the stiffness of the support column and its natural frequency. Hence, the effect of grout is neglected in this study.



a) space left between bottom plate and foundation

b) the same space packed with a grout

Figure 2: Details of the support structure installation on the anchor rods

The difference between completely rigid installation of the column SA and installation with leveling nuts was also studied earlier [3] and summarized in Table 2. The table also presents a summary of natural frequencies obtained from a numerical analysis of other columns.

Support installation	Cantilever stiffness, kN/m	Frequency, Hz	Damping, %
SA: Rigid	972.0	15.4[1)]	0.5
SA: 8 D44.5 mm rods	796.8	NA	NA
SB	NA	13.6[2)]	NA
SC	NA	14.7[2)]	NA
SD	NA	19.6[2)]	NA

Notes: 1) measured in impact test; 2) estimated from the numerical models of the columns

Table 2: Measured structural response of support column.

3.2 Equipment Components: Insulators

A switch design varies from manufacturer to manufacturer. The switch considered in this study was assembled from several porcelain insulators installed on a tubular base of the switch (please refer to Figure 1b). Two insulators are structurally connected to each other to provide main functionality of the switch – to open and close an electrical connection between terminals of the switch. They're usually called rigid and rotating insulators depending on the function they perform. One terminal of the electrical connection is installed on this group and another terminal is installed on a stand-alone insulator (called jaw insulator). A blade is manufactured from a conductive material (aluminum in this case) and provides a flow of electricity when the switch is in a closed configuration. The structural performance of the switch is controlled by the design details of all its connections and strength capacity of the insulators. Increasing the strength of the insulators usually leads to an increase of the insulators' weight.

Since the switch design is under constant development and enhancement, the switch tested in this study had some variations from specimen to specimen. The enhancements of the switch design are aimed at strengthening the connections while utilizing insulators with greater strength (larger mass).

Structural properties of the insulators used in one of the switch designs tested earlier [3] are summarized in Table 3. The table presents the data obtained for the insulators rigidly fixed to a strong structural floor, so the frequencies and the stiffnesses represent physical properties of an ideal rigid installation.

Insulator	Cantilever stiffness, kN/m	Frequency, Hz
Rigid and Jaw	164.6	8.3
Rotating	162.9	8.2

Table 3: Measured structural properties of insulators (rigid installation).

3.3 Equipment Assembly

The switch without a support structure was studied in rigid and, so-called, flexible installation. The latter configuration simulated the flexibility of the support's top plate. A summary of this study is presented in Table 4.

Configuration	Direction	Frequency, Hz	Damping, %
Rigid	In-plane	3.9	1.0
	Out-of-plane	3.0	2.0
Flexible (flexibility of sup-port's top plate was simulated)	In-plane	3.4	2.0
	Out-of-plane	2.5	2.0

Table 4: Measured structural response of switch assembly without a support

3.4 Complete Assembly (Support and Switch)

A complete assembly of the switch will combine all the structural properties of each individual component into one interconnected and complex system. Since the attachment details of each component is quite different from an ideal rigid installation, the overall frequency and stiffness of the switch will be much lower than that of its individual components as presented in Table 5.

Direction	Cantilever stiffness, kN/m	Frequency, Hz	Damping, %
In-plane	87.6	1.7	1.0
Out-of-plane	218.9	2.6	1.0

Table 5: Measured structural properties of switch SW1 on Support SA

Other switches were studied in lesser detail and as such, only natural frequencies are summarized in Table 6.

Switch/Support con-figuration	Frequency in-plane, Hz	Frequency in out-of-plane, Hz
SW1 on SA (2003)	2.6	1.7
SW2 on SB (2011)	2.8	2.2
SW3 on SC (2013)	2.9	2.4
SW4 on SD (2014)	3.5	2.8

Table 6: Measured resonant frequencies of all systems

3.5 Complete Assembly Tested on Shaking Table

All the switches presented in Table 6 were tested on a shaking table to evaluate their seismic performance. One of the main performance parameters studied in this paper is a spectral amplification on top of the support structure. In many cases it serves as a good parameter, showing the frequency content of the energy passed to a switch installed on top of a support structure. A typical result is presented in Figure 3 that shows test results for SW2 and SW3 installed on support columns SB and SC, respectively. The spectral amplification peaks at the natural frequencies of the switch: 2.2 Hz for SW2 and 2.4 Hz for SW3. The plot presents results for out-of-plane direction of the switch in a closed configuration which was the most demanding for the switch.

