Experimental and Analytical Study of Base-Isolation for Electric Power Equipments

by M. Ala Saadeghvaziri and Maria Q. Feng

Research Objectives

The goals of this project are to develop rehabilitation strategies and enhance seismic design guidelines for key equipments in power substations, which are one of the most critical facilities in a power system. Furthermore, it will provide the knowledge base to be integrated into the overall loss estimation model for the entire power network. To achieve these goals, key substation equipments are identified and effectiveness of base-isolation to increase their seismic resilience are assessed using a comprehensive experimental and analytical study.

Critical power system facilities, such as substations, sustained significant damage in California and Japan earthquakes and more recently during the 1999 Chi-Chi, Taiwan, and the Izmit, Turkey earthquakes. Functionality of electric power systems, especially in the age of information technology, is vital to maintaining the welfare of the general public, sustaining economic activities and assisting recovery, restoration, and reconstruction of the seismically damaged built environment. Furthermore, enhanced seismic design and rehabilitation will ensure long-term reliability and longevity of critical equipments. In order to be able to assess the reliability of power systems and to develop seismic resistant mitigation strategies, critical components must be identified and their seismic performance evaluated. Transformers and their bushings are among the most critical components in a complex power system and their seismic performance during past earthquakes has not been satisfactory. Figure 1 shows damage to a transformer in Izmit-2 substation during the Izmit, Turkey earthquake of August 17, 1999 (EERI Newsletter, 1999).

Generally, there are several modes of substation transformer failure during an earthquake, namely movement and turn over of unanchored transformers, anchorage failure that can cause ripping of the transformer case and oil leakage, foundation failure causing rocking and tilting, and failure of the gasket and oil leakage due to the interaction between the transformer and the bushing. Some transformers are supported on rails for ease of installation and because such a set up allows for air circulation to provide additional cooling, thus enhancing corrosion resistance. Another

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form of damage in an unanchored transformer is large movement that can cause damage to other components connected to the unit, such as control cables and bushings. Damage due to the latter factor (i.e., interaction between transformer-bushing and other equipments) can be critical and can cause significant damage and delays in service.

Figure 1. Transformer Failure During the August 17, 1999, Izmit, Turkey Earthquake (EERI, Oct. 99)

It is more common to anchor transformers where considerations are given to seismic loads. This can be done by either bolting the transformer to its footing slab or by welding it to steel embedded in the slab (ASCE, 1999). Designing the anchorage at the supports requires consideration to large forces not only due to gravity and horizontal seismic forces but also from overturning moments in both directions. Furthermore, other appendages such as radiators and reservoirs are attached to a typical transformer. These appendages can cause significant torsional forces that must also be considered in the design of the supports. In addition to strength, the anchorage system must have adequate stiffness and tight tolerances to prevent initiation of impact forces that can damage internal elements or excite higher modes that can damage brittle porcelain members.

There are many cases of bolt or weld failure during past earthquakes (ASCE, 1999). However, with better attention to the details in the design of supports, their performance during an earthquake can be improved. Implementing well-designed anchorage for retrofit of existing transformers, nevertheless, 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 (i.e., the next weak link in the system). The failure shown in Figure 1 appears to be due to foundation settlement.

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

Primary users of this research include utility companies and owners of electrical substation equipments, manufacturers of electrical equipments, and manufacturers of base-isolation devices. The research results can further be used by structural and electrical engineers for design and retrofit of electrical power equipments.

may be the only suitable remedy to alleviate these problems, especially for existing transformers in high seismic regions. Base-isolation will also reduce the input acceleration into the bushing and will lessen the interaction between the transformer and the bushing, which has been the cause of many bushing damages during past earthquakes. Furthermore, by reducing the inertia forces, base-isolation can also prevent the possibility of internal damage.

The after effect of an earthquake on reliability and longevity of a transformer is directly related to the level of shaking of internal elements. High levels of uncontrolled shaking may very well reduce the life expectancy and reliability of internal elements. Internal damage is normally difficult to observe and document because of limitations with post-earthquake inspections of the transformer internal system. However, there are reports of cases of internal damage to transformers (ASCE, 1999).

Satisfying the mobility requirement for maintenance purposes is another advantage of base-isolation over a tightly designed anchorage system. An issue with the use of base-isolation that demands careful consideration is the possible adverse effect of relatively large displacements on the response of inter-connecting equipments, especially bushings. Among possible remedies to be considered are a balanced approach to the design of the isolation system (displacement vs. inertia reduction), appropriate design of conductor slacks, and use of flexible conductor connections. Therefore, a successful application of this technology requires in-depth understanding of the responses of the individual systems involved as well as their interactions.

