Ninth Canadian Conference on
Earthquake Engineering
Ottawa, Ontario, Canada
26-29 June 2007

ADVANTAGES AND CONSIDERATIONS IN APPLICATION OF BASE-ISOLATION TO SUBSTATION TRANSFORMERS

M. Ala Saadeghvaziri[1], N. H. Allaverdi[2], L. Kempner Jr.[3], B. Feizi[2]

ABSTRACT

This paper presents seismic performance of electric substation transformers and discusses advantages and considerations in the use of base-isolation as a viable hazard mitigation option. Substation transformers and bushings are the most critical elements within the power delivery system and their performances during past earthquakes in the US and abroad have not been satisfactory. Finite element analyses indicate that interaction between these two critical elements has a significant effect on seismic vulnerability of substations. In light of dynamic characteristics of this equipment, base-isolation can be very effective in mitigating this adverse interaction. Furthermore, due to high-inertia reduction, base-isolation can also have beneficial effects on long-term longevity of transformers and on foundation performance during seismic events. Larger displacement demand and uplift, however, are issues that must be considered in the application of base-isolation. Through an actual case study (433.3 MVA transformer in a high-voltage substation) design concepts will be investigated that will demonstrate larger displacement can be accommodated; and that considering transformer geometry, peak ground acceleration, amount of inertia reduction and isolator's friction coefficient for this transformer uplift is not an issue.

Introduction

Functionality of electric power systems is vital to maintain the welfare of the general public, to sustain the economic activities and to assist the recovery, restoration, and reconstruction of the seismically damaged environment. One of the most important components of electrical power systems is substation, which serves several key functions such as providing protection to transmission and distribution lines, transfer of power between different voltage levels through the use of power transformer and reconfiguration of the power network by opening of the transmission lines or partitioning multi-section busses. Transformers have been identified as one of the most critical component in a substation. Bushing is another key equipment in a substation that is vulnerable to earthquake ground motion. Experience gained during past earthquakes combined with recent research investigations (ASCE, 1999, Ersoy 2002, and Gilani, 1999) has identified several important modes of damage/failure in a substation. These include: failure/damage to transformer and bushing due to their interaction, sliding and turn over of transformers, foundation settlement, and damage/failure of peripheral attachments. Another possible and critical mode of failure is damage to internal components in a transformer. These are briefly discussed in the following sections.

Furthermore, effectiveness and viability of an advanced base-isolation technology, Friction Pendulum

---

[1] Professor, Dept. of Civil Engineering, New Jersey Inst. of Tech, Newark, NJ 07102
[2] Graduate Research Assistance, Dept. of Civil Engineering, New Jersey Inst. of Tech, Newark, NJ 07102
[3] Principal Structural Engineer, Bonneville Power Administration, Portland, OR 97208

System (FPS), as a mitigation measure for power transformers is discussed. FPS is capable of reducing the inertia forces significantly, alleviating many problems associated with seismic performance of transformers and bushings. Lower loads means not only better seismic response for transformer and bushings, but also lower forces need to be transferred to the foundation resulting in more economical foundation and connections. Furthermore, shaking of transformer internal components will be minimized, thus, preventing possible adverse affect of ground motions on transformer electromagnetic performance and its longevity.

Larger displacement demand and uplift, however, are issues that must be considered in application of base-isolation. Currently, through collaboration with Bonneville Power Administration (BPA) actual transformers are used in case studies to determine the possibility of using base-isolation by determining if larger displacements can be accommodated without any adverse effect on transformer electrical and structural performance. Furthermore, effectiveness of base-isolation can potentially be compromised by uplift and subsequent impact due to overturning moment or rocking. Using governing sliding-rocking principals and actual transformer spatial characteristics this issue is also being considered. This paper presents preliminary results on these case studies.

