



## SEISMIC RESPONSE AND REHABILITATION OF CRITICAL SUBSTATION EQUIPMENT

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### SUMMARY

This paper focuses on assessment of seismic response of critical substation equipment and on the use of advanced technologies for rehabilitation measures. Extensive finite element analysis of transformer-bushing is performed to investigate their seismic response and to quantify the effect of transformer flexibility on bushing response. Friction Pendulum System (FPS) is considered as a rehabilitation measure. The response of FPS isolated transformer to different earthquakes is investigated. Other parameters such as FPS radii, ground motion intensity and vertical excitations are also considered. Furthermore, a finite element model for FPS is developed and implemented into ADINA to study behavior of primary system (transformer) isolation on the response of secondary systems (bushings). Effect of base isolation on foundation design and on interaction between transformer-bushing and the interconnecting equipment are also evaluated. Results of this study indicate that seismic isolation is a viable mitigation strategy as long as the modest increase in required slack is provided.

### 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. Another key equipment in a substation vulnerable to earthquake ground motion is bushing. This paper will present results of a study on the seismic behavior of these critical equipment and their interaction. Experience gained during past earthquakes has identified several important modes of damage/failure in a substation. These include: failure of bushing to transformer connection, sliding and turn over of transformers, failure of foundation, and damage/failure of peripheral attachments. Another possible and critical mode of failure is damage to

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internal components in a transformer. The critical condition for bushings can be either due to shaking of the transformer tank or loads at the terminal end of the bushing due to the out of phase shaking of the transformer-bushing with respect to interconnecting equipment. This paper will discuss the results of an extensive finite element analysis on response of transformers and bushings. This is an integral part of the effort to assess analytically the seismic behavior of transformer and bushing during an earthquake and to determine how probable different failure modes are. The effect of transformer flexibility on bushing response is one of the results of this analyses that helps explain the discrepancy between laboratory and actual performance of bushings during previous earthquakes. Furthermore, effectiveness and viability of an advanced base-isolation technology, Friction Pendulum System (FPS), as a rehabilitation measure for power transformers is discussed. Use of FPS is assessed in terms of both structural and electrical performance requirements. FPS is capable of reducing the inertia forces significantly, alleviating many problems associated with seismic performance of transformers and bushings. Due to flexibility of the conductors the large displacement associated with the use of FPS can be accommodated by providing adequate slack. Lower loads mean not only better seismic response for transformer and bushings, but also lower forces transferred to the foundation and more economical foundation and connection design. Discussions include preliminary cost comparison, which indicates that even on initial cost basis base-isolation could be competitive. In addition to the analytical work performed, the effect of FPS on response of transformer-bushing was studied experimentally using a model for the transformer along with a real size bushing. Also, since the interaction between transformer-bushing and interconnecting equipment has been identified in the past to be one of the factors contributing to failures observed in bushings, this interaction has been studied through the use of a simplified model. The larger displacement associated with the use of seismic isolation has an adverse affect on this phenomenon. A companion paper presents results of an ongoing study on the impact of earthquake ground motion on internal components of transformers (Saadeghvaziri [1]).

## **FINITE ELEMENT STUDY OF TRANSFORMER BUSHING SYSTEM**

The reliability of a power systems exposed to earthquake loading is dependent upon the seismic response of its individual components and interaction of these components with each other. Since transformers and transformer-mounted bushings are critical components of a substation system, which have been damaged in the past earthquakes, they are the focus of the finite element analysis. Transformers perform the vital function of transferring power between circuits operating at different voltages. The important components of transformers with regard to earthquake performance are anchorage, bushings, internal packaging, peripheral equipment such as radiators, and connections to other equipment.

Several researchers have performed experimental and finite element studies on transformers and bushings (Gilani [2, 3], Villaverde [4]). Most recent tests were performed at the PEER (Pacific Earthquake Engineering Research) center and at the Construction Engineering Research Laboratories of US Army Corp of Engineers. Even though the most vulnerable flange to porcelain gasket detail had been used in some of these tests, the performance of all bushings was fairly good in terms of the general response based on the qualification of bushings set forth in IEEE 693-1997 (IEEE [5]). However, many bushings of the same type have failed during past earthquakes. Thus, it appears to be a need for reassessment of the current IEEE 693-1997 qualification procedures for both transformers and bushings to include consideration to their interaction. Electrical equipment are typically designed for electrical requirements more than structural performance requirements. Further research is needed to quantify the effect of transformer on bushing dynamic characteristics and its seismic response. Furthermore, interconnecting substation components can complicate the seismic response of transformer-bushing system. Interconnecting equipment can cause damage through connectors. That is, the critical condition for bushings can be either due to shaking of the transformer tank or loads at the terminal end of the bushing due to the out of phase shaking of the transformer-bushing with respect to interconnecting equipment.

Therefore, shake table tests of bushings alone will not reveal all of the critical situations. Finite element method provides the ideal platform to perform additional studies in order to better understand the response characteristics of transformer and bushing systems.

### **Details of the finite element study**

Three different sizes of power transformers were selected for time history analysis. First transformer type is 25 MVA – 650 HV BIL and it is called transformer type 1 (TT1) in this study. This transformer weighs about 179 kips and does not have a reservoir. The dimensions of this transformer are B=85", L=125", H=170", where B, L, and H are width, length, and height of the transformer tank, respectively. The second transformer type is 33/44/55 MVA 230/133 HV three phase transformer and it is called transformer type 2 (TT2) in this study. It weighs about 300 kips and the radiators (on the side) and reservoir weigh 27 kips and 9 kips, respectively. The dimensions of this transformer are B=100", L=200", H=200". Third transformer, called type 3 (TT3) is 250 MVA 230/119.5 kV. It weighs about 512 kips. The dimensions of this transformer are B=100", L=280", H=180".