Within this study, two base-isolation systems are being investigated under a collaborative effort among several institutions and industrial partners. The following sections discuss the experimental program along with some of the findings. The two systems considered are a friction pendulum system and a hybrid system consisting of sliding and rubber bearings. It represents the first effort in testing base-isolated large-scale transformer-bushing systems using an earthquake simulator.

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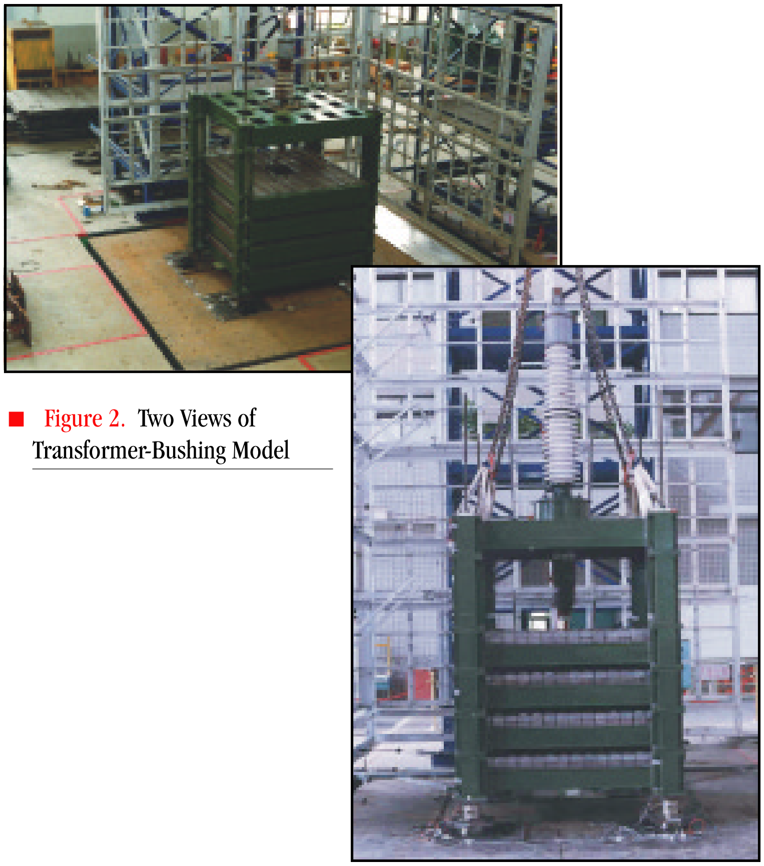
Experimental Study

An extensive series of tests were conducted on a transformer model supporting a bushing. The primary objective was to compare the response of a fixed based transformer-bushing system to that of the system when isolated. The testing was conducted on the earthquake simulator at the National Center for Research on Earthquake Engineering (NCREE) in Taiwan in collaboration with the manufacturers. Uniaxial, biaxial, and triaxial excitations were conducted employing several earthquake records with PGAs in the range of 0.125g to 0.5g. The testing schedule also included white noise tests to identify dynamic characteristics of the bushings and the transformer model, resulting in more than 200 tests.

Considering the payload capacity of the earthquake simulator, the transformer model was designed to weigh 235.5 kN. The model is a four-layer steel frame structure



■ Figure 2. Two Views of Transformer-Bushing Model

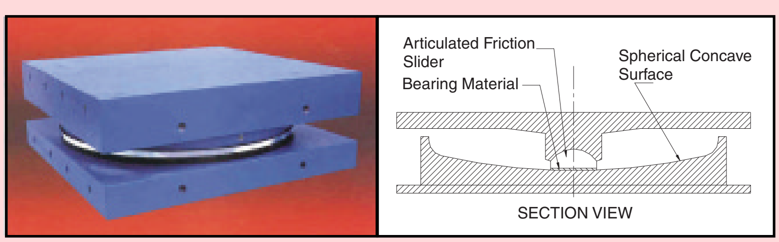
with lead blocks loaded to represent the internal core and coil of a transformer.

Consistent with the practice employed by TaiPower, the bushing was attached to the transformer model top plate at a right angle. The connection represents some of the important structural aspects of the support of the bushing, which has been shown to be very important in quantifying the important interaction between the two components.

