Seismic Response of High Voltage Electrical Transformer–Bushing Systems

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Abstract: High voltage porcelain bushings mounted on transformers have shown vulnerability during past earthquakes. This is contrary to the generally good performance observed during shake table qualification testing of bushings anchored to a rigid base. The seismic vulnerability of porcelain bushings might be caused by the flexibility of transformer tanks and of bushing attachments. Current seismic qualification guidelines consider an amplification factor of 2.0 between the amplitude of the ground motion and the amplitude of the motion at the base of the bushing. This paper investigates numerically the dynamic response of porcelain bushings mounted on transformer tanks. The results of the numerical study show that large amplification occurs when the fundamental frequency of the porcelain bushing is tuned with the fundamental frequency of the transformer tank.

DOI: 10.1061/(ASCE)0733-9445(2006)132:2(287)

CE Database subject headings: Earthquakes; Electrical equipment; Electric transmission structures; Seismic effects.

Introduction

Past seismic events, such as the 1989 Loma Prieta and 1994 Northridge earthquakes in California, have demonstrated the vulnerability of particular electrical substation components to moderate and severe ground shaking, particularly in equipment of 230 kV and above. Failure commonly occurred in porcelain bushings mounted on transformers and also in post insulators. The combined damage inflicted upon electrical substation equipment by the Loma Prieta and Northridge earthquakes has resulted in an estimated $283 million worth of losses (Schiff 1998).

High voltage transformers are substation equipment that step up or step down the voltage within transmission lines. Bushings are oil-filled insulating components used to connect the internal electrical coils of transformers to power equipment in a substation. Bushings are cantilever like components that protrude vertically, or at angle of up to 20° from the top of transformers. Porcelain bushings are often composed of a number of annular rings stacked upon one another and post-tensioned together by the internal conductor.

Due to the nature of their design, porcelain bushings have proven to be one of the most vulnerable pieces of substation equipment during earthquakes. The most common failure mode for a bushing is oil leakage between its base flange and the upper porcelain portion.

The *IEEE-693* standard (Institute of Electrical and Electronics Engineers 1997), which provides seismic design recommendations for substation equipment, states that bushings with voltage ratings of 161 kV and above must be seismically qualified by shake table testing. Since placing a full-scale transformer–bushing system on a shake table is not economically feasible on a routine basis, bushing qualification tests are generally performed by placing the bushing on a rigid frame in lieu of the transformer body itself. Although the transformer body is assumed to be fairly rigid, it is acknowledged that the supporting structure of the bushing, consisting of the turret and transformer tank, amplifies the ground acceleration. For this purpose, the *IEEE-693* standard assumes that the motion at the base of the bushing is equal to the ground motion multiplied by a factor of 2.

Perhaps with the exception of 500 kV porcelain bushings, shake table testing of porcelain bushings on a rigid base using the *IEEE-693* seismic qualification procedure has demonstrated a generally good performance of these components. This good experimental performance is contrary to the failure of bushings observed in the field following past earthquakes. It is believed that the actual seismic vulnerability of porcelain bushings might be caused by the flexibility of transformer tanks and of bushing attachments, which amplify their dynamic response.

Very few detailed numerical finite element studies have been conducted on the seismic response of transformer–bushing assemblies. Bellorini et al. (1998) performed experimental on-site dynamic tests and numerical finite element analyses on 230 kV power transformer in order to evaluate the amplification factor between the ground and the transformer bushing flange and response factor of the bushing itself. In a recent study, Ersoy and Ala Saadeghvaziri (2003) presented the development of finite element models and discussed the results of dynamic time-history analyses conducted on several transformer–bushings systems. It was found that the transformer tank top plate flexibility affects bushing dynamic characteristics. Also, the level of accelerations obtained in the bushings was much higher than that predicted by the *IEEE-693* standard. This could explain the discrepancy

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Note. Associate Editor: Vinay Kumar Gupta. Discussion open until July 1, 2006. Separate discussions must be submitted for individual papers. To extend the closing date by one month, a written request must be filed with the ASCE Managing Editor. The manuscript for this paper was submitted for review and possible publication on July 16, 2004; approved on May 10, 2005. This paper is part of the ***Journal of Structural Engineering***, Vol. 132, No. 2, February 1, 2006. ©ASCE, ISSN 0733-9445/2006/2-287–295/$25.00.

between laboratory and actual performance of bushings during previous earthquakes. The writers also stressed the need for further research on other types of transformer–bushing systems to better evaluate their seismic response. This paper addresses this issue by investigating numerically the dynamic response of porcelain bushings mounted on transformer tanks, with a particular focus on the amplification of the ground motions at the base of bushings.

Numerical Modeling of Transformer-Bushing Systems

Scope of Study

The main objective of the numerical study reported in this paper is to quantify the amplification that occurs between the ground motion and the motion at the base of bushings for various types of high voltage transformers, and to compare these results with the constant (frequency independent) amplification factor of 2.0 assumed by the *IEEE-693* standard.

In this numerical study, linear dynamic time-history analyses on three-dimensional finite element models of four different high voltage transformers were performed using the commercially available structural analysis software *SAP 2000* (Computers and Structures 2003). The analyses were performed in each principal direction of the transformers under 20 different historical strong ground motion time-histories scaled such that their 2% damped spectral acceleration values at the fundamental period of each transformer tank matched the 2% damped high required level response spectrum specified in the seismic qualification procedure of the *IEEE-693* standard.