The Need for Application of Base-Isolation

Past Performance

Recent work have revealed that understanding the seismic interaction among key equipment of a substation (transformers, bushings, foundation, and interconnecting elements) is critical to proper assessment of seismic performance of substations and in qualification of electrical equipment. Response of three different substation transformers and their interaction with the bushings was the subject of a comprehensive analytical study by Ersoy (2002, 2004), using 3-D finite element method and time history analyses. It is observed that the translational modes of transformers have the highest participation in the response at the top of the transformers. Failure of transformer tank was not found in the finite element analyses, assuming adequate anchorage can be provided. However, since the base forces are so high, providing proper anchorage is a challenge. The implementation of well-designed anchorage for retrofit of existing transformers can be difficult and costly. Furthermore, in many situations, for both new and existing transformers, a well-designed anchorage may only change the mode of failure to the foundation. Boundary gaps due to back and forth motion of transformers and rocking of transformers and their footings due to soil-structure interaction have been observed during the past earthquakes (ASCE, 1999). To these one should add the counterintuitive behavior reported by Makris and Zhang (Makris, 2001) that, “although for most of the frequency range anchored blocks survive higher accelerations than free-standing blocks, there is a finite frequency range where the opposite happens.” Furthermore, Makris and Black (Makris, 2002) have shown that when an anchored equipment stretches it restraints the reaction at the pivot point can be as high as or slightly higher than 2mg. This substantial increase in the vertical reaction must be considered in the design of the foundation base. That’s more than twice the weight of the equipment.

Finite element results indicate that transformer tank flexibility affects bushing dynamic characteristics significantly, and that the effect is mainly due to the flexibility of the top plate. As a general tendency, the translation mode of the transformer affects the input into the bushing by filtering the motion and causing higher mode to be excited, and by lowering the bushing fundamental frequency where it is closer to high energy zone of the record. The level of accelerations in the bushings is much higher than that predicted based on IEEE 693 (1998). For the three cases considered the ratio of time history results to IEEE 693 was 3 to over 6. Note that the IEEE 693 case refers to a situation where the bushing is analyzed while fixed at its base, however, the input is doubled (to a PGA of 2.0g) to account for transformer flexibility per the guidelines. This could be one of the reasons for the discrepancy between bushings’ poor performance during previous earthquakes (Fig. 1) and their good to excellent performance under laboratory tests when supported on a rigid frame.

Figure 1. Bushing failure at the flange gasket (ASCE, 1999).

Internal Design of Transformers

Optimal electrical performance requires boltless design of core, which consists of sheets of steel laminations. This requires a high degree of design sophistication to ensure that adequate structural strength and rigidity are provided. Fault and gravity forces have so far determined the design stresses. Seismic forces can have adverse effect on internal packaging that can impact long-term performance of transformers. A challenge to quantifying this is that inspection of internal components after an earthquake is not conducted. However, there has been reportedly unexpected loss of transformers in the years following past earthquakes that can be attributed to sustained internal damage during these events and loss of longevity. It should be noted that design of transformers are proprietary and available data is very scarce. This is further compounded by the lack of uniqueness in transformer design. Thus, a challenge in quantifying impact of earthquake ground motion on internal packaging has been always collecting reliable design information on internal packaging of substation transformers. Nevertheless, based on study of the structure and design of internal components using limited general literature available, site visits to inspect an opened transformer, and discussions with technical staff of several utility companies along with limited information from past performance under earthquakes Saadeghvaziri, et al. (Saadeghvaziri, 2004) have qualitatively identified possible modes of damage to be: sliding of key spacers, loss of close fitting tolerances between limbs and yokes, and flexural and rocking of core-frame system are identified as the most critical ones. The flexural and rocking mode of response can indeed be very important due to slenderness ratio of typical transformer. The use of base-isolation is a viable technique to remedy these possible modes of damage to internal elements in transformers.

Foundation Forces

Transformers are very heavy equipment and in high seismic regions they can be subject to enormous forces that can cause damage to the transformer and foundation supports. Fig. 2 shows a damaged transformer from the Izmit, Turkey Earthquake in 1999 (EERI, 1999) from support failure. Boundary gaps due to back and forth motion of transformers and rocking of transformers and their footings due to soil-structure interaction have been observed during past earthquakes (ASCE, 1999). Therefore, in many cases the use of base-isolation for transformers may be the only suitable remedy to alleviate these problems, especially for existing transformers in high seismic regions.