Figure 2 shows isometric and elevation views of the entire model. As can be seen from this figure, the bushing projects inside the transformer model as is the case in an actual situation. Two types of bushings, 69 kV and 161 kV, were used in the experiment. Several earthquake records were used for the testing, among them were the 1940 El-Centro, 1994 Sylmar (Northridge), and 1995 Takatori (Kobe) records. Transformer frequency was measured to be 12.5 Hz in both x and y directions. The frequencies for the 69 kV and 161 kV bushings were 27.0 Hz and 12.5 Hz in both x and y directions, respectively. The equivalent damping ratio for each component was around 2%.

Friction Pendulum System Results

One of the most recent base isolation systems to improve the earthquake resistance of structures is Friction Pendulum System (FPS), shown in Figure 3. Detailed description of the system along with in depth discussion of experimental and analytical results can be found elsewhere (Ersoy, et. al 2001; Saadeghvaziri and Ersoy, 2001). For structures isolated by this system, the period of vibration (similar to a pendulum) only depends on geometry (in this case radius of curvature) and the gravitational constant, and it does not depend on the mass. Therefore, FPS bearings are one of the most suitable isolation devices for a system with relatively small weight compared to a high-rise building (such as substation equipments). Furthermore, through friction,



■ Figure 3. Photograph and Cross-Section View of an FPS Isolator

■ Table 1. Fixed and FPS Isolated Results for Several Cases Using the Sylmar (Northridge) Record

Case No.	Input and Response	Fixed Base x	Fixed Base y	Fixed Base z	Base Isolated x	Base Isolated y	Base Isolated z
1	PGA_{Target}	0.1250	-	-	0.1250	-	-
	PGA_{Real}	0.1468	-	-	0.1376	-	-
	A_2	0.1602	-	-	0.0778	-	-
	A_3	0.2457	-	-	0.1173	-	-
	A_{B1}	0.2715	-	-	0.1664	-	-
	A_{B2}	0.2507	-	-	0.1280	-	-
	A_{B3}	0.5127	-	-	0.1418	-	-
	A_{B4}	0.9188	-	-	0.2323	-	-
	D_2	0.8638	-	-	7.7837	-	-
	D_3	1.2757	-	-	7.8814	-	-
2	PGA_{Target}	0.2500	-	-	0.2500	-	-
	PGA_{Real}	0.2377	-	-	0.2817	-	-
	A_2	0.2586	-	-	0.1186	-	-
	A_3	0.4555	-	-	0.2044	-	-
	A_{B1}	0.4888	-	-	0.3748	-	-
	A_{B2}	0.4374	-	-	0.2824	-	-
	A_{B3}	1.0256	-	-	0.2111	-	-
	A_{B4}	1.8672	-	-	-	-	-
	D_2	1.6892	-	-	26.2215	-	-
	D_3	2.4049	-	-	26.6045	-	-
3	PGA_{Target}	0.3750	-	-	0.3750	-	-
	PGA_{Real}	0.3781	-	-	0.3793	-	-
	A_2	0.4191	-	-	0.1661	-	-
	A_3	0.6664	-	-	0.3323	-	-
	A_{B1}	0.8257	-	-	0.5718	-	-
	A_{B2}	0.6020	-	-	0.4200	-	-
	A_{B3}	1.4243	-	-	0.2564	-	-
	A_{B4}	2.7489	-	-	0.6234	-	-
	D_2	2.2553	-	-	46.3317	-	-
	D_3	3.0519	-	-	46.7391	-	-
4	PGA_{Target}	0.2500	0.1250	-	0.2500	0.1250	-
	PGA_{Real}	0.2313	0.1093	-	0.2637	0.1462	-
	A_2	0.2513	0.1082	-	0.1227	0.1158	-
	A_3	0.4282	0.1155	-	0.1883	0.2008	-
	A_{B1}	0.4819	0.4807	-	0.3981	0.4484	-
	A_{B2}	0.4267	0.2835	-	0.2722	0.3728	-
	A_{B3}	0.9657	0.6177	-	0.2255	0.2739	-
	A_{B4}	1.7932	1.3097	-	0.4328	0.6308	-
	D_2	1.5519	1.6678	-	21.1447	21.5628	-
	D_3	2.8855	3.3082	-	22.5074	21.7414	-