The finite element package ANSYS is used for development of the finite element model. The transformer tank is modeled by shell elements. Braces around the transformers are modeled by offset beam elements. The core and coil inside the transformer are modeled as mass elements. The radiators and the reservoir are modeled by 3-D solid elements. The contained oil inside the transformer is modeled as a solid with modulus of elasticity equal to the bulk modulus of the fluid since the transformer is filled completely with oil and there is no slashing effect. These three types of transformer all support 3-196 kV bushings that are located on top of the transformer tank. Bushings are composed of several elements like an aluminum support unit, porcelain units, gaskets, aluminum core, and dome. The aluminum support has a built-in flange used to mount the bushing on top of the transformer. The aluminum core runs from the top to the bottom of the bushing and houses the aluminum conductor. Bushings are prestressed through the aluminum core and this prestressing force is distributed evenly to the other components through the dome to hold the units together. There are gaskets located in between the units. The analytical models for the bushings were created by beam elements with equivalent density and stiffness to represent the porcelain units, the dome, and the aluminum core. Gaskets between these elements are modeled using linear axial and shear springs.

Full time history analyses are performed for ground input with PGA of 1g in orthogonal horizontal directions and PGA of 0.8 g in the vertical direction as per IEEE recommendation. For each transformer type, 2-soil and 2-rock earthquake records are utilized for 3-D time history analysis. Based on the IEEE 693-1997, 2% damping value was employed in the finite element model (IEEE [5]). Rayleigh damping is used for all the time history analysis and the Rayleigh damping coefficients were obtained by fixing the damping value at 0.02 for frequencies of 8 Hz and 25 Hz, selected based on the response frequencies of the transformer bushing systems. Details of the model and analyses can be found in Ersoy [6].

### **Finite element analysis results**

In the following discussions weak and strong orthogonal horizontal axes refer to x and y directions, respectively. The vertical axis is referred to as the z direction. Transformer type 1, transformer type 2, and transformer type 3 are described as TT1, TT2, and TT3, respectively.

#### *Dynamic response of the transformers*

Modal analyses show that translational modes of the transformers have the highest participation in their response. Frequency of the translational mode in x-direction (weak horizontal axis) for TT1, TT2, and TT3 is 14.1 Hz, 13.8 Hz, and 11.7 Hz, respectively. Maximum relative displacement and total acceleration responses for TT1 are tabulated in Table 1 (the bushings will be discussed later in the next section). There is almost always a linear relationship for the displacement values throughout the height of the transformer.

The maximum dynamic amplification factor is found to be 2 for TT1. Those of TT2 and TT3 are 2.4 and 2.5, respectively. Therefore it can be stated that the dynamic amplification due to the transformer body stated as 2 by IEEE 693-1997 is not always conservative (IEEE [5]).

**Table 1 Maximum Displacement and Acceleration Responses for TT1**

Transformer Type	EQ Record	Location	Displacement (in)			Acceleration (g)		
			x	y	z	x	y	z
TT1	El-Centro	Mid level of Transformer	0.045	0.022	0.020	1.011	0.999	0.490
		Top of Transformer	0.091	0.039	0.021	1.383	1.308	0.510
		Top of Bushing	0.550	0.244	0.012	6.179	2.967	0.541
	Hollister Airport	Mid level of Transformer	0.038	0.018	0.017	1.021	1.011	0.185
		Top of Transformer	0.074	0.032	0.018	1.134	1.020	0.193
		Top of Bushing	0.282	0.143	0.011	2.858	1.150	0.419
	Pacoima Dam	Mid level of Transformer	0.046	0.020	0.021	1.092	1.074	0.264
		Top of Transformer	0.093	0.035	0.021	1.532	1.129	0.274
		Top of Bushing	0.600	0.263	0.011	7.975	2.750	0.379
	Lake Hughes Array #4	Mid level of Transformer	0.059	0.022	0.025	1.301	1.116	0.421
		Top of Transformer	0.118	0.038	0.025	2.002	1.293	0.437
		Top of Bushing	0.954	0.372	0.011	10.949	3.962	0.370

The maximum reactions from time history analyses are compared to those computed using the static analysis method specified in IEEE recommendations. It is determined that the maximum vertical reactions are within the IEEE values (Ersoy [7]). However, the horizontal reaction obtained from the recommendations is 54% less than the finite element analysis result for TT1. Similarly, the horizontal reactions are 27% and 48% less than the finite element analysis results for TT2 and TT3, respectively. The finite element analysis results for horizontal reactions exceed the static analysis results.

It is observed that the translational modes of transformers have the highest participation in the response at the top of the transformers. For example, the power spectrum of the acceleration response at a top corner point of TT2 transformer has its maximum at 13.85 Hz, which is very close to the translational frequency of 14.1 Hz.

Failure of transformer and its components other than bushing gasket failure was not found in the finite element analyses, assuming adequate anchorage can be provided. For the fixed case, 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 [8]).

