Seismic Isolation of Electrical Equipment "Seismic Table Simulation"

K. Oikonomou, M. C. Constantinou & A. M. Reinhorn
University at Buffalo, the State University of New York, Buffalo, NY, USA

C. Yenidogan
Bogazici University, Kandilli Observatory and Earthquake Research Institute, (KOERI), Istanbul, Turkey

15 WCEE
LISBOA 2012

SUMMARY:
Efforts to develop seismic isolation systems for the protection of sensitive electrical equipment, with focus on transformers as critical components of a power network, are described herein. An experimental study was conducted on a scaled mock-up transformer model with high asymmetry in mass and layout incorporating a bushing on a flexible cover. Shake table testing was carried out for multi-axial excitations of various configurations, including different seismic isolation systems (LRB and reduced and full scale Triple FP bearings - reduced and full scale), symmetric and asymmetric installation of the bushing and variation in the isolator connectivity to the superstructure (friction and bolted connection). The effectiveness of isolation in enhancing the seismic response of the transformer under the different configurations tested is demonstrated through comparison with the non-isolated model response. Seismic isolation is proven efficient in reducing the structural response for a broad frequency range, indicating the potential for its use with a variety of electrical equipment.

Keywords: Asymmetry, Flexibility, Triple FP, LRB, Torsion

1. INTRODUCTION

Recent studies have shown that resilience in the aftermath of a catastrophic earthquake can be significantly impeded when operation of utility lifelines is interrupted. Power transmission and distribution systems are vital lifelines for the society and their failure can lead to major economic, safety and societal consequences. Power networks have undergone considerable damage during past strong earthquakes (1989 Loma Prieta, 1994 Northridge, 1995 Kobe, 1999 Izmit and Chi-Chi earthquakes), with direct losses in the range of hundreds of millions of dollars for each event and other collateral costs, including expenses for the replacement of damaged equipment and daily revenue losses owing to the loss of network functionality. Furthermore, economic and social activities, as well as post-earthquake recovery procedures suffered considerable delays in case of electrical power unavailability during blackouts.

Electrical transformers are structures essential for the performance of a power network. Their function is related to the modification of the voltage level, enabling electricity to be transmitted over long distances and economically distributed to communities. Transformers are typically equipped with one to several high voltage bushings, critical components for their operation. The inherently brittle nature of bushings, in association to the numerous failures observed in past strong motion events, render the electrical transformers seismically vulnerable. A typical electrical transformer is presented in Fig. 1. It basically comprises a flexible oil-filled tank with a variety of equipment attached to it. The total weight of the structure lies in the range of 100-500kip and can be distributed in a highly asymmetric fashion in plan and over the height of the transformer.

The bushings, mounted on the cover (roof) plate, are also connected to other electrical equipment as shown in Fig.1. As a result of connection to non-isolated peripheral equipment, the displacements at the top of each bushing must be limited to values that allow uninterrupted operation during earthquakes. Displacement values of less than 12” are considered acceptable for uninterrupted operation, however, higher values have been reported (Murota et al, 2006). Also, modifications of bushings to bus connections by allowing more slack can provide additional displacement capacity as discussed in Saadeghvaziri et al (2010).

Figure 1. Electrical Transformer

Seismic isolation of electrical transformers has been studied as means of protecting the equipment against damaging earthquakes, which typically induce large accelerations and result in fracture or dislocation and oil leakage of the bushings. Analytical and experimental research efforts have demonstrated that seismic isolation can be very beneficial to electrical equipment (Saadeghvaziri and Feng, 2001, Ersoy, 2002, Murota et al, 2006, Kong and Reinhorn, 2009 and Saadeghvaziri et al, 2010). Of particular interest is the work of Murota et al (2006) that involved shake table testing of seismically isolated transformers at reduced length scale of 1.67. Recorded accelerations in the isolated model were substantially less in comparison to the non-isolated model and isolator displacements of less than about 15” were recorded. However, the earthquake records used in the testing (PGA of 0.5g or less) did not represent strong earthquakes consistent with the Maximum Credible Earthquake (MCE) in areas of strong seismicity (California, Chile, Turkey, New Zealand) and the short frequency spectral content of the records was substantially less than what industry standards require in the US (i.e. the IEEE693 Recommended Practice for Seismic Design of Substations Standard). Accordingly, the measured isolator displacements were relatively small and within the capacity of transformers to properly function.

2. OBJECTIVES AND CONSTRAINTS OF CURRENT STUDY

Application of modern seismic isolation systems to electrical transformers presents several challenges due to the unusual structural characteristics of the equipment. The relatively small weight of the transformer prevents the use of elastomeric systems for isolation through significant shifting of the effective structural period, without compromising the vertical stability of the isolators. Additionally, the asymmetric mass distribution of the transformer and the high vertical stiffness of the tank could generate strong torsional response in isolation systems using elastomeric bearings. On the other hand, sliding systems are ideal for low weight applications as the effective period achieved can be independent of the supported weight. However, isolator displacements should be confined within prescribed limits in order to avoid overstressing ancillary equipment and cable connections.