The ground motion amplification was then quantified in two different ways. First, a frequency dependent spectral amplification was computed by taking the ratio of the 2% damped absolute acceleration response spectrum of the horizontal acceleration time-history obtained at the base of the bushing to that of the horizontal ground acceleration. Second, for three of the four transformer–bushing systems, the ground motion amplification was also computed by taking the ratio of the maximum bending moment obtained at the base of the bushing mounted on the transformer to that of the same bushing rigidly mounted.

Transformer-Bushing Systems Considered

Although most high voltage transformer–bushing systems vary greatly in weight, size, and geometry, they all contain a certain number of key common components: the transformer tank, the core and coil contained within the tank, radiators attached to the outside walls of the tank, bushings mounted on a turret at the top of the tank, oil contained within the tank, and often an oil conservator tank also attached to the upper half of the tank. The majority of a transformer's mass is comprised of the internal core, copper coils, and oil. The tank walls are comprised of steel plates with a typical thickness of 12 mm and stiffeners such as channels, I-beams, or plates welded to the tank walls which provide the majority of the lateral stiffness of a transformer tank.

In an attempt to capture these variations in properties, four different high voltage transformer–bushing systems were considered in this numerical study in order to gain a better understanding of the supporting structure's seismic response for various transformer sizes and characteristics. The four transformer models were: a 525 kV Transformer A, a 500 kV Transformer B, a 230 kV Transformer C, and a 500 kV Transformer D. Table 1 presents the overall dimensions and weights of each transformer. Fig. 1 shows the finite element mesh generated for each transformer. A detailed description of each transformer can be found elsewhere (Matt and Filiatrault 2004).

Table 1. Dimensions and Weights of Transformers

Transformer	Voltage rating (kV)	Plan dimensions (m)		Height (m)	Total weight[a] (kN)
		Longitudinal direction	Transverse direction		
A	525	3.02	2.68	6.95	2,060
B	500	3.48	1.74	4.82	1,339
C	230	7.38	3.05	4.39	2,126
D	500	7.93	3.29	5.12	2,994

[a]Including internal core, oil, and appendages.

Modeling Assumptions

The three-dimensional finite element models of the four transformer–bushing systems were constructed using the structural analysis software *SAP2000* (Computers and Structures 2003). Eight-node shell elements with the appropriate thickness

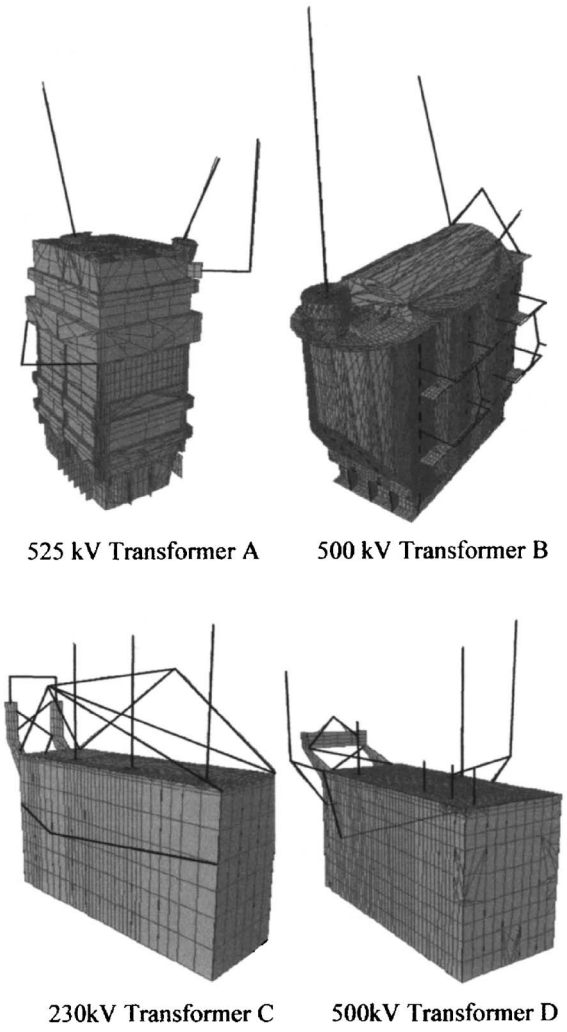


Fig. 1. Finite element models of transformer–bushing systems

and mass were used to model the transformer tank walls. The shell elements allow for in-plane deformations and out-of-plane bending. Tridimensional beam elements as well as eight-node shell elements were used to model the stiffeners attached to the tank sides. The geometry, thickness, location, and mass of all walls, plates, and beams were obtained through manufacturer's structural drawings, surveying, and previously provided static models (Westinghouse 1966; Gundy 2000, 2002). Only the major modeling assumptions are discussed in this section; details of the finite element models can be found elsewhere (Matt and Filiatrault 2004).

Several modeling assumptions had to be made during the development of the finite element models. The first modeling assumption was related to the oil contained inside the transformer tank. Transformer tanks are generally filled with oil up to their top. For this condition, oil-sloshing effects become negligible and were not accounted for in the models. To account for the mass of the oil within the tank, additional mass was symmetrically added to the vertical perimeter of the steel tank walls leading to an appropriate location for the center of gravity of the oil mass. This simple approach, however, neglects the potential uneven distribution of lateral loads induced by the oil on the walls of the tank.