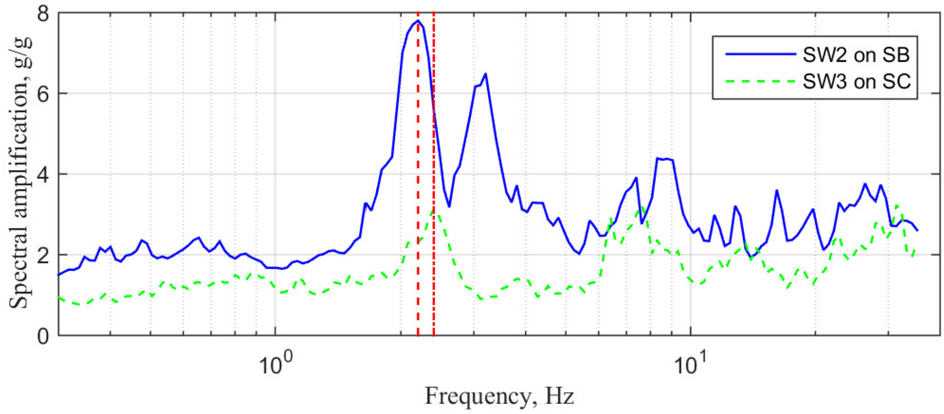


Figure 3: Spectral amplifications estimated from the accelerations recorded during shaking table tests (response on top of support structure versus input at the bottom of the supports)

4 THEORETICAL ESTIMATES AND FINITE ELEMENT ANALYSIS

4.1 Simplified Frequency Estimate for Tubular Columns of Support Structure

As a starting point, it was assumed that the structural performance of the support columns can be closely approximated by thin-walled cylindrical tubes with the same wall thickness as the support columns studied. In this case, the frequency of the column can be estimated from an analytical expression derived from the Euler–Bernoulli beam theory [8]:

$$f_n=(\beta_n)^2 sqrt(EI/\rho A)/(2\pi L^2),$$

where E is the Young modulus of the tube's material, I is the second moment of area of the beam's cross-section, A is the cross-section's area, ρ is the density of the tube's material, (β_n) is the factor obtained from the eigenvalue solution which is equal to 1.875 for the first frequency of a cantilever beam.

If the inner diameter is denoted by R_i and the outer radius of the tube is denoted by R_o, the following expressions can be obtained for I and A:

$$A = \pi(R_o^2 - R_i^2) \text{ and } I = \pi(R_o^4 - R_i^4)/4.$$

The latter equation can be simplified to the following:

$$I = A(R_o^2 + R_i^2)/4.$$

Hence, a change in radius of the tubular support, while keeping its height and wall thickness the same, will result in a new frequency $f_n^{(2)}$ that is related to the original frequency $f_n^{(1)}$ by the following expression:

$$f_n^{(2)}=sqrt((R_o^{(2)2}+R_i^{(2)2})/(R_o^{(1)2}+R_i^{(1)2}))\,f_n^{(1)},$$

where it is assumed that the radii of the tube charges from $R_i^{(1)}$ and $R_o^{(1)}$ to $R_i^{(2)}$ and $R_o^{(2)}$. In many practical applications, including the cases considered in the study, the wall thickness is much less than the radius of the tube. Ignoring terms of higher order, the last equation can be simplified to the following:

$$f_n^{(2)}=(R_o^{(2)}/R_o^{(1)})\,f_n^{(1)} \quad (1)$$

Hence, for a thin-walled tubular column the new frequency will be proportional to the ratio of the new radius to that of the original. Therefore, one of the first suggestions in the increasing frequency of the support structure would be the increasing radius of the support column as it was done in the experimental phase of this study. For example, a radius change from 0.222 m to 0.330 m will result in a 49% increase of frequency.

In opposite to that, increasing the height of the support structure leads to drop in the resonant frequency. From the equations provided above, this change will be proportional to the ratio of the heights $L^{(1)}$ *to* $L^{(2)}$ in the second power:

$$f_n^{(2)}=(L^{(1)}/L^{(2)})^2\,f_n^{(1)} \quad (2)$$

For example, a height increase from 4.29 m column to 4.64 m column will result in a 17% percent drop of the resonant frequency.