Further complexities are introduced by the requirement for quick installation and removal of the equipment from the isolation system, during retrofit or maintenance, so that transmission of power is not interrupted for long periods of time. Isolators not connected to the equipment above but connected through friction at the isolator to equipment interface appear most desirable. Finally, location of transformers in high seismicity regions in addition to the requirements imposed by the IEEE693 standard for high spectral components in the low frequency range will result in large isolator displacement demands.

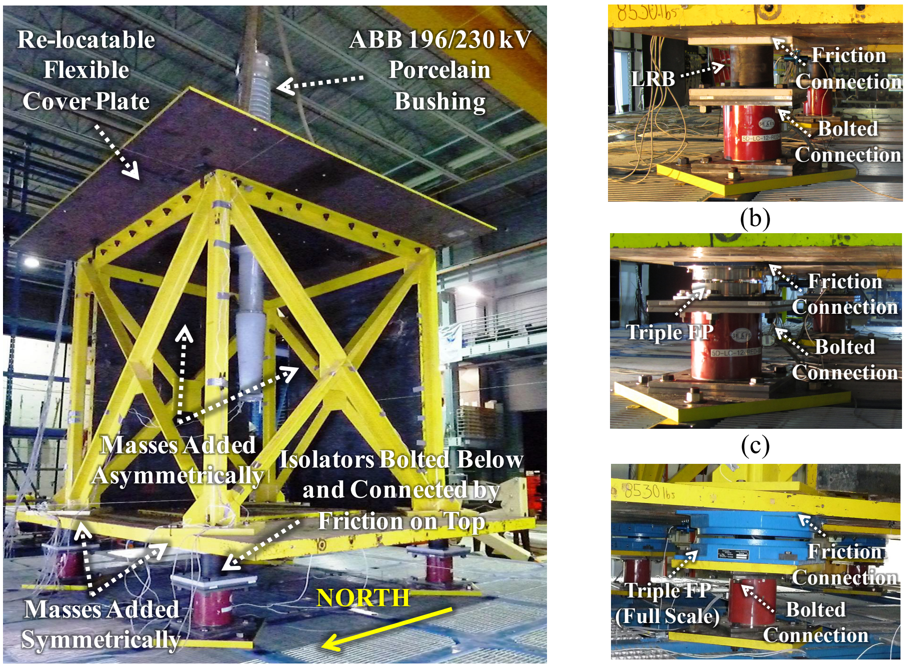
The objectives of the current study are (i) to develop seismic isolation system designs, appropriate for low weight, highly asymmetric structures and with displacements ideally less than 12” in strong seismic excitation and (ii) validate their efficiency through seismic table simulation. Based on the constraints identified above, stiff and highly damped Lead Rubber Bearings (LRB) and high friction Triple Friction Pendulum bearings (Triple FP) were selected. Presented herein are the seismic table simulations conducted for those isolation systems.

3. SEISMIC TABLE SIMULATION SETUP

A series of tests were carried out on shake table in order to investigate the effectiveness of the isolation systems selected. Testing was performed for a transformer model at reduced (length scale 1:3) and full length scale (length scale 1:1) under isolated and non-isolated conditions and a variety of structural and isolation system configurations. The model was developed considering appropriate asymmetry in mass distribution, allowance for symmetric and non-symmetric installation of bushing, appropriate flexibility at the bushing-mounting interface (flexible cover plate) and utilization of connection details that facilitate installation of the isolation system.

3.1. Transformer Model

The model developed for testing, approximately simulates basic characteristics of a 500kV transformer at a reduced length scale of 1:3. For that scaling, a 47kip weight model corresponds to a prototype of 425kip which is appropriate for a transformer in the 500kV range. The model (Fig 2) consists of an 8’x 8’x8’ rigid frame which comprises a flexible cover plate and an ABB 196/230kV bushing directly installed on the plate. It is noted that the flexible plate may be repositioned on the frame so that the bushing is installed either symmetrically as shown in Fig 2, or eccentrically. Data from previous experimental studies (Reinhorn *et al*, 2012) have demonstrated that the as-installed frequency of the ABB 196/230kV bushing on the plate is 11Hz. This is an acceptable value for simulating a 500/550kV bushing installed on the prototype transformer, as the frequency of the latter will be in the range of 4.5 to 13.3Hz.



(a) (b) (c) (d)

Figure 2. Transformer Model with Symmetric Bushing Installation (a) and Seismic Isolation Systems (b, c, d)

The weight of the model was increased to a value of 47 kip with the addition of four large steel plates, each of 8.6kip in weight. Asymmetric distribution of mass was simulated placing the two plates vertically on two adjacent sides of the frame, while symmetrically placed internal components in the transformer were simulated with two of the plates added below the frame horizontally.