Due to the nature of its design, the core and coil can be assumed rigid. However, one significant modeling issue is related to the bracing of the core and coil to the interior walls of the transformer tank. If the core and coil are not braced, they do not provide any stiffness to the tank, as both components will act as two separate and independent structures. In addition, their mass should not be included in the dynamic analysis. On the other hand, if the core and coil are rigidly braced to the transformer tank, then the whole transformer becomes essentially rigid and the mass of the core and coil should be included in the dynamic analysis. Although some cores and coils can be lightly braced to the transformer tank, most are not. Even the ones that are braced may only be braced at midheight or braced by wood shims between the core and transformer shell. Therefore, for modeling purposes, it was decided to consider the coil and core as unbraced elements and not to include any stiffness or mass from these internal components in the finite elements models.

Another modeling assumption made was that the radiators and oil conservator tank were considered rigidly attached to the transformer tank. This allowed for simplification of the models and eliminated some of the noncritical local modes of vibration. To ensure the validity of this assumption, comparison of the transverse and longitudinal frequencies of the transformers were done when allowing for flexibility of these components. It was concluded that making these appendages rigid had no significant effect on the global longitudinal and transverse modal properties of both the bushing and transformer tank (Matt and Filiatrault 2004). The mass of each radiator and oil conservator tank, however, was included in the models at their respective center of gravities.

All porcelain bushings were modeled as multiple beam elements with the appropriate geometry, stiffness, and mass. Much of the flexibility of transformer bushings results from gaskets used to prevent oil leaks at the flange connection and at various other locations along the bushing height. Therefore, gasket elements were introduced into the bushing models at the proper locations in order to capture this additional flexibility. These gasket elements were modeled as short beam elements with their proper material properties. Bushing and gasket models were based upon information from available bushing qualification reports and structural drawings included in the transformer manufacturer's reports.

Table 2. Earthquake Ground Motions Considered for Numerical Study

Seismic event	Year	Moment magnitude	Recording station	Recorded PGA (g)
Superstition Hills	1987	6.7	Brawley	0.116
			El Centro	0.258
			Plaster City	0.186
Northridge	1994	6.7	Beverly Hills	0.416
			Canoga Park	0.356
			Glendale	0.357
			Hollywood	0.231
			N Faring Rd	0.273
			Coldwater	0.271
			Sunland	0.157
Loma Prieta	1989	6.9	Capitola	0.529
			Gilroy #3	0.555
			Gilroy #4	0.417
			Gilroy #7	0.226
			Hollister	0.279
			Saratoga	0.332
Cape Mendocino	1992	7.1	Fortuna	0.116
			Rio Dell	0.385
Landers	1992	7.3	Desert Hot Springs	0.154
			Yermo	0.152

The final major modeling assumption dealt with the support conditions of the transformers. Pin supports were used at bolt locations and fully fixed conditions were used at weld locations. Since transformer tanks are typically supported by a concrete pad, roller supports were added at each node under the tank base to prevent out of plane bending of the bottom shell.

Earthquake Ground Motions Considered

The 20 ground motions chosen for the numerical study are historical events that have occurred in California (Krawinkler et al. 2000). These strong ground motions were recorded from various recent seismic events with varying fault mechanisms. All ground motions are such that the location of measurement was far enough from the fault rupture to be free of any near-fault directivity effects. Table 2 presents details of the 20 ground motions selected for the analytical study.

Each of the time histories were scaled to match the *IEEE-693*, 2% damped, high required response spectrum at the fundamental frequency of each transformer tank in the transverse and longitudinal direction, respectively (Matt and Filiatrault 2004).

Analysis Procedures

Linear time-history dynamic analyses were performed separately in the longitudinal and transverse direction for each of the four transformers considered in this study under the 20 scaled historical earthquake records selected. Based on the results obtained, dynamic amplification factors between the motion at the base of the transformer tanks and that at the base of the bushings were quantified in two separate ways.

In the first procedure, a horizontal dynamic amplification was

computed as a function of frequency. For a given record, the dynamic amplification was obtained by taking the ratio of the 2% damped response spectrum computed from the horizontal acceleration at the base of the high voltage bushing (i.e., top of the transformer) to the corresponding 2% damped response spectrum from the ground motion being considered. This spectral ratio is defined as a "spectral amplification," which explicitly gives the horizontal dynamic amplification as a function of frequency. The mean, mean +1 standard deviation (SD) and mean −1 SD values of the spectral amplification of the 20 earthquake records analyzed were computed for each of the four transformers in both the longitudinal and transverse directions and then compared to the *IEEE-693* assumed frequency independent amplification value of 2.0.

It must be noted that this first approach does not directly consider the rotational acceleration at the base of the bushing, which will also affect its dynamic response. In order to consider this effect, a second procedure was used to quantify the dynamic amplification between the motion at the base of the transformer tanks and that at the base of the bushings.

Three different bushings were considered for this second numerical study: the 500 kV bushing from Transformer D, the 230 kV bushing from Transformer C, and the 525 kV bushing from Transformer A. As shown later, the bushing from Transformer B exhibited very small spectral amplification and was not considered in the second numerical study. For each of these bushings, a dynamic time-history dynamic analysis was performed under two mounting conditions. First, the bushing was analyzed as being mounted on the transformer. In the second analysis, the bushing was assumed rigidly mounted. The time-history dynamic analyses were performed using the 1992 Landers earthquake record that has been filtered to match the *IEEE-693*, 2% damped, high required response spectrum (Fenves et al. 2003). For a given bushing, a "bending moment amplification" was computed by taking the ratio of the maximum bending moment obtained with transformer-mounted boundary conditions to the maximum bending moment obtained for fixed base conditions. This peak bending moment amplification was then compared with the amplification value of 2.0 defined within the *IEEE-693* standard as well as the spectral amplification values as computed in the first numerical study described above.