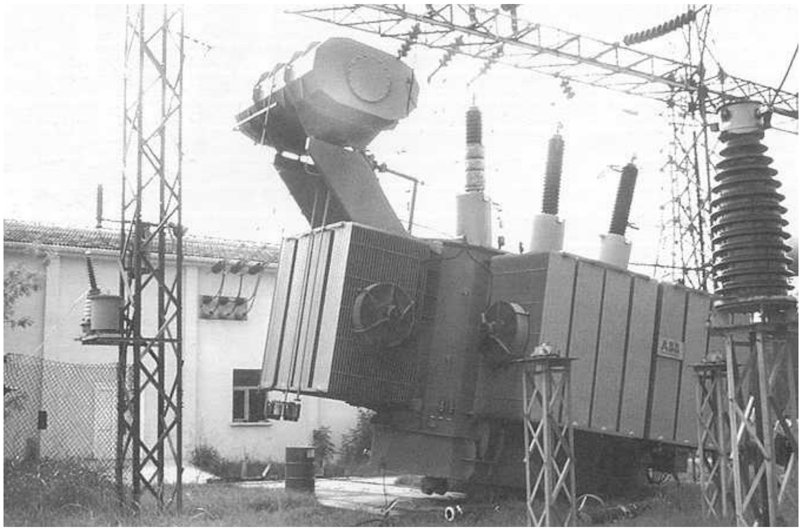

Figure 2. Damage to a transformer cused by support failure (EERI, 1999).

Base-Isolation Viability

Friction Pendulum System

Seismic isolation is a simple structural design approach to mitigate or reduce potential earthquake damage. The general idea in base isolation is to partially separate the base of the structure from the ground movements, thus, limit the amount of excitation and force absorbed by the structure. Friction Pendulum System (FPS) is a very effective system among the frictional systems used for seismic mitigation. FPS bearing has a spherical sliding surface. The curvature of the surface provides the structure with a restoring force due to its own weight. This effect is more pronounced in higher displacements (Mokha, 1990). Hence, FPS tends to provide an ever-increasing force as the displacement of the slider increases. This will have the effect of reducing the maximum displacement incurred and having a small permanent displacement in the bearing. This increased force will on the other hand translate into higher shear forces. The FPS bearings have several advantages such as their fixed period. Since the amount of the re-centering force is proportional to the vertical load on FPS, the period of the system is independent of mass. Also, the center of stiffness will be the same as the center of mass, hence preventing torsional movements in structures based on FPS (Mokha, 1990).

Fig. 3 shows displacement and inertia reduction for FPS with various radii. These are the average results for a collection of 18 earthquake records scaled to 1-g peak ground acceleration (Ersoy, 2001). Displacements and inertia reduction increase with FPS radius.

Uplift

Overturning or rocking can cause large tensile forces in the bearings that can overcome gravity load. Thus, causing uplift in some of the bearings that can potentially limit effectiveness of the isolation system or may even aggravate the system response. Although a mechanism has been developed to restrain uplift (Roussis, 2005), effective application of FPS to substation transformers generally requires that rocking and consequently uplift be prevented. There are two reasons for this, namely: i) a low number of bearings (possibly four) are expected to be used in isolating typical substation transformers, thus, rocking can cause uplift of 50% of the bearings, ii) large impact forces upon reversal of motion can have adverse effect on bushings, foundation, and internal components.

Fig. 4 shows the boundaries of response for a rigid block relative to a moving foundation for an aspect ratio (height/width or H/B) of 2, which happens to be common for substation transformers.