3.2. Seismic Isolation Systems Tested

Three different isolation systems were used in the shake table simulations, namely, LRB (Fig.2b), Triple FP bearings in reduced (Fig.2c) and full scale testing (Fig.2d). Testing for all systems was performed using four bearings in total, installed underneath each frame column. The bearings were installed bolted to a multi-axial load cell at the bottom but connected through friction only at the top. The LRB testing was also performed with the bearings bolted both at the bottom and at the top. The LRB, used in reduced scale tests has characteristic strength of 2.2kip, elastic stiffness of 28.5kip/in and post-elastic stiffness of 1.5kip/in (Constantinou et al, 2007). The combined isolation system has a characteristic strength at 19% of the model weight and a period of 1.52 sec in prototype scale (based on the post-elastic stiffness). The Triple FP bearings, used in reduced scale tests have effective properties of $R_{1eff}=R_{4eff}=17.12$”, $R_{2eff}=R_{3eff}=2.09$”, $d_1^*=d_4^*=2.32$”, $d_2^*=d_3^*=0.52$”, $\mu_1=\mu_4=0.13$, $\mu_2=\mu_3=0.04$, as per the schematic of Fig.3 (Fenz and Constantinou, 2008). The isolation system has a characteristic strength at 13% of the weight and a period of 3.24 sec in prototype scale (based on the post-elastic stiffness). The large scale Triple FP bearings, used in full scale tests, have effective geometric properties of $R_{1eff}=R_{4eff}=36.50$”, $R_{2eff}=R_{3eff}=6.50$”, $d_1^*=d_4^*=6.55$”, $d_2^*=d_3^*=0.81$” as per Fig.3. Proper and stable frictional properties of these isolators under the small vertical loads expected, where achieved through lubrication of the isolators and extensive sinusoidal testing of the isolated structure. The characteristic strength of this system was obtained at approximately 10% of the weight and the period was calculated at 2.73 sec based on the post-elastic stiffness of the isolator.

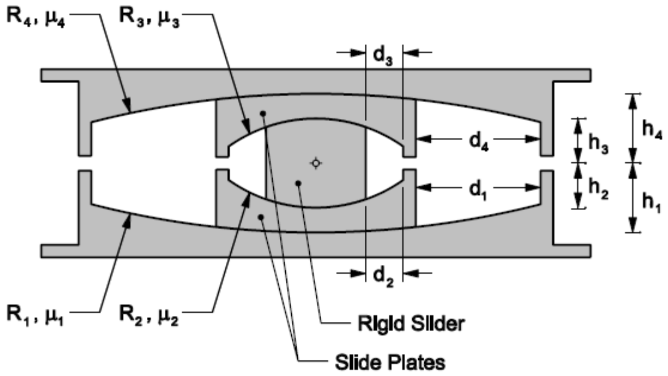


Figure 3. Schematic of Geometrical and Frictional Properties of Triple FP

3.3. Test Ground Motions

Testing was conducted under bi-axial (horizontal) and tri-axial excitation based on historic earthquakes and earthquakes scaled to represent a particular seismic hazard. Specifically, seven horizontal pairs of motions were scaled to represent in an average sense a particular site-specific response spectrum in California (1000-year return period with adjustment for near fault effects). The vertical components of these motions were spectrally matched to a vertical site-specific response spectrum. Fig.4 (right) demonstrates that the site-specific spectrum follows well the IEEE693 High Required Response Spectrum (RRS) for large frequencies but starts deviating from that for frequencies below 3Hz. The historic motion ensembles were amplified in magnitude in order to adequately match the low frequency range of the IEEE693 High RRS. In that case, the same scaling factor was applied in all three directions. Fig.4 (left) provides a comparison between the horizontal components of the scaled motions and the IEEE693 High RRS. Overall, many of the horizontal components of the motions used in the testing far exceed the IEEE693 High RRS in the frequency range of the bushings (high frequencies) and approximate well the low frequency tail of the IEEE693 spectrum down to frequencies of about 0.33Hz.