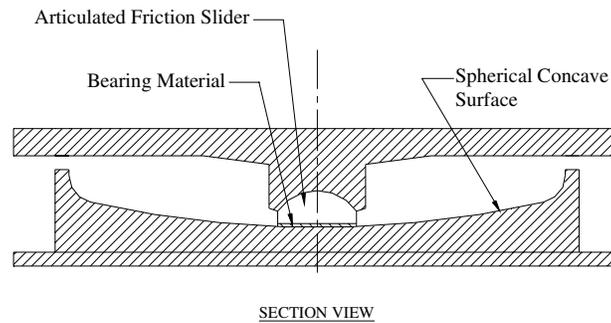
#### *Dynamic response of the bushings*

Finite element results indicate that the flexibility of the transformer top plate has a major effect on dynamic characteristics of the bushings. For example, for a TT2 transformer mounted bushing the fundamental frequency drops to 10 Hz from its fixed based value of 14.4 Hz. 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 frequency. The maximum displacement response at the top of the bushings in x-direction (weak horizontal axis) considering all four records is 0.55 inch for bushings mounted on TT1. That of the bushings mounted on TT2 and TT3 is as 0.56 inch and 1.2 inch, respectively. The maximum total acceleration response at the top of the bushings in x-direction (weak horizontal axis) considering all four records is 6.2g for bushings mounted on TT1. Those for bushings mounted on TT2 and TT3 are 5.5g and 12.4g, respectively. To be able to make comparisons consistent with IEEE 693, inputs with PGA of 2.0g are used and the bushing is analyzed alone when fixed at its flange. The maximum displacement is 0.18" and the maximum acceleration is 3.0g. This could be one of the reasons for the discrepancy between bushings' poor performance during previous earthquakes and their good to excellent performance under laboratory tests when supported on a rigid frame.

One of the common failure modes involves movement of the upper porcelain unit relative to its support flange, causing oil leakage. No formation of a gap is observed in the time history analyses performed for TT1. However, a gap forms during the analysis for TT2 and TT3. There was no damage to the porcelain units. Also, the relaxation effect of the axial dynamic force is examined. It is found that the effect of axial vibration of the bushing on the prestressing is insignificant, indicating that there has not been any prestressing loss.

### **FRICITION PENDULUM SYSTEM AS A REAHBILITATION MEASURE**

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. Basically, base isolation systems provide both a restoring force and energy dissipation. Friction Pendulum System (FPS) is a very effective system among the frictional systems used for seismic mitigation. It consists of an articulated slider sliding on a stainless steel spherical surface covered with low friction material (EPS [9]). 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 [10]). 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. The FPS bearings have several advantages such as their fixed period and coincidence of their centers of stiffness and mass that prevents torsional movements in the structure (Mokha [10]). Figure 1 shows a sketch of a typical FPS bearing. Detailed results of an analytical and experimental study on the use of FPS bearings for seismic rehabilitation and design of substation transformers can be found in (Ersoy [6, 11]). Additional parametric study and results of effect of primary system (transformer) isolation on secondary system (bushing) are presented in the following sections. To study primary-secondary interaction a finite element formulation is developed and implemented into the ADINA [12] finite element package. The details of element formulation and results can be found in Ashrafi [13].