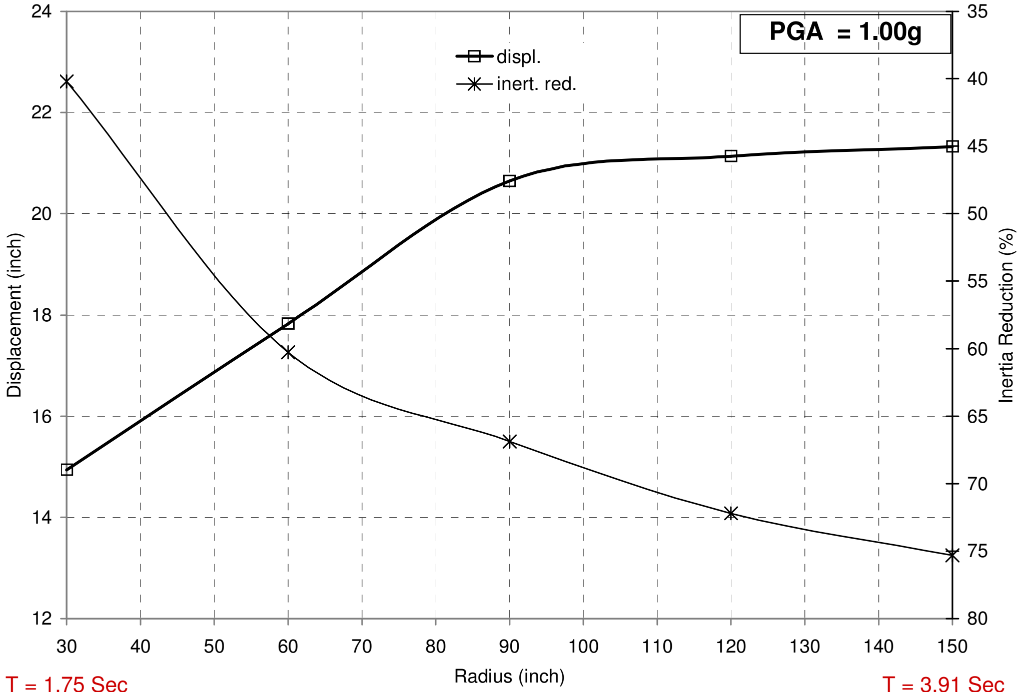

Figure 3. Typical displacement and inertia reduction charts for friction pendulum system.

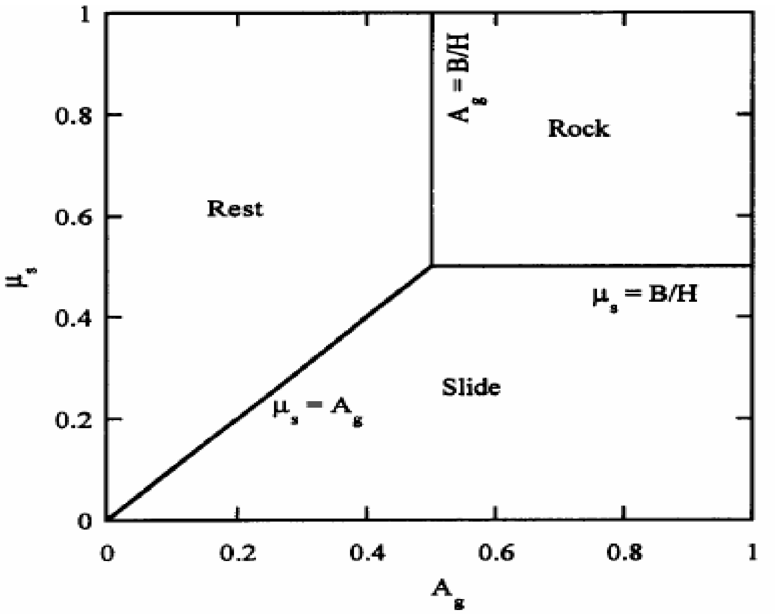

Figure 4. Boundaries of rest, slide, and rock modes for height/width ratio of 2 (Shenton 1996).

Fig. 4 is plotted in the coefficient of friction (μ_s) vs. peak acceleration space. For a rigid body system the peak acceleration is the same as the peak ground acceleration (PGA). However, when base-isolation is used the system acceleration can be significantly lower than PGA as shown on the inertia reduction chart (Fig. 3). Thus, desired sliding mode (no uplift) is possible for much larger PGAs. On the other hand, for

FPS systems the base-shear is not determined only by the coefficient of friction. As mentioned before, due to curvature of the sliding surface the weight of the system has a restoring component along the path of motion. Typically FPS bearings have coefficient of friction in the range of 0.05 – 0.13. However, considering the restoring component of system's own weight the equivalent coefficient of friction to be used in the above chart (Fig. 4) is higher, which means more likelihood of undesired rocking mode of response. These factors are considered in the following section through a case study on an actual substation transformer.