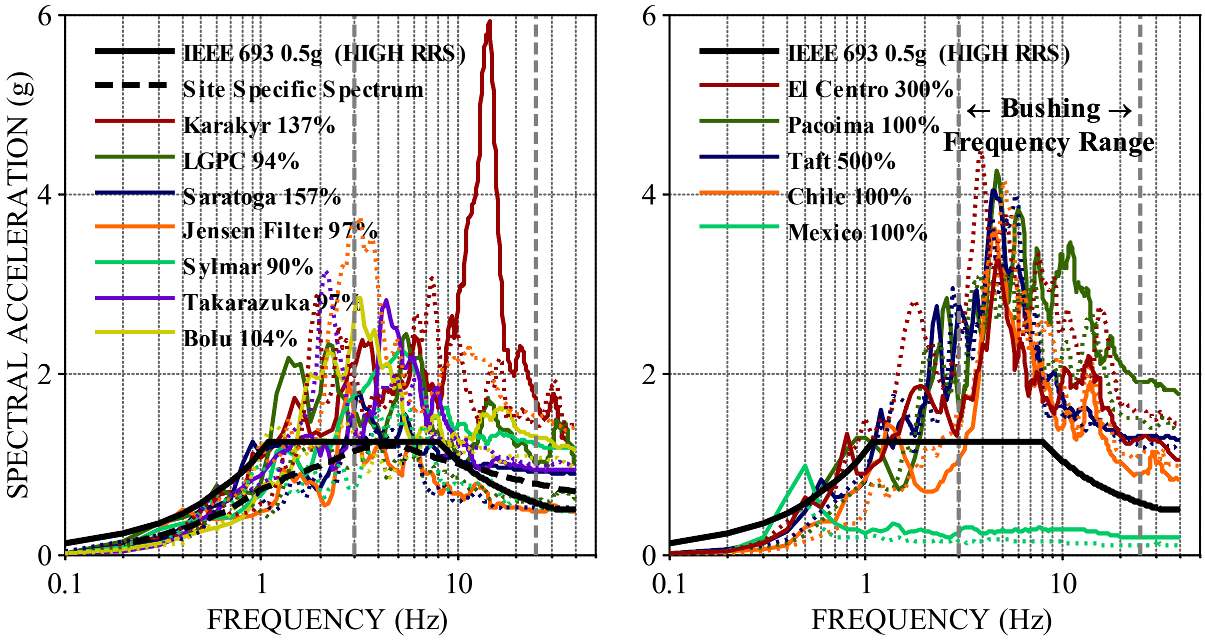


Figure 4. Response Spectra of Ground Motions Scaled to Represent the Site Specific Spectrum in an Average Sense (Left) and Historic Ground Motions (Right) as Achieved on the Shake Table (5% Damped)

4. SEISMIC TABLE SIMULATION RESULTS

4.1. Results from Reduced Scale Tests

The effectiveness of isolation in reducing the seismic demand on the transformer can be readily observed from direct comparison between the responses of the isolated and non-isolated cases tested. Fig.5 demonstrates response spectra in prototype scale, obtained from acceleration histories on the rigid frame under reduced scaled testing for fixed (non-isolated) and isolated conditions with Triple FP bearings, as well as the High RRS at that location as per IEEE693 (twice the High RRS).

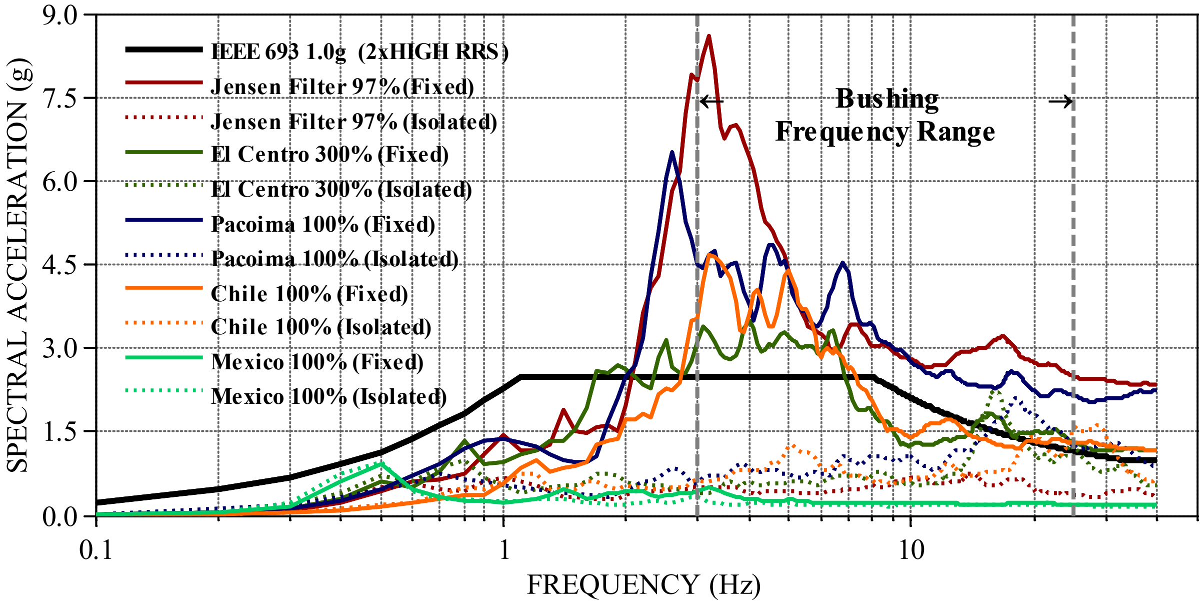


Figure 5. Response Spectra (5% Damped) at the Top of the Frame for Fixed and Isolated Conditions

The most adverse horizontal components from the motions selected are presented in Fig.5. It may be seen that isolation effectively "filters" the input accelerations and significantly reduces the demand on the transformer for frequencies above 0.3Hz, which coincides with the response frequency of the isolation system. It is noted that for some motions, uplift and rocking of the superstructure on the isolators was observed. Their effects are shown in the spectra in Fig.5 as an amplification in the high frequency range.