The combined effect of the height and radius variations on the frequency is presented in Figure 4.

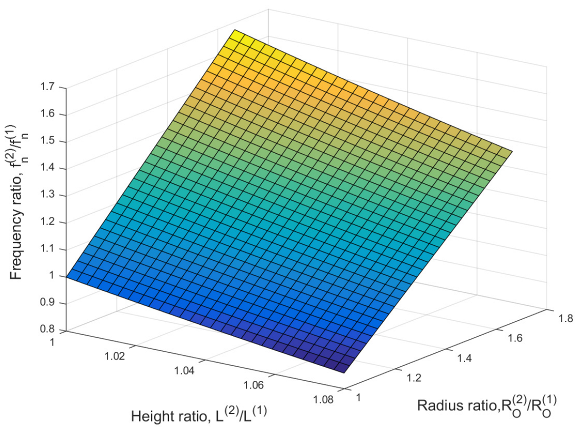
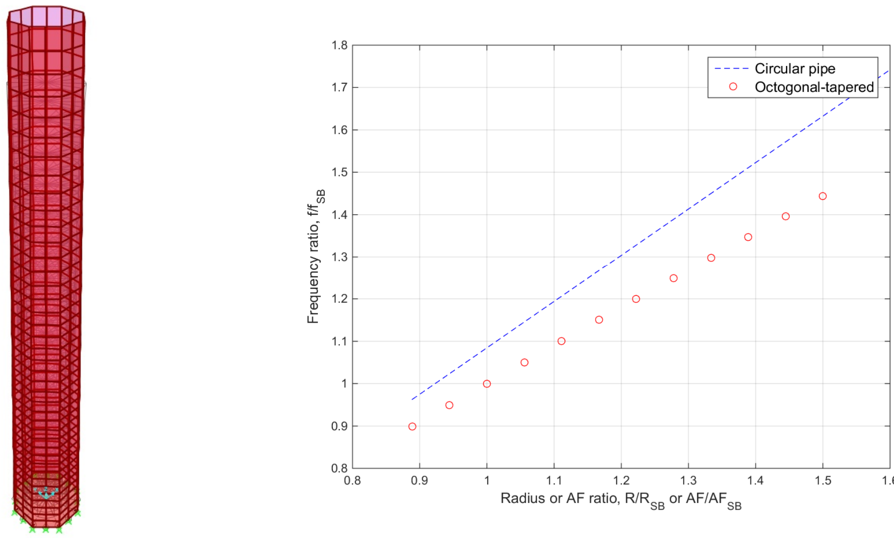


Figure 4: Combined effect of height and radius variation on resonant frequency of thin-walled tubular support column with constant wall thickness.

4.2 Finite Element Analysis of Tapered Columns

A number of finite element models of the tapered columns with octagonal cross sections were created as presented in Figure 5a. The models were generated by generating a mesh in Matlab [9] environment and running analysis in SAP2000 [10]. An extensive parametric study was conducted on a large set of tapered columns, a small subset of which, was represented by the columns used in the testing program. The natural frequencies of the models were compared against that of the straight circular pipe. The taper and the distance across the flats (AF) were varied independently from each other.