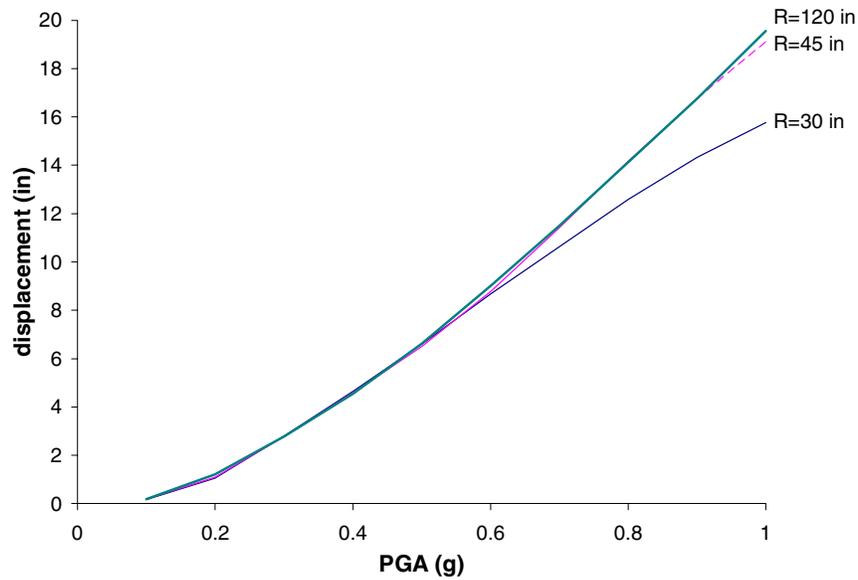


**Figure 1 Typical elevation and section of FPS**

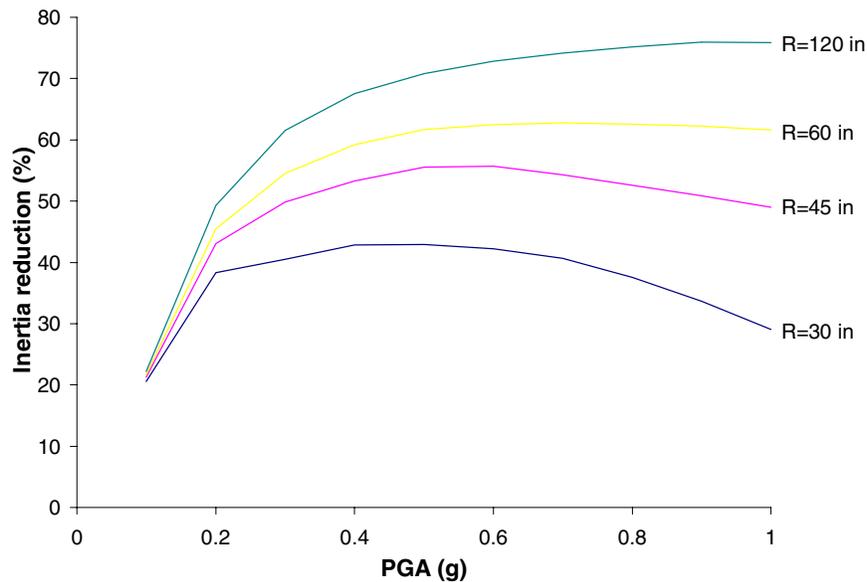
### **Behavior of rigid body on FPS**

The period of a structure isolated by FPS bearings in its rigid body condition depends only on the radius of sliding surface of the isolators and gravitational constant. Thus, bearing radius will determine the overall system displacement and the inertia reduction that can be achieved. Therefore, using radius as a parameter design charts can be developed to determine these response parameters for different levels and characteristics of earthquake ground motions. Consequently, one can determine the amount of slack that should be provided in the connecting cable to prevent interaction between transformer-bushing and interconnecting equipment. Several rock and soil records are used for this parametric study.

Figures 2 and 3 show the average displacement response and inertia reduction for FPS bearings on soil under horizontal and vertical excitations where the peak of vertical excitation is set equal to 80% of the peak horizontal input consistent with IEEE [5]. Displacements increase with ground motion intensity and FPS radius. At lower PGAs the static friction is not exceeded at all times and the system behaves like a fixed case. Therefore, the isolator is more effective for higher PGAs. Inertia reduction is higher for high radii, and a change in radius usually has more effect on inertia reduction compared to displacement. While the inertia reduction increases with increasing PGA, it tends to flatten in PGAs higher than about 0.5g. In the case of  $R < 60$  inch, the shape of inertia reduction graph is slightly different and it starts decreasing after a certain PGA. This is because large displacements require the slider to climb a rather steep (low R) sliding surface putting it under a rather large re-centering force. Choice of the radius should be based on a balance between displacement, inertia reduction, and bearing cost. The cost increases with increasing radius and displacement capacity; therefore, the bearing with lowest radius that satisfies the structural requirements should be chosen. Based on these graphs, a radius of 30~60 inch seems appropriate for transformer applications. Higher radii will provide less benefit in terms of higher inertia reductions, have higher displacements, and have much higher costs. Also, looking at benefits for different PGAs, it can be said that for structures in places with  $PGA < 0.2g$ , cost is the only important factor and  $R = 30$  in is suggested. For  $0.2g < PGA < 0.6g$ , cost and inertia reduction are the factors to be balanced. For  $PGA > 0.6g$ , all factors should be considered.



**Figure 2 Average FPS displacements versus FPS radius for soil records**



**Figure 3 Average inertia reductions versus FPS radius for soil records**

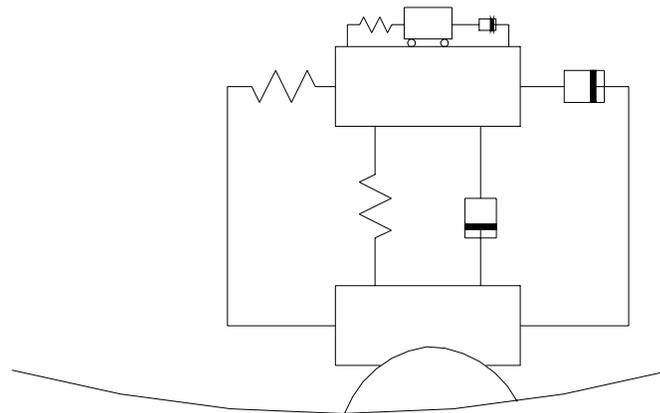
Similar graphs for rock earthquake records are developed, but in the sake of brevity are not presented here. It is determined that type of ground motion, especially at higher PGAs, has an affect on the response of FPS bearings and should be considered in the design.

Considering multi-directional motions, 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 effect of vertical motion is more pronounced on inertia reductions than displacements and it is only significant for records of higher PGAs and of lower frequency contents. Thus, for relatively rigid superstructures the effect of this component of ground motion can be ignored for sites where the design PGA in the vertical direction is less than 0.5g and filtering of the motion due to local soil conditions is not expected. In the following section the effect on flexible superstructure is investigated.

### **Behavior of Fixed and Isolated Primary-Secondary Systems**

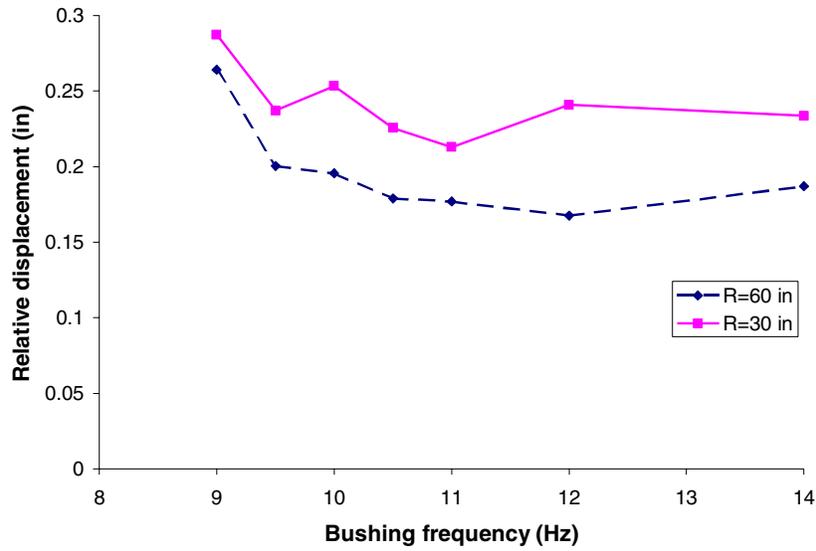
A primary-secondary system was parametrically studied for both fixed and isolated cases, with a more specific aim of assessing the response of isolated transformer-bushing system (Ashrafi [13]). The flexibility of primary system is considered in the model because of its effects on FPS and secondary system response. The primary system has three degrees of freedom, two horizontal and one vertical. The secondary system has two horizontal degrees of freedom and has the same vertical displacement as that of the primary system. All elements have linear elastic force-displacement behavior. The vertical degree of freedom is considered for the primary system to make possible the study of vertical excitation of the primary system, that can change the magnitude and frequency content of normal force, and hence the friction force. Figure 4 shows a 2-D diagram of the model considered. The model has the same characteristics in the other horizontal direction. The physical characteristics of the model are chosen in a range close to actual transformer-bushing systems and the words transformer and bushing might be used interchangeably with primary system and secondary system.