A Case Study

In collaboration with Bonneville Power Administration (BPA) three actual transformers are being considered to better quantify the advantages and issues discussed vis-à-vis application of base-isolation. The trial cases will compare design of actual transformers under fixed base condition, which have recently been completed for BPA, to the base-isolated case.

Elevations of the larger transformer are shown in Fig. 5, which is a single-phase auto-transformer with 433.3 MVA capacity.

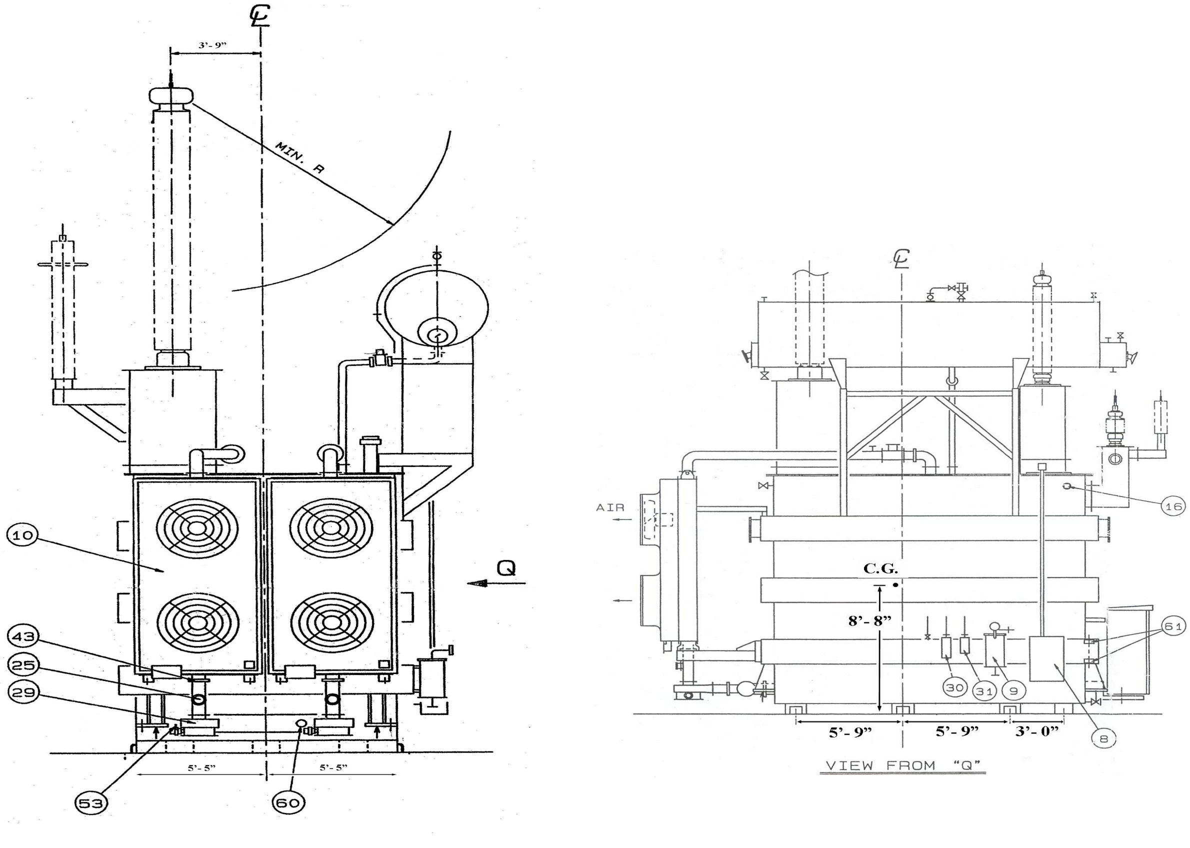

Figure 5. Front and side elevations of 433.3 MVA substation transformer (not to scale).