Case No.	Input and Response	Fixed Base x	Fixed Base y	Fixed Base z	Base Isolated x	Base Isolated y	Base Isolated z
5*	PGA_{Target}	0.3750	0.2500	-	0.3750	0.2500	-
	PGA_{Real}	0.3699	0.2094	-	0.3809	0.2454	-
	A_2	0.4213	0.2167	-	0.3642	0.5833	-
	A_3	0.6257	0.4479	-	0.7031	1.0592	-
	A_{B1}	0.9549	1.1157	-	1.4774	4.6122	-
	A_{B2}	0.6118	0.5967	-	0.9029	2.7761	-
	A_{B3}	1.3414	1.1542	-	0.7015	1.2588	-
	A_{B4}	2.6399	2.5825	-	1.4507	3.0900	-
	D_2	2.6765	3.3448	-	65.0059	79.1818	-
	D_3	4.8021	5.5605	-	71.0776	80.1011	-
6	PGA_{Target}	0.2500	0.1250	0.1250	0.2500	0.1250	0.1250
	PGA_{Real}	0.2362	0.1160	0.1193	0.2676	0.1526	0.1239
	A_2	0.2570	0.1280	-	0.1367	0.1273	-
	A_3	0.4323	0.2539	0.1537	0.2017	0.2005	0.1728
	A_{B1}	0.5214	0.4160	0.1606	0.4075	0.4234	0.1745
	A_{B2}	0.4129	0.2671	0.1784	0.3052	0.3440	0.1727
	A_{B3}	1.0605	0.5432	0.1880	0.2478	0.2714	0.1633
	A_{B4}	2.0097	1.1053	0.1611	0.4534	0.6593	0.1762
	D_2	1.4588	1.8311	-	20.8579	22.5745	-
	D_3	2.9084	3.3387	-	22.2175	22.3609	-
7	PGA_{Target}	0.3750	0.2500	0.2500	0.3750	0.2500	0.2500
	PGA_{Real}	0.3833	0.2161	0.2362	0.4031	0.2414	0.2316
	A_2	0.4150	0.2123	-	0.2205	0.2330	-
	A_3	0.6180	0.4404	0.2844	0.4769	0.2743	0.3494
	A_{B1}	1.1053	1.0184	0.4418	1.0202	0.7539	0.3314
	A_{B2}	0.6412	0.5460	0.3679	0.7059	0.4971	0.3358
	A_{B3}	1.2734	1.0664	0.3858	0.5316	0.3782	0.3358
	A_{B4}	2.6668	2.3398	0.3550	1.0828	0.7979	0.3340
	D_2	2.5987	3.7217	-	60.4434	75.6554	-
	D_3	4.8967	5.9023	-	96.8357	65.5843	-

Note:
* For the base isolated case, the displacement limit of the FPS bearing is reached, causing impact.

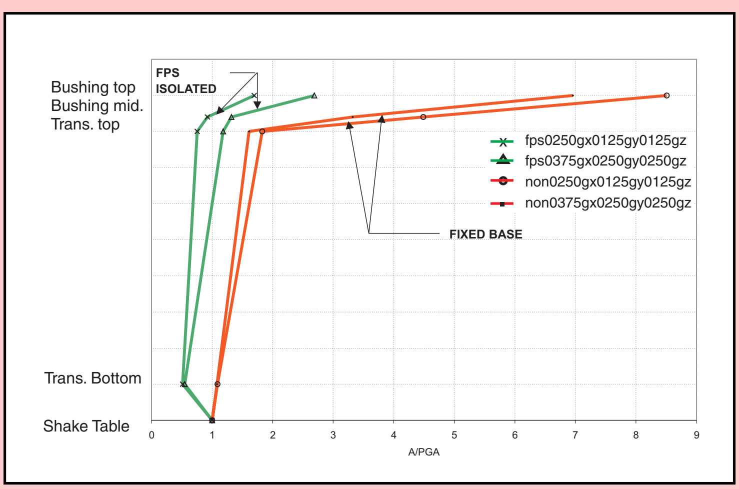
the system can provide a high level of damping. Four 18.64" radius FPS bearings at the four corners were used to support the model for the isolated case.

The test results for Sylmar record are tabulated in Table 1 for isolated and non-isolated cases. In these tables, A_2 and A_3 show the acceleration values (in g) at the bottom and the top of the transformer model, respectively. A_{B1},A_{B2},A_{B3},A_{B4} represent the accelerations at different locations along the bushing. A_{B1} is the bottom of the bushing and A_{B4} is the top. Note that the bushing projects inside the transformer model. That is, it is connected to the transformer model somewhere between points A_{B2}, and A_{B3}. Thus, the bottom of the bushing (i.e., point A_{B1}) can have a response as large as the top of the bushing (A_{B4}). D_2, and D_3 (in mm) are the relative displacement values of the transformer model at the bottom and top, respectively.