Table 3. Computed Modal Properties of 525 kV Transformer A

Mode	Natural frequency (Hz)	Mode shape	Modal mass participation (%)	
			Longitudinal direction	Transverse direction
1	2.7	Surge arrestor, Mode 1	0.2	0.2
2	2.9	High voltage bushing, Mode 1	0.3	1.0
3	3.0	Surge arrester, Mode 2	1.4	0.1
4	3.4	High voltage bushing, Mode 2	1.8	0.9
5	8.4	Transformer tank, Mode 1, Transverse direction	0.0	67.5
6	11.4	Transformer tank, Mode 1, Longitudinal direction	72.2	0.0
7	13.2	High voltage bushing, Mode 3	0.2	0.0
8	14.6	Surge arrester, Mode 3	0.9	0.3
9	15.3	Surge arrester, Mode 4	0.4	0.5
10	20.2	Transformer tank, Mode 2, Transverse direction	0.0	13.6
11	24.8	Wall plate bending, Mode 1	0.7	0.0
12	33.9	Transformer tank, Mode 2, Longitudinal direction	13.5	0.1
13	42.8	Transformer tank, Mode 1, Torsion	0.1	2.2
14	50.7	Wall plate bending, Mode 2	0.6	7.0
Total			92.3	93.4

Numerical Results

Modal Properties of Transformer-Bushing Systems

Tables 3–6 present the computed natural frequencies and associated percentage of modal mass participation for each of the four transformer finite element models considered. For each transformer model, the number of modes considered for the dynamic analyses was such that at least 90% of the total modal mass was accounted for in each principal horizontal direction. The first few modes of vibration were generally associated with the deformation of extraneous elements such as oil conservators, surge arrestors, and bushings with negligible modal mass contribution. As described above, these elements were made rigid for the purpose of conducting dynamic time-history analyses. The modes that contributed the largest modal mass participation are that of the transformer frame in the transverse and longitudinal directions.

For each model, the transverse (narrow) direction had a lower transformer tank fundamental frequency than in the longitudinal direction. The computed transformer tank fundamental frequencies are 8.4, 14.2, 10.8, and 10.5 Hz in the transverse direction and 11.4, 25.3, 25.1, and 20.8 Hz in the longitudinal direction for Transformers A, B, C, and D, respectively. The high voltage bushing fundamental frequencies are 2.9, 3.2, 9.1, and 3.4 Hz for Transformers A, B, C, and D, respectively. It is worth noting that these frequencies are representative of the modes of vibration of the bushing attached to the transformer supporting structure. Bushings mounted to rigid frames have much higher frequencies, as shown in Table 7.

Spectral Amplification Results

Figs. 2 and 3 present the mean, mean +1 SD and mean −1 SD values of the spectral amplifications computed across the ground motion ensembles for the four transformer models along the longitudinal and transverse directions, respectively. The numerical results are also reproduced in Table 8. The spectral amplifications exhibit three common trends across the transformer models. First, for a given transformer in a given direction, there are generally

Table 4. Computed Modal Properties of 500 kV Transformer B

Mode	Natural frequency (Hz)	Mode shape	Modal mass participation (%)	
			Longitudinal direction	Transverse direction
1	3.2	High voltage bushing, Mode 1	0.3	3.0
2	4.9	High voltage bushing, Mode 2	2.8	0.4
3	14.2	Transformer tank, Mode 1, Transverse direction	0.0	72.4
4	21.9	Transformer tank, Mode 1 Longitudinal direction	26.9	0.0
5	25.3	Transformer tank, Mode 2 Longitudinal direction	38.8	0.0
6	34.7	High voltage bushing, Mode 3	0.0	0.9
7	41.1	Wall plate bending, Mode 1	0.1	0.4
8	41.9	Transformer tank, Mode 3 Longitudinal direction	1.4	0.0
9	46.2	High voltage bushing, Mode 4	0.7	0.9
10	46.5	Oil conservator tank, Mode 1 Longitudinal direction	0.5	0.1
11	54.9	Transformer tank, Mode 2, Transverse direction	0.2	1.9
12	58.2	Wall plate bending, Mode 2	0.5	2.5
13	63.1	Transformer tank, Mode 1, Torsion	4.4	0.1
14	68.1	Wall plate bending, Mode 2	0.3	0.0
15	78.5	Transformer tank, Mode 3 Longitudinal direction	11.1	0.0
16	82.2	Transformer tank, Mode 3, Transverse direction	0.1	9.9
17	94.7	Wall plate bending, Mode 3	7.2	0.1
Total			95.3	92.6