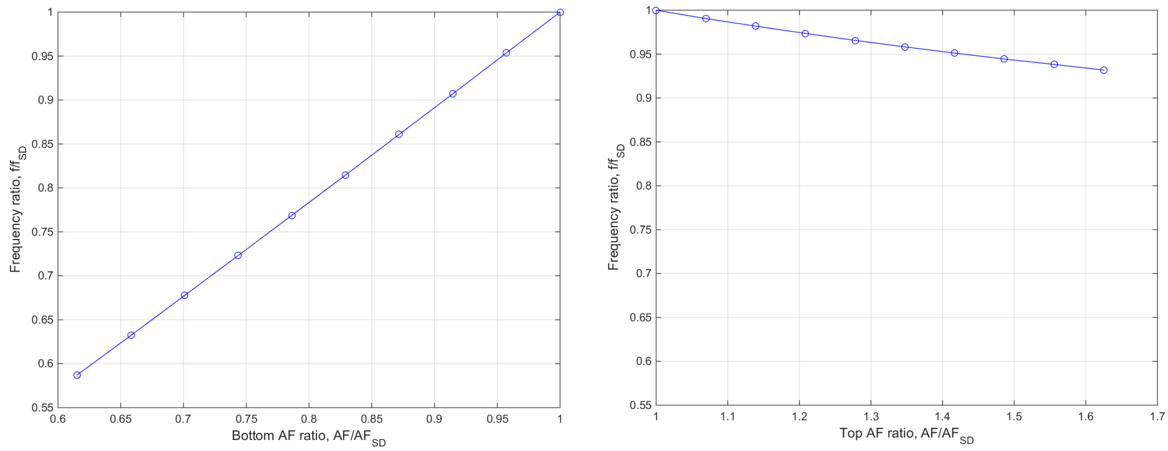
For the parametric study investigating the AF distance effect on the natural frequency, the columns length, its taper, and the wall thickness remained the same from model to model. A taper of column SB was selected as a benchmark. When the taper remains constant, the ratio of frequencies has almost linear relationship with the AF ratio as presented in Figure 5b. This type of a linear correlation between the frequencies and radii of the thin-walled circular columns was discussed earlier and can be closely described by Eq. 1. In the case of the tapered thin-walled columns, the natural frequency of the column is lower than that of the pipe with the same diameter as AF distance and the slope of the frequency change is less than that for the circular column. For example, a 50% increase in AF distance will result in about a 45% increase in the natural frequency (please refer to Figure 5b).



a) Typical FE model b) Relationship between frequency and AF ratio (red)

Figure 5: Comparative analysis for circular versus tapered-octagonal support column (taper is constant).

A taper of the octagonal columns also varied from the largest one studied (support SD) all the way to zero. The latter corresponds to a column with no taper. For this parametric study, the column length, AF distance on top or bottom, and the wall thickness remained the same from model to model. Column SD was selected as a benchmark. Figure 6a shows a significant frequency decrease when the top of AF is fixed and the bottom of AF is reducing. The latter fact is expected, since the second moment of the cross section's area will reduce dramatically at the bottom of the column when the bottom of AF is reducing. This will reduce the column's effective stiffness and natural frequency. It is quite opposite for the case when the cross section at the bottom of the column is fixed and top cross section is changing as presented in Figure 5b (vertical axes in Figure 6a and Figure 6b are in the same scale). These results on Figure 5b are less expected. A significant reduction in the top cross section (to AF is reduced by about 60%) results in only a 6-7% reduction of the natural frequency. This result demonstrates a clear advantage of tapered columns that were utilized in the design of the disconnect switch.

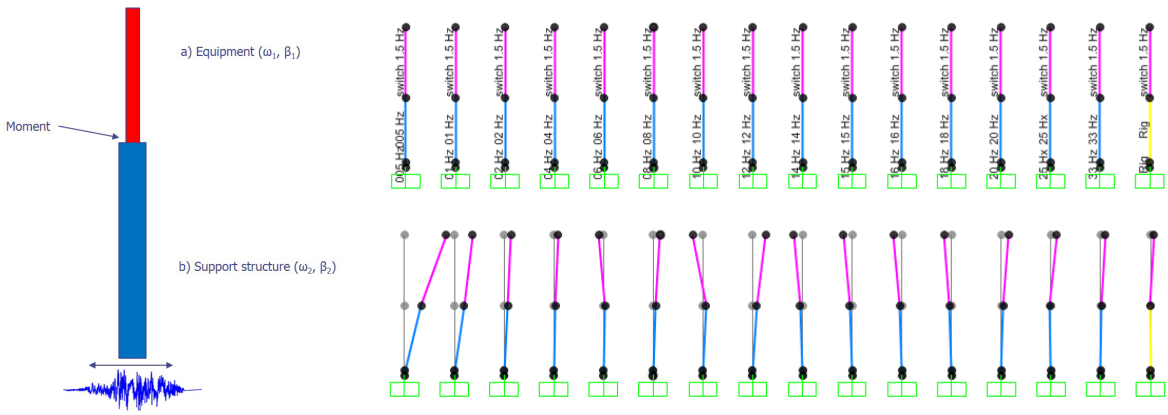


a) Top AF fixed and bottom AF is changing b) Bottom AF is fixed and top AF is changing

Figure 6: Comparative analysis on variation of column when taper changes from that of column SD to zero (no taper).