In comparing these numbers a point should be noted with regard to the base-isolated results for Case

5. Inspection of the displacement results for this case indicates that the displacement capacity of the bearing has been reached causing impact. Thus, the results are not useful for comparison to the fixed base situation. However, they do highlight the fact that vertical motion has a noticeable effect on the response of FPS isolated structures. In this case, vertical motion has caused reduction in the horizontal displacements. Thus, for the 3-D case (Case 7 in Table 6), unlike the 2-D case, the displacements are within the bearing capacity.

The response acceleration maps for one case is shown in Figure 4. In this figure, x-axis shows the acceleration values normalized with respect to PGA. The y-axis shows different locations along the height of the test specimen ranging from the top of the shake table to the top of the bushing. As one can see from this figure, acceleration response of the transformer model is reduced significantly at different levels throughout its height. The level of acceleration reduction depends on the type of earthquake record used. That is, in addition to acceleration level and nature of the input (e.g., 1-D vs. 2-D), the ground motion characteristics affect the level of acceleration reductions.



■ Figure 4. Acceleration Maps: Triaxial Simulation, FPS Bearings, Sylmar (Northridge) Record

The experimental results can be summarized as follow:

- Inertia reductions depend on peak ground acceleration (PGA) and bearing radius. The FPS system is more effective in reducing inertia forces for higher PGAs. Furthermore, both inertia reductions and maximum displacements are affected by the earthquake record used. Records with dominant period in the vicinity of the isolator period reduce the isolator effectiveness.
- FPS bearings can provide, on the average, 60% acceleration reductions within their displacement limits. This number is with respect to the isolation level. For a flexible system (as seen from the acceleration maps) accelerations are different at various levels, and the effectiveness of the base-isolation is more apparent when one considers the entire picture. For example, there is a significantly greater reduction in the bushing acceleration than that of the transformer.
- Coupling of responses in two horizontal directions does exist, which is due to dependency of frictional characteristics on total velocity. However, the effect tends to diminish for higher PGAs, since at higher velocities, frictional constants are less sensitive to the magnitude of velocity.
- The vertical component of ground motion has an effect on the response of the FPS bear-

ings. This effect is expected to be more pronounced for near field earthquakes (higher PGAs) and for sites where filtering of the motion due to local soil conditions is possible.

Hybrid Base-Isolation Results

It is difficult to use normal rubber bearings for seismic isolation of lightweight structures, such as transformers, due to their limited ability to elongate the natural period of the entire isolated system without buckling. This difficulty was alleviated in this study by combining sliding bearings (to support the entire weight) with rubber bearings (to provide restoring forces). The hybrid system was tested under a transformer-bushing model, as discussed, and the results were compared to the fixed base situation to investigate its effectiveness.

Four sliding bearings were installed at the corners of the transformer model and two rubber bearings were placed at the middle on two opposite sides, as shown in Figures 5. The sliding bearings carry the entire weight of the transformer model and the bushing, while the rubber bearings provide a horizontal restoring force without sustaining any vertical load. Detailed information on the design of the hybrid-isolation system and experimental results can be found in (Murota and Feng, 2001).

Peak response accelerations along with acceleration maps over the height of the transformer model and bushing, with and without the base isolation, are shown as a function of PGA in Figures 6 and 7 for the El Centro ground motion. Under other ground motion records, the peak responses show a similar trend. Like the FPS bearings, the hybrid system is very effective in reducing the accelerations, especially in terms of the response of the bushing top. Without base isolation, the peak acceleration at the top of the bushing reached 3.66 g, resulting in an amplification factor of 10.80.

On the other hand, for the base-isolated case, the peak response acceleration at the top of bushing was 0.354(g) with an amplification factor equal to 1.05. Note that in these discussions, including those on the FPS bearings, the PGA referred to and shown on the corresponding figures is the target PGA. The actual

> ***"Research efforts over the past several years have revealed that understanding the seismic interaction among key equipments of a substation is critical to properly assessing their seismic performance."***