Table 5. Computed Modal Properties of 230 kV Transformer C

Mode	Natural frequency (Hz)	Mode shape	Modal mass participation (%)	
			Longitudinal direction	Transverse direction
1	9.1	High voltage bushing, Mode 1	0.0	17.9
2	10.3	High voltage bushing, Mode 2	0.1	1.4
3	10.8	Transformer tank, Mode 1, Transverse direction	0.1	23.8
4	11.6	Transformer tank, Mode 2, Transverse direction	0.1	13.5
5	12.0	Oil conservator tank, Mode 1 Longitudinal direction	12.5	0.2
6	13.2	High voltage bushing, Mode 3	0.0	0.1
7	13.5	High voltage bushing, Mode 4	1.1	0.0
8	16.9	Transformer tank, Mode 3, Transverse direction	0.0	13.8
9	19.2	Wall plate bending, Mode 1	0.1	10.5
10	25.1	Transformer tank, Mode 1, Longitudinal direction	58.2	0.5
11	26.0	Transformer tank, Mode 4, Transverse direction	2.3	9.2
12	37.2	Wall plate bending, Mode 2	0.6	1.9
13	37.9	Transformer tank, Mode 2, Longitudinal direction	14.8	0.0
14	41.3	Wall plate bending, Mode 3	1.3	0.3
Total			91.2	93.1

two major peaks in the spectral amplification. These two peaks occur at the fundamental frequencies of the transformer tank and of the bushing, respectively. In addition, the amplification at the transformer frequency is consistently larger than the amplification at the frequency of the bushing. Finally, the amplification in the transverse (narrow) direction is larger than that in the longitudinal direction. Note that for Transformer D in the transverse direction the first two modes of the transformer tank are closely spaced (see Table 6) leading to two peaks in the spectral amplification, as shown in Fig. 3.

The main focus of this study is the ground motion amplification that occurs at the fundamental frequency of the bushing since this frequency will govern the behavior of the bushing under seismic excitation. Based on the results shown in Figs. 2 and 3 and Table 8, the mean spectral amplification at the bushing fundamental frequency in the transverse direction is equal to 1.6, 1.1, 17.1, and 2.3 for Transformers A, B, C, and D, respectively. The mean spectral amplification at the bushing fundamental frequency in the longitudinal direction is equal to 1.3, 1.1, 2.8, and 1.2 for Transformers A, B, C, and D, respectively. Only the 500 kV Transformer D and 230 kV Transformer C have mean amplifications larger than the *IEEE-693* standard prescribed value of 2.0 at the bushing frequencies. In fact, the 230 kV Transformer C experi-

Table 6. Computed Modal Properties of 500 kV Transformer D

Mode	Natural Frequency (Hz)	Mode shape	Modal mass participation (%)	
			Longitudinal direction	Transverse direction
1	2.7	High voltage arrestor, Mode 1	0.0	0.2
2	2.9	High voltage arrestor, Mode 2	0.1	0.0
3	3.4	High voltage bushing, Mode 1	0.0	0.4
4	6.3	Oil conservator tank, Mode 1 Longitudinal direction	0.5	0.0
5	7.0	Oil conservator tank, Mode 2 Longitudinal direction	6.4	0.0
6	7.4	Low voltage arrestor, Mode 1	0.0	7.1
7	8.1	Low voltage arrestor, Mode 2	0.0	0.9
8	8.4	High voltage bushing, Mode 2	0.4	0.0
9	8.4	High voltage bushing, Mode 3	0.0	4.6
10	9.9	Oil conservator tank, Mode 1 Transverse direction	0.0	2.3
11	10.5	Transformer tank, Mode 1 Transverse direction	0.0	37.5
12	11.0	High voltage arrestor, Mode 3	0.0	0.0
13	12.5	Low voltage bushing, Mode 1	0.0	0.0
14	14.9	Low voltage arrestor, Mode 3	0.3	0.5
15	15.8	Transformer tank, Mode 2 Transverse direction	0.0	29.8
16	17.7	Wall plate bending, Mode 1	0.0	1.5
17	19.9	Low voltage arrestor, Mode 4	0.5	0.6
18	20.8	Transformer tank, Mode 1 Longitudinal direction	30.9	0.3
19	21.9	Transformer tank, Mode 2 Longitudinal direction	37.6	0.4
20	22.8	Transformer tank, Mode 3 Longitudinal direction	10.4	0.4
21	28.7	Wall plate bending, Mode 2	0.0	0.1
22	37.8	Oil conservator tank, Mode 2 Transverse direction	0.1	5.6
23	44.9	Wall plate bending, Mode 3	0.2	0.0
24	47.9	Oil conservator tank, Mode 1 Longitudinal direction	5.0	0.2
Total			92.4	92.4

ences a very large amplification in the ground motion (17.1) in its transverse direction. This result can be explained by comparing the bushing and transformer fundamental frequencies for this system. As shown in Table 5, these two fundamental frequencies are much closer to each other for the 230 kV Transformer C (9.1 and 10.8 Hz) than for the other transformers considered. The fact that the highest amplifications occurred when these two fundamental frequencies are relatively close to each other seems rather intuitive; however, no clause in the *IEEE-693* standard currently accounts for such a situation.

Table 7. Fundamental Frequencies of High Voltage Bushing Mounted on Transformer and Rigidly Mounted

Bushing	Fundamental frequency (Hz)	
	Mounted on transformer	Rigidly mounted
525 kV Transformer A	2.9	8.9
500 kV Transformer B	3.2	8.7
230 kV Transformer C	9.1	18.9
500 kV Transformer D	3.4	8.9

Fig. 4 shows the variation of the mean spectral amplification as a function of the transformer-to-bushing fundamental frequency ratio based on the results obtained in the dynamic analyses. As the transformer-to-bushing fundamental frequency ratio becomes closer to one, a larger amplification occurs at the bushing frequency. In fact, the variation seems to follow an exponential pattern. The difference in amplification between frequency ratios of 1.0 and 2.0 is much larger than between the frequency ratios of 2.0 and 3.0.