A comparison between the responses of the seismic isolation configurations tested and the response of the non-isolated (fixed) transformer model is presented in Fig.6. Shown on the left are the peak accelerations recorded over the height of the model in the NS direction for three isolation configurations tested at reduced scale, in comparison to the peak values obtained from the fixed base testing. It is noted that testing of the fixed structure was performed at lower amplitude due to shake table limitations and results herein are presented extrapolated. It may be seen that significant reduction of accelerations of the fixed model was achieved for all the isolation systems investigated. More specifically, a significant cut-off in the peak ground (shake table) acceleration was succeeded directly above the isolation level (frame bottom) for all isolation systems, while some amplification occurred between the top of the frame and the top of the bushing due to the cover plate flexibility. Despite that amplification, the accelerations at the top of the bushing for any of the proposed isolation systems tested were reduced by at least a factor of 3 with respect to the non isolated cases, provided that the isolators did not reach their displacement limits and the bushing was symmetrically installed.

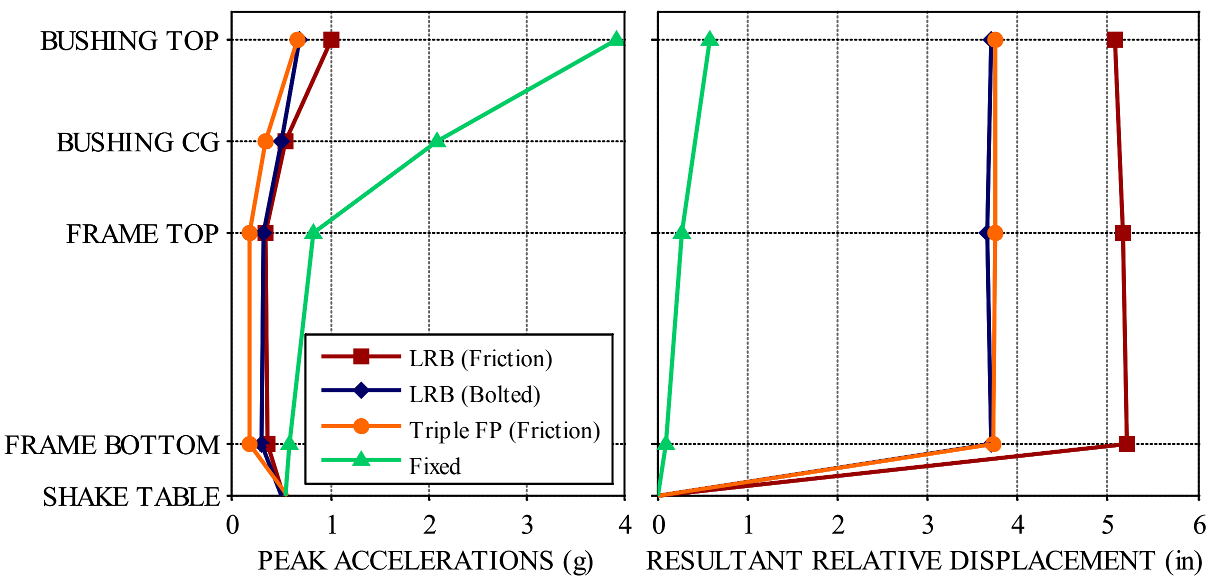


Figure 6. Peak Accelerations (NS Direction) and Resultant Displacements for Isolation Systems Tested (Saratoga 157% of Original, 2D Horizontal, Bushing Symmetrically Installed)

An increase in displacement of the isolated system is presented in Fig.6. For the case in which connection to the superstructure is achieved through friction, large displacements are largely attributed to extensive and cumulative sliding of the structure on the LRB isolation system. Measured (average) displacements in the isolation system were in the range of 3” to 4”, while average fixed base system displacements measured at the top of the bushing were in the order of 1”. When extrapolated to the prototype scale, the isolator displacements are expected to be in the range of 9” to 12”, which is within the constraints of the current study.

4.2. Effect of Mass Asymmetry in System Response

An important feature in the experiments conducted is the simulation of highly asymmetric mass distribution which is typically observed in commercial transformers. Asymmetry in the experimental model achieved through the connection of the two massive vertical plates on two adjacent sides of the rigid frame, resulted in an eccentricity between the center of mass and the center of rigidity of the superstructure of about 10% of the frame plan dimensions in each direction.

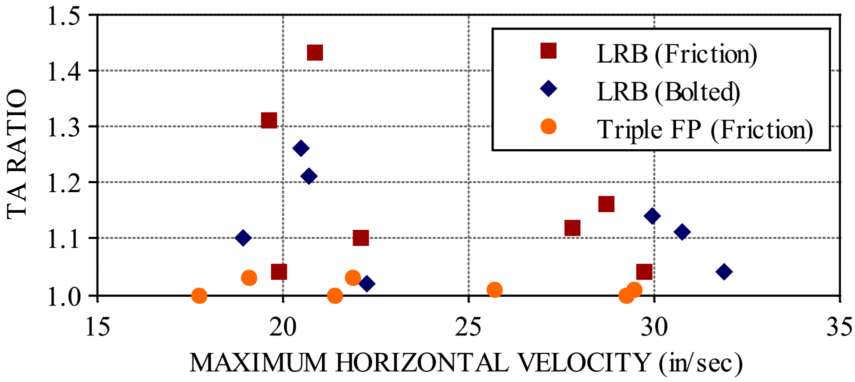


Figure 7. TA Ratios for Various Systems Tested Under the Same Motion Ensemble (Reduced Scale Testing)