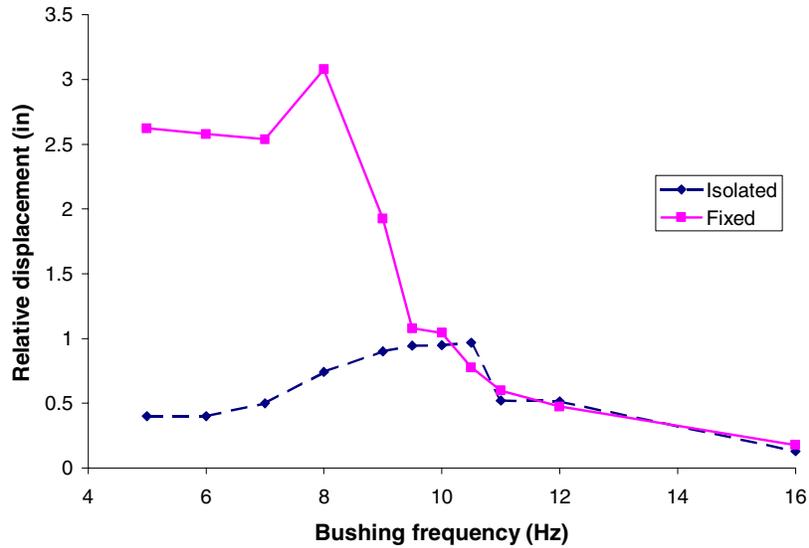
**Figure 4 Model of a primary-secondary system**

Figure 5 shows the bushing relative displacement for different radii of FPS. The primary system used represents a transformer with horizontal frequency of 14 Hz and vertical frequency of 26 Hz (TH14V26). As expected, the FPS with lower radius causes more displacement (and more force) in the bushing. For comparison, it should be said that a 230 kV bushing with a frequency in the range of 11~14 Hz depending on its support condition experiences failure in relative displacements between 0.3~0.35 according to Gilani [2]. Lower frequencies belong to bushings with higher capacities and larger structures that will have higher allowable displacements. The results in this figure are all under 0.3 in, showing that use of FPS prevents any damage to the bushings. Figure 6 shows a comparison of the bushing response for bushings mounted on fixed and isolated TH8V16 transformers. Again, the FPS is effective in reducing the bushing response, especially for lower frequencies. This is due to higher response of bushings with low

frequencies in general. Base isolation is particularly effective when bushing has a frequency close to transformer since the FPS prevents the amplification of bushing response.



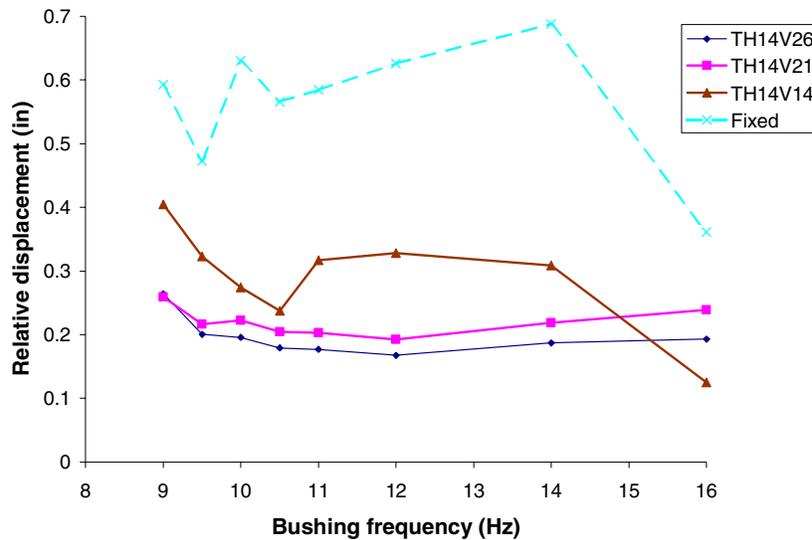
**Figure 5 Bushing response curves when mounted on TH14V26**



**Figure 6 Bushing response curves when mounted on TH8V16**

Figure 7 shows the effect of vertical frequency of transformer on the bushing response. As can be seen, the closer the vertical frequency is to the horizontal frequency, the higher the bushing response. This amplification can particularly be observed for the case when vertical frequency is equal to horizontal frequency. However, the FPS is still effective in reducing the bushing response compared to the fixed-base case. It should be noted that the vertical frequency of transformer is usually far enough from the horizontal

frequency and the TH14V14 case is unrealistic. It is provided to only to demonstrate primary-secondary effect for situations that it may apply, such as in a building.