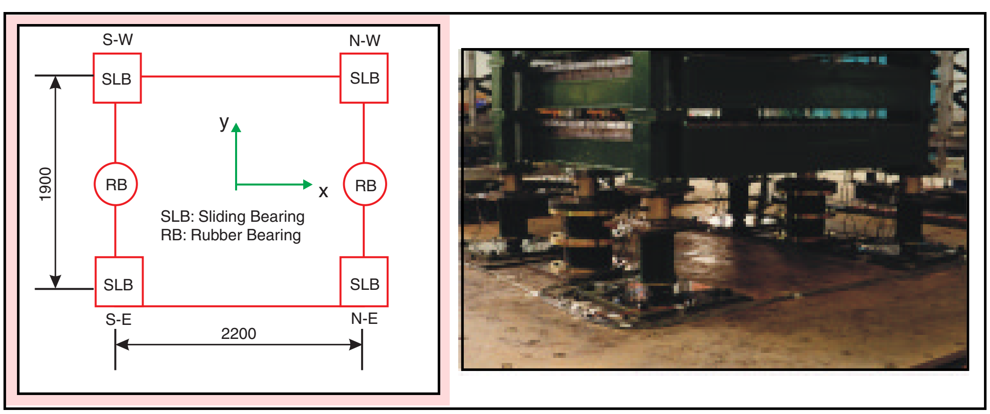
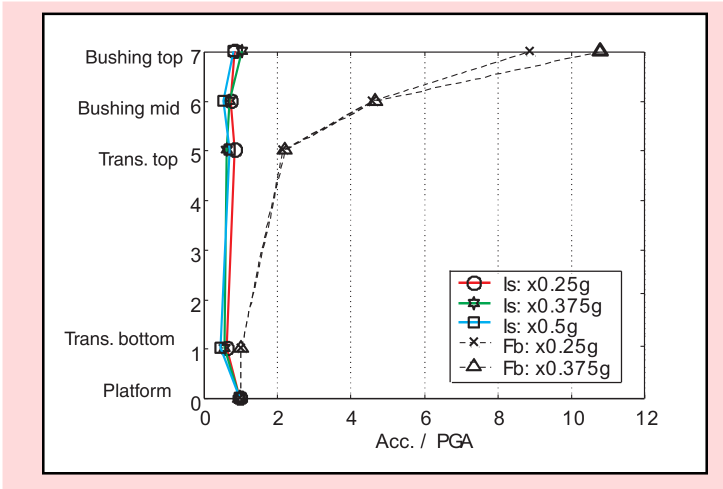
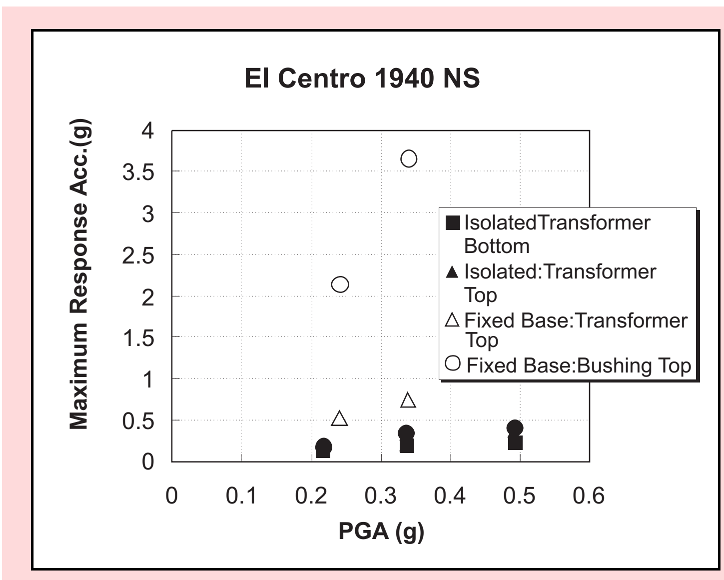


Figure 5. Layout and Experimental Set-up of the Hybrid Sliding-Rubber Bearings



■ Figure 6. Acceleration Maps: Uniaxial Simulation, Hybrid Bearings, El-Centro Record.



■ Figure 7. Peak Response Accelerations Under Uniaxial Shaking

or real input acceleration may have been different due to difficulty in exactly matching the intended PGA. Of course, response parameters (such inertia reduction) are calculated with respect to actual acceleration, not the target acceleration.

The hybrid base isolation becomes more effective as the PGA becomes larger (Figure 7), which is typical of a sliding isolation system. It is observed that for the base isolated system, the transformer response is not sensitive to the ground motion. For the fixed-based case, the interaction between the transformer (12.5 Hz) and the bushing was observed. As a result, the response of the 161kV bushing, with 12.5 Hz frequency, became larger than that of the 69kV bushing, which has a dynamic frequency of 27 Hz.

Under triaxial shaking, the transformer-bushing system showed significant difference in response from those under uniaxial and biaxial shaking. The response accelerations at the tops of both 161kV and 69kV bushings for the isolated cases were amplified, and in some cases (especially for the 69kV bushing), the response exceeded that of the fixed-based system. Figure 8 shows the acceleration response maps (amplification factors) for the worst case.