4.3 Finite Element Analysis of Complete Switch Assembly

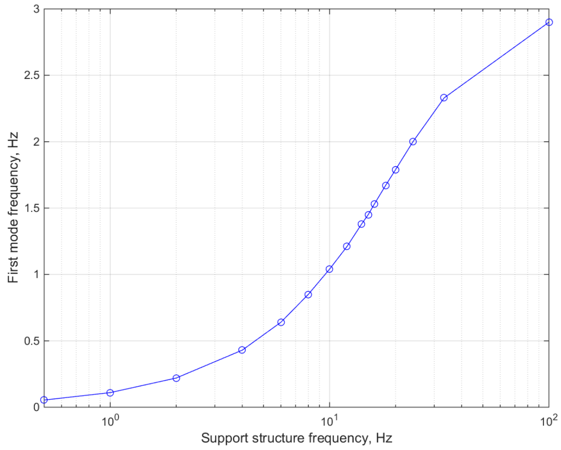
A parametric study on a number of switches installed on different support structures is conducted. The switch's complete assembly is simplified to two Euler–Bernoulli beams installed one on top of another. It is assumed that the switch is the one extensively investigated in [3] with natural frequency of 3 Hz (see Table 4). This beam model of the switch is installed on supports structures with natural frequency varied from 0.5 Hz (very flexible) to 100 Hz (essentially rigid) as presented in Figure 7.



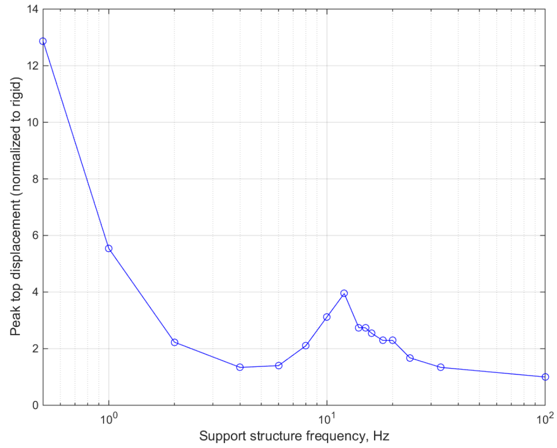
a) FE model of coupled systems b) Models studied (top) and deformed shapes (bottom

Figure 7: General approach followed for FE model generation of a switch as a coupled system

The overall frequency of the switch as a coupled system will depend on the frequency of the support structure as presented in Figure 8a. A peak displacement on top of the switch has a peak at 12 Hz support structure and drops down after that as presented in Figure 8b. This is consistent with the test results which also showed that the stiffer support structure is more beneficial for reducing spectral accelerations on top of the support structure (please refer to Figure 3) and for reducing peak displacements on top of the switch (as shown in Figure 8b). The variation of the peak moment at the bottom of the equipment from model to model is presented in Figure 9. In the case of equipment constructed with porcelain or polymer insulators, strain gages are usually installed at this location to estimate a moment at the bottom of the equipment and correlate it to the insulator's cantilever strength. Clearly, the moment can be minimized by selecting a correct support structure for each equipment and, as such, the seismic performance of the switch can be optimized by means of the proposed finite element analysis.

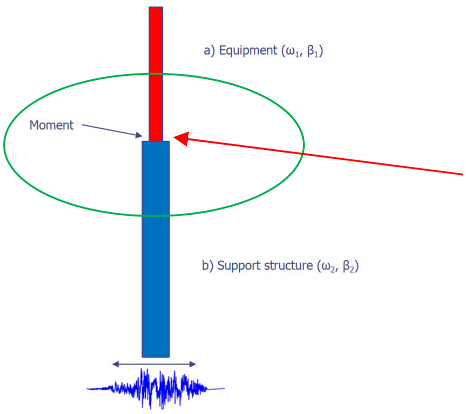


a) Overall frequency of coupled system

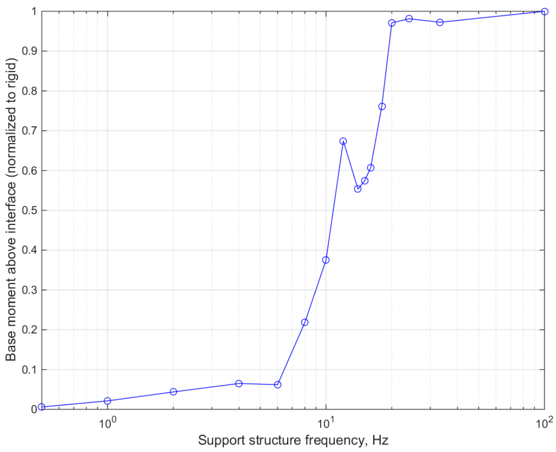


b) Peak displacement versus frequency of support structure

Figure 8: Variation of the system's overall frequency and peak displacement at top of the equipment from model to model