**Figure 7 Effect of vertical frequency and support fixity on bushing response**

### Effect of Isolation on Foundation Design of Transformers

Transformers are very heavy equipment subject to enormous forces under earthquake and failure of the foundation is one of the major modes of damage in an electrical substation. Proper design of foundation to withstand large vertical and lateral loads and moments is an integral part in seismic design of the substation. Enormity of the seismic loads requires very large foundations for transformers that are very costly. Use of FPS can help reduce the loads, hence reducing the cost of foundation.

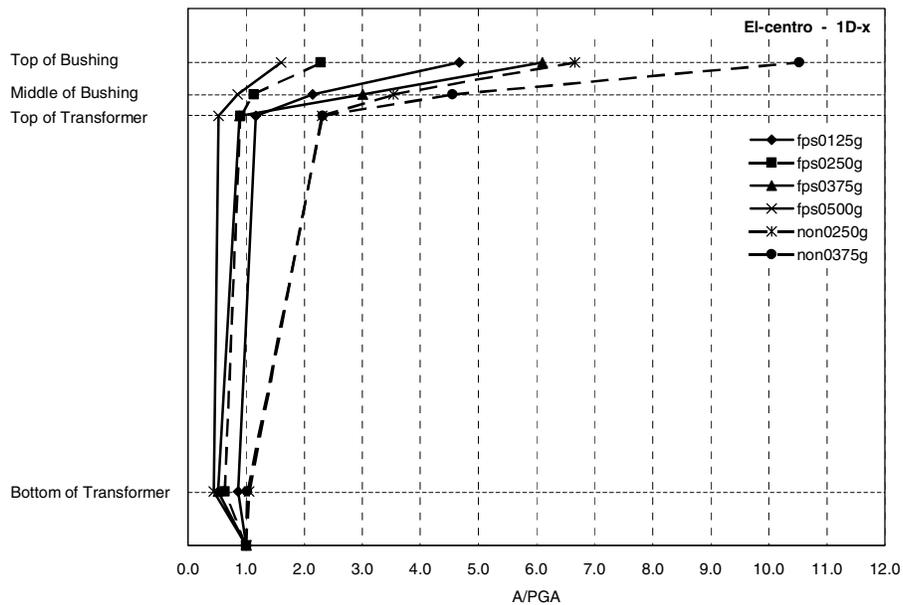
Results from the primary-secondary system analyses were used for foundation design. The designs were done for high and moderate seismic performance levels and it was tried to avoid using piles in the design if possible. Details of design can be found in Ashrafi [13]. It was determined that a shallow foundation is sufficient to sustain the loads applied to the isolated transformer under moderate and high seismic performance levels. Meanwhile, fixed transformers need 9 - 3' diameter piles and length of 15'~30' to sustain the loads under the same seismic performance levels. The difference is due to higher point of effect for loads applied to a fixed transformer in addition to the fact that the value of these loads is also higher. The bigger moment arm puts a higher moment demand on the foundation that necessitates use of piles. Based on limited data provided by LA Department of Water and Power (LADWP), design and construction of seismic foundation (i.e. piles) will add an additional cost of \$50,000 to \$100,000. Use of four FPS bearings will cost about \$60,000 depending on volume and stroke required. This suggests that use of FPS bearings can be even justified on an initial cost basis. Further data should be collected in order to make a more accurate initial cost analysis.

### Experimental study of friction pendulum system

As a part of this research project, about 100 tests were conducted at the National Center for Research on Earthquake Engineering (NCREE) in Taiwan through a collaboration effort (Ersoy [6, 11]). The objective was to compare the response of fixed base transformer model supporting a bushing to those when the systems are isolated using FPS bearings. The testing schedule included white noise tests to identify dynamic characteristics of the bushings and the transformer model and 1-D, 2-D and 3-D excitations were

conducted employing several earthquake records with PGAs in the range of 0.125g to 0.375g. The bushing type 161 kV was used in the experimentation. The dimensions of the transformer model are 7'-10 1/2" x 7'-2 10/16" in plan. The height of the transformer is 8'-10 5/16". Four 18.64" radius FPS bearings with displacement capacity of 4" were used to support the model for the isolated case.

Figure 8 shows a typical acceleration response profile. It can be seen that use of FPS is very effective in reducing the acceleration response, especially for the bushing. For the range of accelerations considered, the effectiveness of FPS usually increases with an increase in input acceleration. The effectiveness also depends on the record used. For example, inertia reductions (compared to input PGA) of 47% and 62% were attained with PGA of 0.25g and 0.375g for the Chi-I Ray-Li record. The corresponding values for the El-Centro record were 37% and 49%.



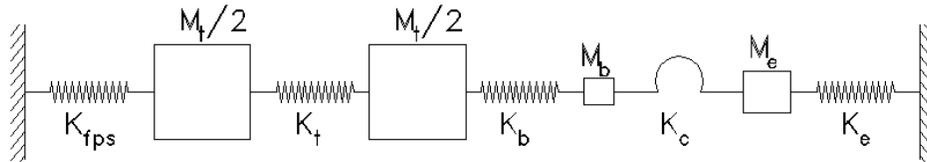
**Figure 8 Acceleration profile for El-Centro record for 1-D case**