Detailed inspection of the results indicates that this is due to the effect of vertical motion on the friction force acting on the sliding bearings. Vertical records are generally rich in frequency content, resulting in high frequency fluctuations in the frictional force (20-30 Hz), which in turn causes excitation of high frequency modes. Thus, the reason for the 69 kV bushing, which has a fundamental frequency around 27 Hz, to be more affected by triaxial excitation. This is valuable information that has not be observed and/or investigated before. It also has significant implications for other structures (e.g., response of secondary systems in a building within the framework of performance-based design) and it will be investigated further.

In summary, the proposed hybrid sliding-rubber bearing isolation system is quite effective in reducing the response acceleration of a transformer-bushing system under uniaxial and biaxial earthquake simulator tests. It should be noted that the seismic performance of an actual transformer-bushing system equipped with the proposed isolation system will be even better, because the isolation period of an actual transformer will be much longer than that of the transformer-bushing model used in the test due to a much heavier weight of the actual transformer. Among ongoing objectives of the project are numerical studies and modifications to the design of the hybrid system to improve its effectiveness under triaxial motion.

Analytical Study

SDOF Model

Over the past decade or so, there have been several analytical and experimental studies on the seismic performance of FPS isolators. These works proved the effectiveness of FPS in reducing inertia forces within the displacement limit of the device. Practical applications of the system in the design of new structures and the rehabilitation of existing ones, including the historic Ninth Circuit U.S. Court of Appeals in San Francisco (Mokha, et al., 1996), have taken place. A more recent work by Almazan, et al., (1998) addresses several other important aspects of modeling and response such as constitutive relationships (small vs. large displacement), and refinement of the structural model.

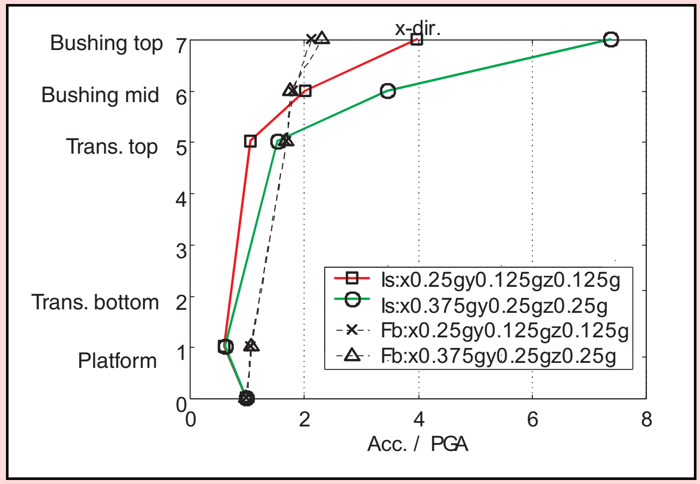
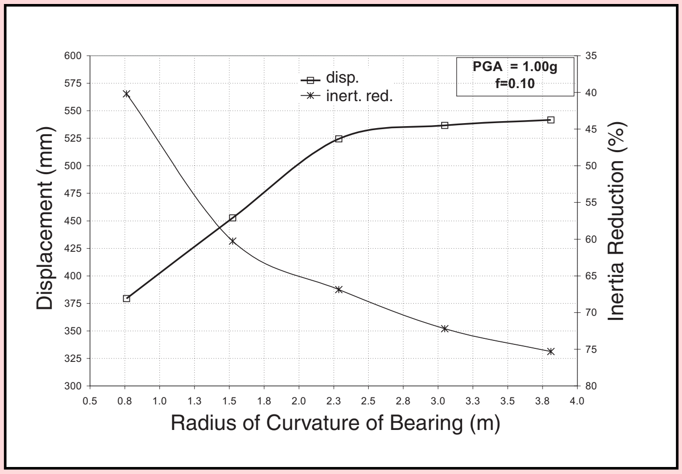


Figure 8. Acceleration Maps: Triaxial Simulation, Hybrid Bearings, El-Centro Record

During the initial phase of this study and parallel with the shake table tests, an extensive analytical work was conducted. Using SDOF idealization and equilibrium of the forces involved, the differential equations of motion were established and solved using IMSL routine IVPAG (Ersoy et al., 2001). Although the focus of this study is on application of FPS devices to transformers, it also addresses additional parameters and aspects of response that either have not been investigated before or have only been considered on a limited basis. Therefore, some of the findings are general and could have applications in the design of FPS bearings for other structures as well. Among the parameters considered are ground motion characteristics, bi-directional motions, the effect of vertical motion, and isolation radius.