In order to quantify the effect of mass eccentricity in the response of each isolation system used in the shake table simulations performed, a torsional amplification (TA) ratio was defined as the ratio of the maximum resultant displacement of the frame bottom corners (pedestals) to the maximum resultant displacement at the center of the base (both measured relative to the shake table). The TA ratio is demonstrated in Figure 7, for three isolation schemes tested, as a function of the maximum horizontal velocity. The results are presented for testing with an ensemble of motions was scaled to the site specific spectrum. It can be observed that the LRB system exhibits strong torsional response for both installation configurations (frictional and bolted connection) tested. On the other hand, the Triple FP system was practically insensitive to torsion with a TA ratio ranging from 1.00 to 1.05.

Isolation systems based on friction (i.e. the Triple FP bearings), have the natural property of adapting their behavior in accordance to the variation of the axial force on their components. Namely, any asymmetric distribution of vertical load on the isolators due to mass eccentricity in the superstructure will result in the Triple FP bearings adjusting their stiffness characteristics. Provided that the coefficients of friction are similar for all the isolators used (as is the case for the present study), the center of rigidity and the center of mass of the isolated structure tend to coincide, thus eliminating irregularities in mass distribution. Lead Rubber bearings are weight-independent and maintain a fixed center of rigidity. In such systems, high mass asymmetry is expected to produce inevitably highly asymmetric distribution of load and strong torsional response. An important characteristic of the LRB is that they are stiff systems with large self centering capability. Thus, in a configuration where sliding at the top of the LRB is permitted, the bearing is very likely to self-center (snap-back) once its vertical load is reduced so that the restoring force surpasses the friction force. When the Triple FP system is subjected to the same conditions, self centering due to small vertical loads is not an issue as the lateral restoring force of the bearing is negligible (directly proportional to the vertical load).

Figure 8. Cumulative sliding over the NW LRB isolator

When LRB were connected to the superstructure through friction, all of the isolators experienced snap-back during testing and maximum sliding of up to 4.5” was recorded on the isolation interface

(NW isolator). Sliding, though beneficial to the stability of the bearings, becomes critical after a number of earthquake simulations, as residual displacements are accumulated (Fig. 8) and manual recentering is required so that the stability of the superstructure is not lost.

A comparison between the force displacement loops obtained for the bearing at the same location, for the system bolted to the superstructure and the system connected only through friction is also provided (Fig. 9). It is noted that the displacement presented is measured relative to the top plate of the bearing and the shake table. It can be observed that due to the friction and self-centering of the LRB during testing, the isolator displacements and forces are bounded as compared to the ones obtained from testing of the bolted LRB.

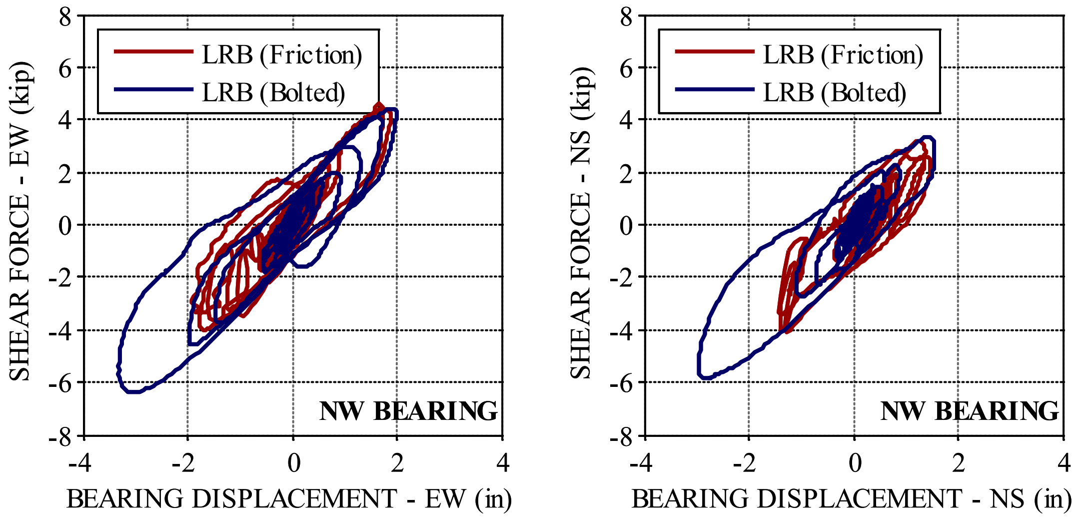


Figure 9. Comparison of Force-Displacement Loops in EW and NS Directions for the NW LRB Isolator Bolted and Connected to the Superstructure through Friction (Saratoga at 157% of Original, 2D Horizontal Excitation)

4.3. Effect of Cover Plate in the Bushing Response

The effect of the flexible transformer cover (see Fig. 2) on the dynamic response of the bushing has been indicated by several analytical and experimental studies in the past. More particularly, the frequency of the bushing when installed on the cover plate is significantly reduced as compared to the corresponding fixed base frequency. The frequency reduction is a function of the plate flexibility and the location of installation of the bushing on the plate. Table 4.1 presents the identified natural frequencies for the two different bushing mounting locations tested, as well as the fixed base of the bushing as measured in a previous experimental study (Reinhorn *et al*, 2012).