a) Moment at the bottom of the equipment can be correlated to cantilever strength



b) Peak moment at the bottom of the equipment

Figure 9: Variation of peak moment at the equipment's bottom from model to model

Similar conclusions about the feasibility of support structure optimization were made earlier in a hybrid simulation study investigating a coupled system consisting of a FE model of the support structure and a physical object (electrical equipment) [11].

5 CONCLUSIONS

- Similar to a theoretical prediction for a thin-walled cylindrical support column, a frequency of a tapered thin-walled octagonal support column linearly increases when the AF distance increases and it is independent of the wall thickness.
- The increasing taper of the thin-walled octagonal support column results in a relatively small decrease of the natural frequency. Hence, such columns are beneficial for use in support structures.
- Stiffer support structure reduces spectral accelerations on top of the support structure that results in smaller spectral amplifications.
- Stiffer support structures help to minimize peak displacements on top of the switch which is important for interconnected electrical equipment.
- Proper finite element analysis with well-calibrated models can help with optimization of the seismic performance of switches and other electrical equipment installed on support structures.
- The simplified analysis demonstrated the validity of the concept. A numerical analysis of more detailed switch models is required to reconcile test results with the analysis.

6 ACKNOWLEDGEMENTS

Acknowledgements are due to Southern States, LLC for providing access to the test data and sponsoring publication of the test results.

REFERENCES

[1] Eric Fujisaki, Shakhzod Takhirov, Qiang Xie, and Khalid M. Mosalam. *Seismic Vulnerability of Power Supply: Lessons Learned from Recent Earthquakes and Future Horizons of Research.* EURODYN 2014: 9th International Conference on Structural Dynamics, 30 June – 2 July 2014, Porto, Portugal.

[2] *IEEE693: IEEE Recommended Practice for Seismic Design of Substations.* IEEE, 2006.

[3] Takhirov, S., Fenves, G., and Fujisaki, E. (2005). *Seismic Qualification and Fragility Study of Line Break 550-kV Disconnect Switches.* Pacific Earthquake Engineering Research Center, University of California at Berkeley, PEER 2004/08.

[4] K.M. Mosalam, M.A. Moustafa, M.S. Günay, I. Triki and S. Takhirov. *Seismic Performance of Substation Insulator Posts for Vertical-Break Disconnect Switches.* California Energy Commission. Publication number: CEC-500-2012-XXX, March 2012.

[5] Shakhzod M. Takhirov. *Seismic Qualification Study of 550-kV Vertical Break Disconnect Switch, Report No. PEER – STI/2011-02.* Pacific Earthquake Engineering Research Center University of California, Berkeley, September 2011.

[6] Shakhzod M. Takhirov, *2013 Test Program of 500-kV Vertical Disconnect Switch Conducted for Two Different Support Structures. Short Memo/Report 2013/01.* Pacific Earthquake Engineering Research Center, February 2013.

[7] Shakhzod M. Takhirov. *Seismic Qualification Study of 550-kV Vertical Break Disconnect Switch, Report No. PEER – STI/2014-10*. Pacific Earthquake Engineering Research Center University of California, Berkeley, March 2014.

[8] S. Timoshenko, D.H. Young, W. Weaver. *Vibration Problems in Engineering. 4th Edition,* John Wiley & Sons, Inc., 1974.

[9] Matlab R2014b. The MathWorks, Inc., 2014.

[10] SAP2000 Version 16. Computers and Structures, Inc., 2015.

[11] Shakhzod Takhirov, Selim Günay, and Khalid Mosalam. *Real-Time Hybrid Simulation on a Long-Stroke High-Velocity Shaking Table Configuration as a Valuable Tool for IEEE693 Standard Development*, Transactions of SMiRT-22, San Francisco, California, USA - August 18-23, 2013.