Inertia reduction and the maximum displacement of the system were the criteria used in evaluating the seismic response and the effectiveness of FPS bearings. Based on the results of the parametric



■ Figure 9. Analytical Displacement-Inertia Reduction Chart for FPS System (input PGA = 1.0 g)

study, charts for inertia reduction and the maximum displacement were developed. Shown in Figure 9 is a chart corresponding to ground motion with peak acceleration of 1.0g. The challenge in design will be the selection of radius of curvature of the bearing such that there is a balance between the desired inertia reduction and the displacement limits vis-à-vis bushing interaction with interconnecting equipments.

As can be seen from figure 9, the bearings can provide large inertia reductions. For example, for a system with radius of curvature equal to 1.5 m (60" inches) the inertia reduction is about 60%. That is, the transformer acceleration will be 0.4g when the peak ground acceleration is 1.g.

For this radius, the system period is 2.5 sec (i.e., frequency of 0.4 Hz) regardless of the weight of the transformer. However, the associated large displacement needs to be accommodated. To this end, there is a need for a simplified 3-D model to investigate the interaction between the transformer-bushing and interconnecting elements. To develop the knowledge base to achieve this goal, finite element models of typical transformers and bushings were developed, as discussed below, for time history analysis.

Finite Element Model

A power transformer is composed of six parts: transformer tank, radiators, reservoir, core and coil, oil, and bushings. The transformer tank is the main structural component of power transformers. It has core and coil centrally placed within it and the tank is completely filled by mineral oil. Radiators and reservoir are appendages and they are externally attached to the transformer tank.

A finite element model of a power transformer (55 MVA, 230/135 kV) from a substation in New Jersey is shown in Figure 10. The transformer weighs 1,335 kN (300 kips), and the radiators (on the side) and reservoir (on the top) weigh 120 kN and 40 kN, respectively. Thus, one can see the possibility of torsional response and higher demands on the supports in light of the relative weights of the appendages compared to the weight of the transformer itself.

The finite element package ANSYS was used to develop the finite element models. The transformer tank was modeled by shell elements. Braces around the transformer were modeled by offset beam elements. Currently, the core and coil inside the transformer were modeled as mass elements. Radiators and reservoir were modeled by 3-D solid elements. The contained oil inside the transformer

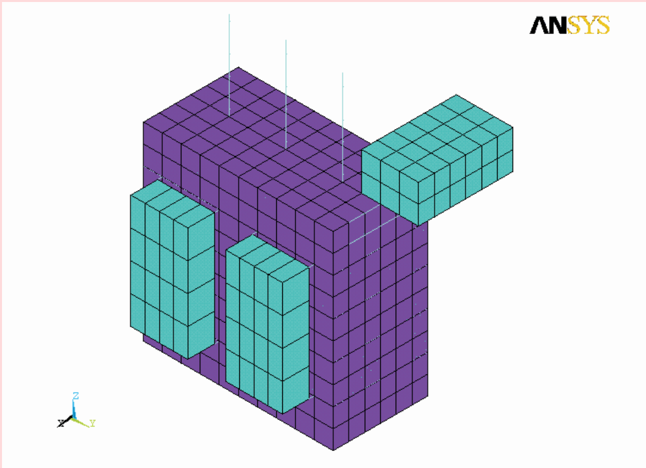


Figure 10. Finite Element Model of a Transformer-Bushing System

was modeled as solid with modulus of elasticity equal to the bulk modulus of the fluid.

The seismic response of bushings was dominated by the behavior of the gaskets between the porcelain units. The common failure mode involved movement of the upper porcelain unit relative to its support flange, causing oil leakage Therefore, the analytical model for the bushings uses simple beam elements with equivalent density and stiffness to represent porcelain units, dome, and aluminum support.

Gaskets between these elements were modeled using nonlinear axial and shear springs. For a fixed transformer, the translational degrees of freedom were removed at the location of the supports. The soil-structure interaction may be investigated using Winkler foundation elements to evaluate the level of stresses in the subgrade. Currently, time history analyses using various earthquake records are being conducted.

Conclusions

Research efforts over the past several years have revealed that understanding the seismic interactions among key equipments of a substation (transformers, bushings, foundation, and interconnecting elements) is critical to conducting a proper assessment of their seismic performance. Thus, the thrust of future efforts will be to evaluate seismic response, and propose design and rehabilitation guidelines, based on system performance. This will be achieved through further experimental tests and by developing a simplified model that can accurately represent critical elements of a substation in order to investigate their interactions in detail through a parametric study. The model will be developed based on the results of ongoing 3-D finite element analyses and the experimental results conducted over the past several years.

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