Table 4.1. High Voltage Bushing Frequencies

Boundary Conditions	Frequency (Hz)	
	North-South	East-West
Fixed	25.0	25.0
As-installed (Center of Cover)	10.5	10.9
As-installed (Side of Cover)	12.5	9.6

The comparison in Fig.10 between the responses of the non-isolated model and the model isolated with Triple FP at reduced scale, non-symmetrical installation of the bushing on the cover plate and tri-axial testing conditions, demonstrates the enhanced structural performance of the isolated transformer for all ground motions tested (fixed model results shown extrapolated from testing at reduced amplitude). It is noted that in some of the isolated model simulations, uplift and rocking was observed which amplified the bushing response in addition to the vertical input.

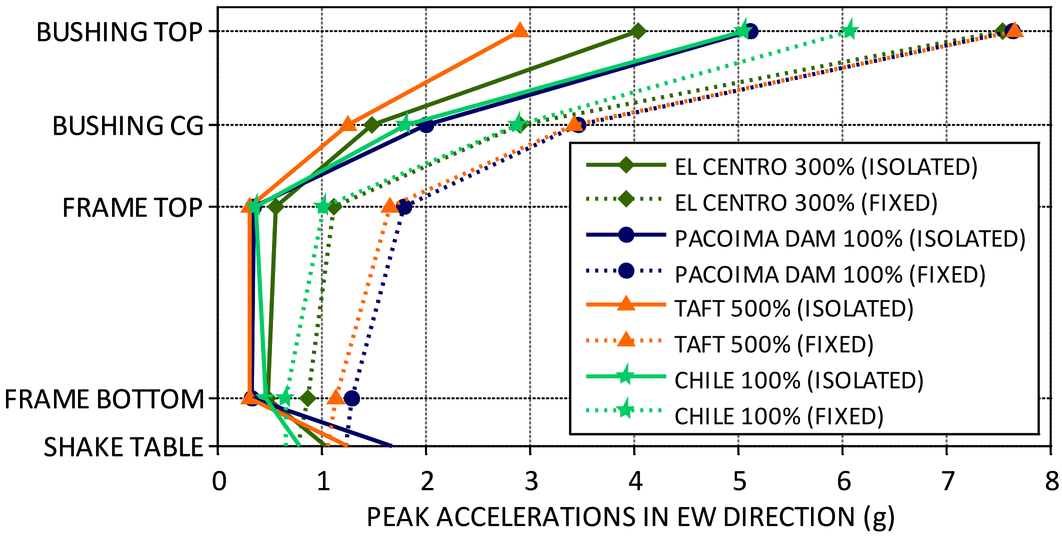


Figure 10. Peak Accelerations (EW Direction) for Tri-axial Testing, Reduced Scale Triple FP Isolators and Non-symmetrical Installation of the Bushing

The effect of the cover plate on the bushing response is better illustrated in the results of Table 4.2, obtained from biaxial and triaxial testing of the full scale transformer model, for installation of the bushing on the center and side of the cover. It is noted that no uplift or sliding between the bearing and the superstructure was monitored during testing. As can be directly inferred from the data presented, the response of the bushing when mounted on the side is larger as compared to the case when the bushing is symmetrically installed on the cover. Furthermore, when the bushing is installed on the side of the cover and subjected to tri-axial excitation, the response is amplified considerably, especially in the East-West direction which is the direction of the bushing installation eccentricity from the center.

Table 4.2. Full Scale Bi-axial and Tri-axial Testing Results for two Mounting Locations of the Bushing

Excitation	As-Installed Location	Directions of Motion		Peak Table Response		Peak Superstructure Acceleration (g)		
				Accel. (g)	Vel. (in/sec)	Frame Top	Bushing Bottom	Bushing Top
Pacoima Dam	Side	3D	EW	1.29	22.52	0.23	0.23	1.98
			NS	0.84	18.93	0.18	0.21	1.33
			Z	0.63	11.00	0.65	0.58	0.79
		2D	EW	1.30	23.47	0.16	0.18	0.81
			NS	0.93	17.80	0.12	0.13	1.09
			Z	0.07	1.16	0.09	0.19	0.25
	Center	3D	EW	1.25	23.80	0.22	0.20	0.99
			NS	0.91	18.22	0.17	0.25	1.09
			Z	0.62	11.67	0.70	0.90	1.20
		2D	EW	1.26	23.83	0.16	0.16	0.59
			NS	0.92	17.99	0.13	0.14	0.87
			Z	0.07	1.15	0.14	0.25	0.30