Bending Moment Amplification Results

The influence of the transformer tank and flexibility of the top plate increased the peak bending moment experienced by the bushing in comparison to the same bushing rigidly mounted. For the 525 kV Transformer A bushing, the 500 kV Transformer D

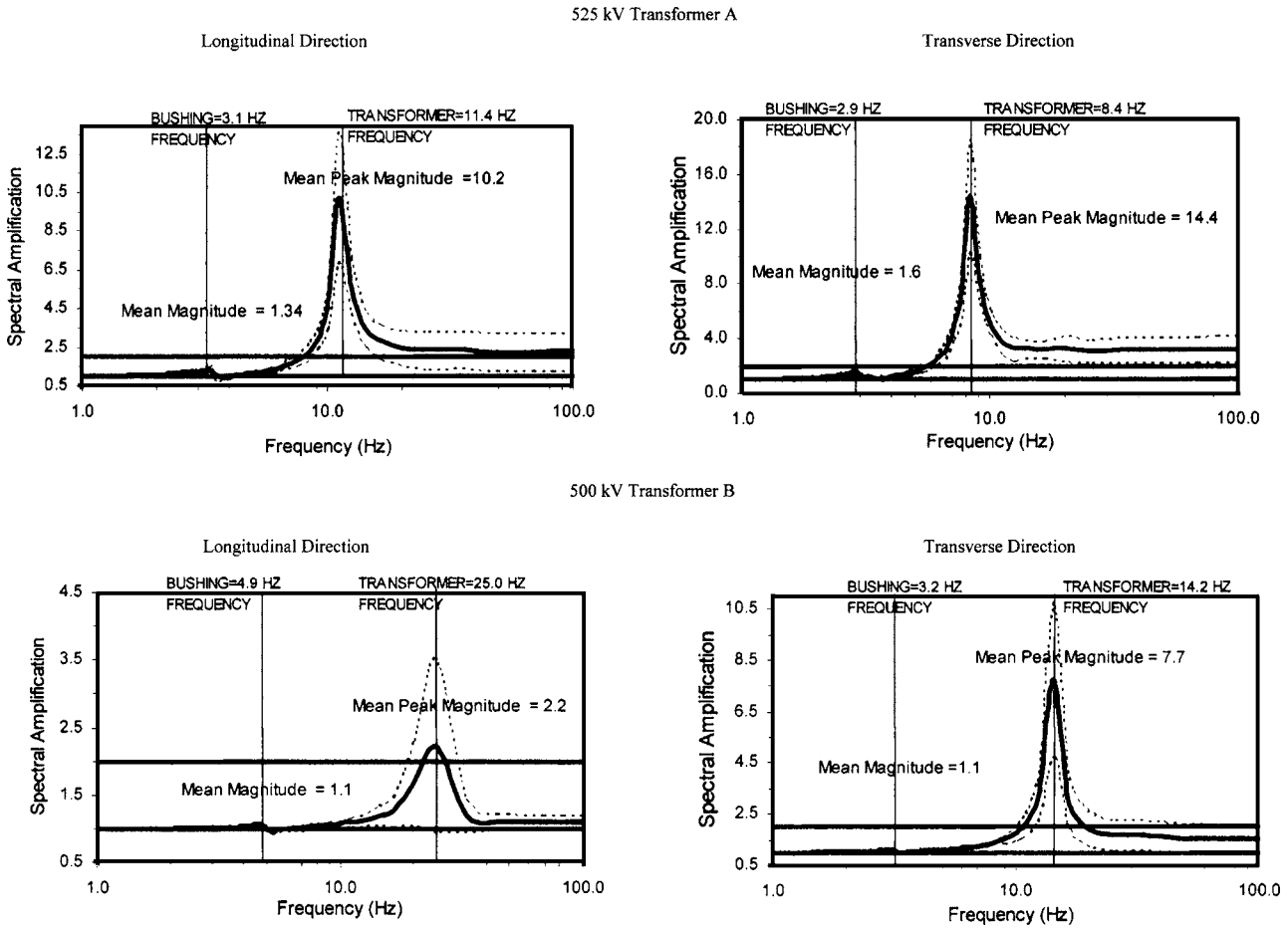


Fig. 2. Mean, mean +1 standard deviation and mean −1 standard deviation of spectral amplifications, transformers A and B

bushing, and the 230 kV Transformer C bushing, the peak moment amplification was 1.1, 1.7, and 7.9, respectively. In other words, for the Transformer C bushing, the peak bending moment of the bushing was 7.9 times greater when mounted upon the transformer than when it is rigidly mounted, as is the case during seismic qualification tests.

Using the same Landers ground motion time-history that matched the *IEEE-693*, 2% damped, high required response spectrum, spectral amplifications were computed for the same three transformers in order to compare the two different amplification definitions in this study. It was found that the peak bending moment amplification is significantly less than the spectral amplification, as shown in Fig. 5. For the 230 kV Transformer C, the amplification of the peak bending moment is half of the spectral amplification at the bushing fundamental frequency. Both Transformers A and D experienced spectral and bending moment amplifications less than 2.0 at their corresponding bushing fundamental frequency. Also, both Transformers A and D experienced an amplification of their peak bending moment of about 70% of the spectral amplification at their respective bushing fundamental frequency. Only the 230 kV Transformer C bushing has a bending moment amplification larger than the *IEEE-693* specified amplification value of 2.0.