Seismic Forces and Displacements

The transformer is located in a high seismic region and has to be qualified for high performance level based on IEEE 693. For limit state condition, this means that it has to be designed to withstand earthquakes with peak ground acceleration of 1.0g in horizontal directions and 0.8g in the vertical direction. Although finite element results indicate (Ersoy, 2002) dynamic amplification in the transformer, IEEE 693 assumes a rigid body response, thus, the PGAs can be used in determining the inertia forces in the transformer. Considering a total weight of 512.6 kips, for the fixed based case the horizontal and vertical seismic forces are 512.6 kips and 410.1 kips, respectively. These forces must be used in the design of anchorage system.

By using a base-isolator system the above seismic forces can be reduced substantially. For example, by using four FPS bearings with radius of 88" and using the chart shown in Fig. 3 the maximum displacement and inertia reduction are estimated at 21-inch and 66%, respectively. Thus, the horizontal force in the transformer is reduced significantly to 34% of the fixed based case or 174.3 kips. This will have great implications on the response of the peripheral and internal equipment in addition to alleviating the adverse interaction between the bushing and transformer. It is possible to achieve a stroke of 21" on an 88" FPS bearing.

Beneficial effect of isolation on the response of the bushings for this case study has not been completed yet. However, extrapolating results of a comprehensive study on the effect of base-isolation on transformer-bushing interaction (Ashrafi, 2003), it is estimated that the maximum bushing response when supported on isolated-transformer will be smaller by a factor of five or more compared to the fixed transformer case.

Check for Uplift

A critical issue with the use of base-isolators, as discussed before, is the possibility of rocking and uplift, which can potentially limit or compromise effectiveness of the isolators.

Fig. 4 can be used to check the mode of response for the isolated case. Coefficient of friction for the bearing is 0.08, however, as discussed the base-shear consists of the sum of friction and self-centering component of the transformer weight. In other word, the equivalent coefficient of friction[2], μ_{eqvl}, to be used in Fig. 4 is related to inertia reduction (IR) as follow:

$$\mu_{eqvl} = 1 - IR = 1 - 0.66 = 0.34$$

For the response to be governed by sliding mode (i.e., no rocking and uplift), this value must be smaller than width to height (or B/H) ratio for the transformer. Considering Fig. 5, the worse case (or smaller) value for B/H is 0.62 (or 5'-5" / 8'-8"). Thus, the base-isolated system will have an adequate margin of safety against rocking and uplift.

Additional Slack Required

The maximum displacement is estimated at 21-inch in the horizontal directions. Using 100% and 40% combination rule the maximum total horizontal displacement is estimated to be the vector sum of 21" and 8.4" or 21.5-inch. The total slack to be provided must equal the absolute sum of this value and the maximum displacement of the interconnecting equipment. Assuming the later to be about 2.5", the total slack needed is 24" or 2-ft.

The electrical connection slack to accommodate the potential movement of a base isolated transformer will require new design concepts. For new transformer installations the overhead electrical connections

---

[2] Maximum of this value or static coefficient of friction must be used. Clearly, this will control.

must provide adequate slack without impairing electrical clearances during transformer movement. The electrical control cables at the base of the transformer will require special provisions to account for the transformer base motion. Techniques used in building base isolation may provide design suggestions for transformer applications. The design of the transformer foundations may require special detailing to accommodate the base isolation system and control cabling. All these design issues will be investigated as part of this research project.

Foundation Seismic Forces

Based on IEEE 693, pad-type foundations are designed for a lower force than what is developed in the transformer. For this case study the value of foundation force will be about 45% of transformer weight, which is much smaller than forces that will be developed in the transformer even under rigid body assumption. It can be argued that this is consistent with IEEE 693 Required Response Spectrum (RRS) approach, where 50% spectral values are used in conjunction with allowable stress method.

However, due to nonlinear nature of isolation, a more appropriate comparison between the two cases of fixed and isolated transformer will require the use of actual transformer seismic forces in the design of the foundation. In such situation, it has been shown (Ashrafi, 2003) that the difference between the two cases is significant.