Past experimental studies have demonstrated that eccentricity in the as-installed location of bushings on flexible plates generates coupling in their vertical and rotational dynamic properties (Kong, 2010). In the present study, coupling occurs in the direction of eccentricity (EW) and the acceleration response is significantly amplified due to the effect of the vertical input to the bushing response. Some amplification also occurred for the tri-axial excitation of the structure with the bushing installed symmetrically, though this should be attributed to accidental eccentricities in the plate-bushing system. Based on the above results, and despite the satisfactory performance of the isolation demonstrated in the reduced scale testing, it can be argued that the inability of the Triple FP system to filter the vertical ground motion input may reduce its ability to effectively protect sensitive electrical equipment.

5. SUMMARY OF STUDY AND CONCLUDING REMARKS

The current study develops seismic isolation systems suitable for practical application in the protection of electrical equipment. The paper presents the shake table simulation performed in order to validate the effectiveness of the systems developed. Lead Rubber and Triple FP isolators were investigated through shake table testing of a model representative of a typical electrical transformer with a bushing on its cover. The experimental results obtained, demonstrate the effectiveness of the selected systems in reducing the seismic demand in the superstructure in comparison to the non-isolated case. The main observations from the simulations performed are summarized below:

1. Substantial reduction of the horizontal input was achieved at the level above the isolation studied here. Isolation acts as a filter between the ground and the superstructure, reducing the input for a wide range of frequencies. This result indicates the potential of seismic isolation for application in the protection of a wide variety of electrical equipment.
2. All configurations (LRB, Triple FP friction-connected and LRB bolted to the superstructure) resulted in similar average reduction of acceleration response at the top of the bushing by more than 70% for symmetric installation of the bushing on the cover.
3. Displacements between 2”-4” were measured in the reduced scale isolated model, while displacements of 5”-11” were measured for the full scale tests, well within the design constraints.
4. Mass eccentricity generated large torsional response in the LRB system, for both configurations (bolted and friction-connected to the superstructure). When the LRB were installed through friction, the structure experienced permanent residual displacements due to sliding. Sliding of the in case of Triple FP bearings was negligible, due to their adaptability for vertical load variations.
5. The cover flexibility amplified the bushing response. Amplification is significant when the bushing is eccentrically installed and excited vertically. Though not effective in reducing the vertical input, seismic isolation achieved considerable reduction in the bushing response in comparison to the fixed base case.

ACKNOWLEDGEMENTS
Financial support for this study was provided by the Bonneville Power Administration, Vacouver WA, USA. The seismic simulation testing was carried out at the SEESL laboratory at the University at Buffalo.

REFERENCES

Murota, N., Feng, M.Q. and Liu, G.Y. (2006). Earthquake Simulator Testing of Base-Isolated Power Transformers. *IEEE Transactions of Power Delivery*, **Vol. 21**, No. 3, July, 1291-1299

Saadeghvaziri, A.A. and Feng, M.Q. (2001). Experimental and Analytical Study of Base-Isolation for Electric Power Equipments. *MCEER Volume on Research Progress and Accomplishments*. **2000-2001**,29-40.

Ersoy, S. (2002). Seismic Response of Transformer Bushing Systems and their Rehabilitation Using Friction Pendulum System. Ph.D. Dissertation, New Jersey Institute of Technology, Newark, NJ

Kong, D. (2010). Evaluation and Protection of High Voltage Electrical Equipment Against Severe Shock and Vibrations. Ph.D. Dissertation, University at Buffalo, Amherst, NY

Saadeghvarizi, A.A., Feizi, B., Kempner Jr., L. and Alston, D. (2010). On Seismic Response of Substation Equipment and Application of Base Isolation to Transformers. *IEEE Transactions of Power Delivery*. **Vol. 25**, No. 1, Jan., 177-186.

IEEE Power Engineering Society (2006). IEEE Recommended Practice for Seismic Design of Substations, Standard IEEE-693

Reinhorn, A.M.; Filiatrault, A., Fahad, M., Kong, D., Koliou, M., Oikonomou, K., Oliveto, N. and Schiff A. (2012). Evaluation of the Seismic Performance of High-voltage Transformer Bushings. California Energy Commission. Publication number: CEC-XXX-2012-XXX.

Constantinou, M.C., Whittaker, A.S., Kalpakidis, Y., Fenz, D.M. and Warn, G.P. (2007). Performance of Seismic Isolation Hardware under Service and Seismic Loading. Report No. MCEER-07-0012, Multidisciplinary Center for Earthquake Engineering Research, Buffalo, NY, USA

Fenz, D.M. and Constantinou, M.C. (2008b). Mechanical Behavior of Multi-spherical Sliding Bearings. Report No. MCEER-08-0007, Multidisciplinary Center for Earthquake Engineering Research, Buffalo, NY.