### **INTERACTION OF TRANSFORMER-BUSHING SYSTEM WITH INTERCONNECTING EQUIPMENT**

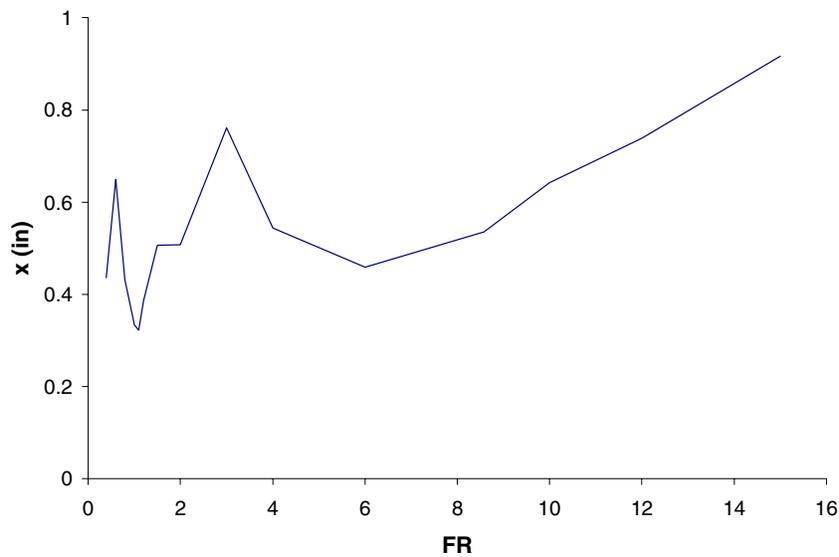
Transformers are only one element in an electric substation. Substations designs involve interconnection of many electrical equipment in order to achieve the desired electrical function. An isolated transformer will undergo large displacements under earthquake. However, the interconnecting equipment are usually fixed and have small displacements in comparison. This means that interaction between transformer-bushing and the interconnecting equipment will be inevitable unless measures are taken to provide enough extra displacement capacity between these elements. It has been revealed in field investigations during recent earthquakes that this interaction may be largely responsible for the observed damage to connected electrical substation equipment (Der Kiureghian [14], Hong [15]).

To study the interaction of isolated transformer-bushing with other electrical equipment a simplified model is employed as shown in Figure 9. The parameter used for this study is the relative frequency of the interconnecting equipment to that of the FPS (or transformer-bushing system isolated by the FPS). Thus, a frequency ratio, FR, is defined as the ratio of the interconnecting equipment frequency to FPS frequency. The FPS frequency is used for this comparison instead of that of the fixed transformer or bushing because

results have shown that FPS displacement dominates the overall system response and that transformer and bushing have a displacement very close to it. They move as a rigid body. The radius of  $R = 40$  inch is used for FPS that corresponds to a period of 2.0 seconds for the isolation. A weight of 200 kips and frequency of 11 Hz for transformer and 5 kips and 10 Hz for bushing are assumed. The strong horizontal component of the 1940 El Centro earthquake with a peak acceleration of 1.0g is applied to the model. Figure 10 shows the displacement in the bushing for different ratios of FR. The bushing response has a minimum around  $FR = 1$  with the minimum value of 0.32" that is equal to the failure displacement of the 196 kV bushing (0.3~0.35 in) (Gilani [2]). If there were enough slack to prevent interaction, the relative displacement of bushing would be slightly less than 0.05 in, which is acceptable. This shows that interaction has adverse effects, even in frequency ratios that would result in little or no interaction in linear systems.