Conclusions

Substations are critical nodes within the power system. Performance of key substation components, such as transformers and bushings, during past earthquakes has not been satisfactory. By highlighting important damage modes of substation transformers and bushings, it is proposed that the beneficial effects of base-isolation technology can be employed to mitigate seismic hazard of these equipment.

Large displacements and possibility of uplift of isolation bearings are issues that must be addressed in successful application of this technology. The results of this case study on an actual transformer will be used to investigate design concepts that demonstrate large displacement can be accommodated without any adverse effect on electrical performance. Furthermore, it is shown that for the transformer considered, uplift is not an issue and it can be prevented with a large margin of safety. Beneficial effect of base-isolation in reducing inertia forces by 66% is quantified. This has significant implications for the dynamic response of the bushings and peripheral equipment, design of anchorage system, and safety of the foundation.

Acknowledgments

The National Science Foundation under the Multidisciplinary Center for Earthquake Engineering Research (MCEER) program supports this research study. The results and conclusions are those of the authors and do not necessarily reflect the views of the sponsors.

References

ASCE, 1999. Guide to Improved Earthquake Performance of Electric Power Systems, Manuals and Reports on Engineering Practice No. 96, Edited by A. J. Schiff, Virginia.

Ersoy S., 2002. Seismic Response of Transformer Bushing Systems and Their Rehabilitation Using Friction Pendulum System, *PhD Thesis*, New Jersey Institute of Technology, Newark, NJ.

Gilani A. S., A. S. Whittaker, G. L. Fenves, and E. Fujisaki, 1999. Seismic Evaluation of 550-kV Porcelain Transformer Bushings, Report No. PEER 1999/05, Pacific Earthquake Engineering Research Center, University of California, Berkeley.

Ersoy S., and M. A. Saadeghvaziri, 2004. Seismic Response of Transformer-Bushing Systems, *IEEE Transactions on Power Delivery,* Power Engineering Society, IEEE, 17(1).

Makris, N., and J. Zhang, 2001. Rocking Response of Anchored Blocks Under Pulse-Type Motions, *Journal of Engineering Mechanics,* Vol. 127, No. 5, ASCE, pp. 484-493, May.

Makris, N., and C. Black, 2002. Uplifting and Overturning of Equipment Anchored to A Base Foundation, *Spectra: Journal of Earth. Engr. Research Inst.*, 18(4), 631-661.

IEEE, 1998. *IEEE Std. 693-1997, Recommended Practices for Seismic Design of Substations,* Piscataway, New Jersey.

Saadeghvaziri M. A., N. H. Allahverdi, A. Ashrafi, 2004. Qualitative Assessment of Seismic Response of Internal Components of Power Transformers, Proceedings of the 13th World Conference on Earthquake Engineering, IAEE, Vancouver, Canada, August.

EERI Newsletter, 1999, *The Izmit (Kocaeli), Turkey Earthquake of August 17, 1999,* Vol. 33, Number 10, Oakland, CA, October.

Mokha A. S., M. C. Constantinou, and A. M. Reinhorn, 1990. Experimental Study and Analytical Prediction of Earthquake Response of a Sliding Isolation System with a Spherical Surface, Technical Report NCEER 90-0020, National Center for Earthquake Engineering Research, State University of New York, Buffalo.

Ersoy S., M. A. Saadeghvaziri, G. Y. Liu GY, and S. T. Mau, 2001. Analytical and Experimental Evaluation of Friction Pendulum System for Seismic Isolation of Transformers, *Earthquake Spectra*, 17(4).

Roussis, P. C., and M. C. Constantinou, 2005. Experimental and Analytical Studies of Structures Seismically Isolated with an Uplift-Restraint Isolation System, Technical Report MCEER-05-0001, University at Buffalo, NY.

Shenton, H., 1996. Criteria for Initiation of Slide, Rock, and Slide-Rock Rigid-Body Modes, *Journal of Engineering Mechanics,* ASCE, Vol. 122, No. 7, July.

Ashrafi, A., 2003. Issues of Seismic Response and Retrofit for Critical Substation Equipment, *Masters Thesis,* New Jersey Institute of Technology, Newark, NJ, August.