Discussion of Numerical Results

The numerical results obtained herein clearly indicate that the seismic response of a transformer–busing system is filtered at the fundamental frequency of the transformer. In other words, once the accelerations reach the base of the bushing, much of the energy is concentrated at the transformer tank fundamental frequency. Therefore, bushings that have fundamental frequencies tuned to the fundamental frequency of the transformer induce significant interaction, which results in large ground motion amplifications.

The spectral amplification values computed in this study show that the *IEEE-693* specified amplification value of 2.0 appears to be conservative for some, but not all transformer–bushing systems.

Due to differences in weight, geometry, and size between transformers of different voltages or manufacturers, it is difficult to generalize the results obtained in this study. However, it can be stated safely that the seismic qualification test procedure for bushings as defined in the *IEEE-693* standard does not completely represent the true structural dynamics of the bushing–transformer system. It would be highly appropriate that seismic qualification tests consider such cases as the 230 kV Transformer C, where tuned bushing and tank fundamental frequencies increase the amplification that occurs between the ground and bushing base motion. In addition, the fundamental frequency of a bushing attached to a qualification test support should more accurately represent the fundamental frequency of the same bushing when attached to an actual transformer top.

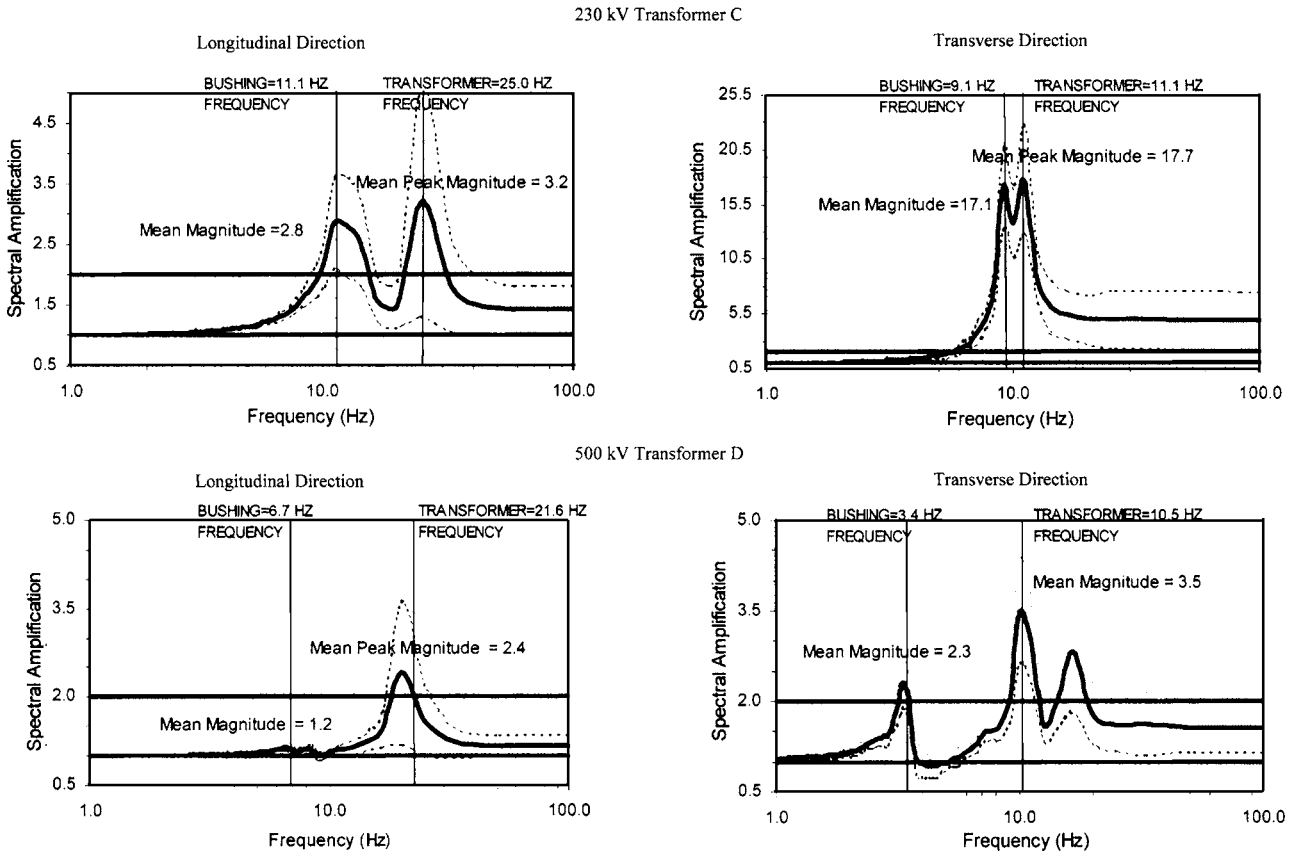


Fig. 3. Mean, mean +1 standard deviation and mean −1 standard deviation of spectral amplifications, transformers C and D

Conclusions

The numerical results obtained in this study have provided several insights into the seismic response of high voltage transformer–bushing systems. The main conclusions that can be drawn from this study are summarized below:

1. The flexibility of the top plate of the transformer tank reduces significantly the fundamental frequency of a bushing compared to that of the same bushing rigidly mounted.
2. The top plate flexibility of the transformer tank provides the largest influence on the amplification between the ground and the base of the bushing.
3. In a given direction, the ground motion amplification occurs at two predominant frequencies: the fundamental frequency of the transformer tank and the fundamental frequency of the bushing.
4. The lower fundamental frequency transverse direction of the transformer tank consistently results in larger ground motion amplifications than the higher frequency longitudinal direction.
5. The ground motion amplification factor of 2.0 specified in the *IEEE-693* standard may not be conservative for transformer–bushing systems for which the bushing funda-

Table 8. Spectral Amplifications at Natural Frequencies of Transformer Tanks and Bushings

	Spectral amplifications at bushing natural frequencies				Spectral amplifications at transformer tank natural frequencies			
Transformer/ Direction	Frequency (Hz)	Mean	Mean+1 standard deviation	Mean−1 standard deviation	Frequency (Hz)	Mean	Mean+1 standard deviation	Mean−1 standard deviation
A/Longitudinal	3.1	1.3	1.4	1.2	11.4	10.2	13.6	6.8
A/Transverse	2.9	1.6	1.8	1.4	8.4	14.4	18.6	10.2
B/Longitudinal	4.9	1.1	1.2	1.0	25.0	2.2	3.5	0.9
B/Transverse	3.2	1.1	1.1	1.1	14.2	7.7	10.7	4.7
C/Longitudinal	11.1	2.8	3.6	2.0	25.0	3.2	5.1	1.3
C/Transverse	9.1	17.1	20.8	13.4	11.1	17.7	22.6	12.8
D/Longitudinal	6.7	1.2	1.3	1.1	21.6	2.4	3.6	1.2
D/Transverse	3.4	2.3	2.7	1.9	10.5	3.5	4.4	2.6

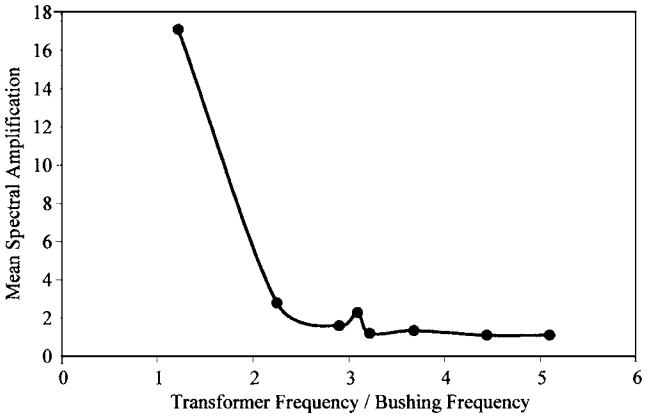


Fig. 4. Variation of mean spectral amplification as function of transformer to bushing fundamental frequency ratio

mental frequency is tuned to the fundamental frequency of the transformer tank.

Changes to the *IEEE-693* standard may need to be considered to reflect the fact that the dynamic properties of a bushing mounted on a transformer tank are significantly different from that of the same bushing mounted on a rigid support. Two different paths may be considered. The first path could be to keep the current rigid test stand, as currently specified in the *IEEE-693* standard, and to introduce some transformer tank design requirements to ensure that the bushing support is sufficiently stiff. Another approach could be to modify both the bushing qualification procedure in the *IEEE-693* standard, along with the introduction of new transformer tank design requirements. In either case, it seems practical to anchor the seismic qualification testing on a standard test stand since bushings and transformers are usually supplied by different manufacturers, and interchangeable bushings are necessary for utilities.

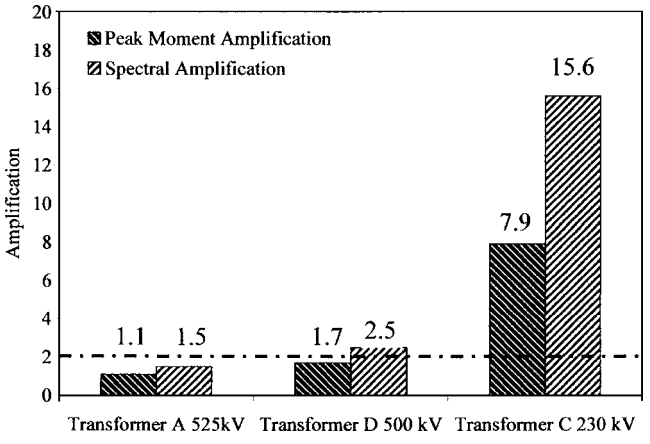


Fig. 5. Comparison of peak bending moment amplification and spectral amplification, Landers record

Acknowledgments

The research project described in this paper was sponsored by the Pacific Earthquake Engineering Research Center's Program of Applied Earthquake Engineering Research of Lifeline Systems supported by the California Energy Commission, California Department of Transportation, and the Pacific Gas & Electric Company. This work made use of Earthquake Engineering Research Centers Shared Facilities supported by the National Science Foundation under Award No. EEC-9701568. The writers greatly appreciated the input and coordination provided by Dr. Michael Riemer from PEER and Mr. Eric Fujisaki from the Pacific Gas and Electric Company (PG&E) during the development of this research project. The support of Mr. David Chambers from the California Energy Commission is also gratefully acknowledged. Special thanks must be also given to Mr. Bill Gundy for supplying two of the original transformer models, as well as Mr. Rulon Fronk, Dr. Anshel Schiff, and Mr. Chris Stearns for their individual contributions to the research task.

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