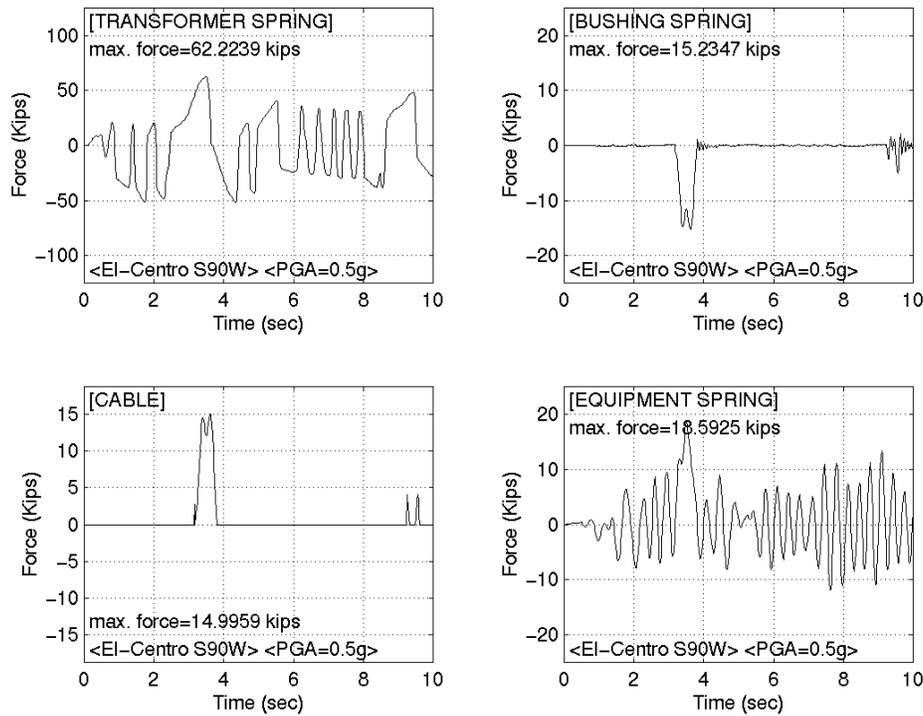


**Figure 9 Simplified model**



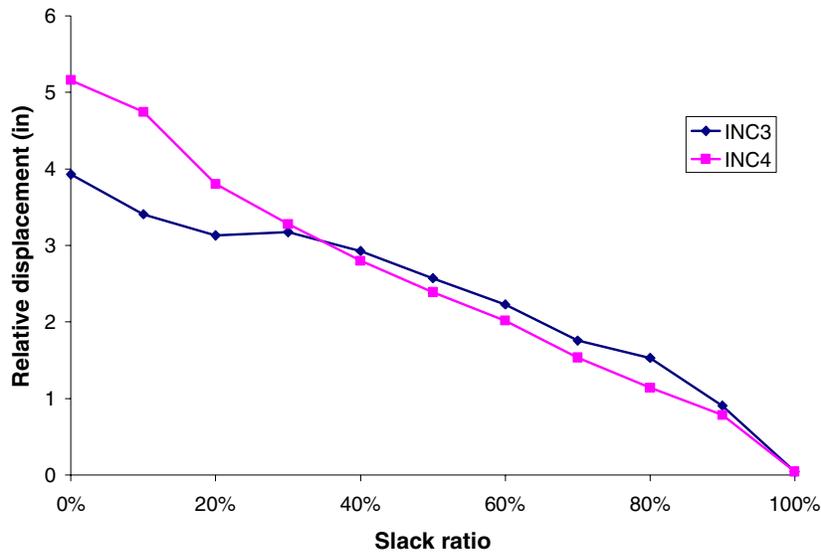
**Figure 10 Relative displacement of bushing versus frequency ratio**

Figure 11 shows different force values for a base-isolated case with a slack amount half the amount required to preclude interaction. The displacement of FPS is dominant and transformer and bushing have total displacements that are very close to it. Sliding of FPS away from the interconnecting equipment is the salient factor determining the interaction responses. When the FPS slides beyond the point where the cable becomes taut, the forces in the transformer, bushing, connecting cable, and interconnecting equipment all have sudden jumps. This is especially evident in the cable force and bushing force. Subsequently the system returns to its bounded response until when the FPS again slides beyond the critical point (out of bound).



**Figure 11 Force response curves in simplified model**

To study the effect of the amount of slack on interaction among the equipment another set of analyses is performed using the slack ratio as the parameter (Ashrafi [13]). The slack ratio is defined as the ratio of the provided slack to the slack required to prevent interaction. The interconnecting equipment used have frequencies in a range of 1 to 4 Hz. The transformer and bushing have frequencies of 14 Hz and 11 Hz, respectively. An FPS with  $R = 60$  in ( $T = 2.48$  s) is used for isolation. To see the effect of slack ratio on interaction among equipment, the analyses are performed for interconnecting equipment with frequencies 3 Hz and 4 Hz. These are thought to be the most typical values and are denoted as INC3 and INC4. Slack ratios are varied from 0 to 100%, where 100% corresponds to the case of large enough slack that there is not interaction. Figure 12 shows the relative displacement of bushing. As expected it is observed that even small tautness of the cable will amplify the response of the bushing considerably. For slack ratio of 90%, interaction with INC3 causes a relative displacement of 0.91 in the bushing that is more than 21 times that of the sufficient slack case. This ratio is 18 for interaction with INC4. These values are much higher than the allowable displacement in the bushing that is in the order of 0.3 in for a 230 kV bushing according to Gilani [2]. This suggests that any interaction should be prevented to ensure that bushing does not undergo excessive displacements and sustain large forces. Even the slightest interaction has the potential of damaging the bushing. As expected, it is seen that as the slack is reduced, the bushing response is increased. To prevent any interaction, it is recommended to provide a slack equal to the sum of the maximum absolute values of the FPS and the interconnecting equipment.



**Figure 12 Relative bushing displacements versus slack ratio**

## CONCLUSIONS

Transformers and bushings were identified as the most critical elements of electric substations. Finite element studies were performed on transformer-bushings and the flexibility of the transformer was found to have an effect on the bushing response. Translational modes of the transformers have the highest effect on the response of the bushing. Consistent with performance during past earthquakes, failures were observed in transformer-mounted bushings. It was determined that the dynamic amplification factor specified in IEEE code is not always conservative. Friction Pendulum System was investigated as a means of retrofit and rehabilitation for transformer-bushing. Among parameters considered are peak ground acceleration, bi-directional motions, effect of vertical motion, and isolation radius. Inertia reduction and the maximum displacement of the system are the criteria used in evaluating the seismic response and the effectiveness of FPS bearings. Furthermore, impact of primary system isolation on the response of secondary system was considered. It was observed that FPS provides considerable inertia reductions depending on the peak ground acceleration and the bearing radius of curvature. The FPS system is more effective in reducing inertia forces for higher peak ground accelerations. The effect of vertical motion on the response of FPS is more pronounced on inertia reductions than on displacements. Graphs showing the average inertia reductions and displacements for several earthquake records were developed. FPS was also very effective in reducing the seismic response of bushings for all frequencies. For the cases considered, the response of 196 kV bushing mounted on isolated transformers was within its experimentally determined displacement capacity. For bushings with lower fundamental frequency the response reductions are even more significant. For the practical range of horizontal and vertical frequencies of transformers coupling between horizontal and vertical responses has limited effect on FPS response and its efficiency. FPS was very effective in reducing the foundation size in a way that its use might be even justified on an initial cost basis. The analyses showed that even the slightest interaction between the transformer-bushing and interconnecting equipment has significant adverse effects and must be prevented. To achieve this, either time history analysis should be performed to determine the slack in the connecting flexible cable or it can be conservatively assumed to be equal to the sum of the maximum absolute values of FPS and interconnecting equipment displacements. The displacement of FPS can be determined from graphs provided in this study and that for the interconnecting equipment from the appropriate design response spectrum.

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