Seismic Qualification of Transformer/Bushing Systems

By

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Executive Summary

Experience from laboratory tests and earthquake damage indicates that the procedures for seismic qualifying transformer bushings (center-clamped, non-cemented) in IEEE 693 are not valid. The amplification (factor of two) introduced in the procedure to account for not mounting the bushing on the transformer for qualification does not adequately captured the effect of the transformer on the bushing's response. This paper is directed to the Bushing Advisory Committee to stimulate interaction between committee members and improve the effort to develop a valid qualification procedure for IEEE 693. This paper summarized key points in the IEEE 693 for qualifying transformers, reviews and discusses observations from earthquake investigations, identified possible shortcomings in the standard, discusses implication of different construction methods and their impact on performance, reviews selected research efforts that looked at transformers and bushings, discusses the impact of installing the bushing on the transformer, and interprets observations on the testing program. The last section contains lists of specific questions that are directed to the testing program for people knowledgeable about transformer and bushing. Comments and suggestions or other thoughts are being sought and these should be forwarded to schiff@stanford.edu

Background

This paper is being prepared for the Bushing Advisory Committee that was formed to help researchers develop a valid qualification procedure for seismically qualifying transformers and transformer bushings using IEEE 693, "IEEE Recommended Practice for Seismic Design of Substations". This document reflects my personal views and understanding. I suspect that some of my understanding may be incomplete or flawed and I am sure that other valid or better alternatives to suggestions presented could be put forward. This paper was developed to provide a basis for and stimulate discussion. To facilitate discussion and make it easier to reference the paper, I have given a numerical designation to each section. I will insert editorial comments and notes as I feel appropriate and I will designate them for clarity. For completeness I have included a few sections on earthquake performance of transformers that are not the focus of this effort, and I have marked them with an * so the save time you may want to skip them.

Contents

1. Purpose of the Paper

1.1 Briefly review key provisions in IEEE 693 for seismically qualifying transformers.
1.2 Review the earthquake performance of power transformers and their bushings.
1.3 Review construction features of bushings that may affect their seismic performance.
1.4 Identify possible areas of bushing-transformer interaction that may affect bushing performance.
1.5 Identify issues associated with developing a valid qualification process for transformer bushings.
1.6 Establish a common base of understanding of qualification issues and procedures and provide an opportunity for representatives of bushing and transformer manufacturers, utility personnel, and researchers to exchange ideas and expand or correct this knowledge base.
1.7 Stimulate discussion between members of the Bushing Advisory Committee.

2. Current Qualification Practices

The following description is a brief listing of key requirements in IEEE 693-2005 for qualifying transformers (Annex D) to the High Seismic Qualification Level that operate at or above 161 kV. The requirements are listed rather than explained and some are paraphrased.

Note: There have been significant changes in the requirements for qualifying transformers and transformer bushings in the 2005 version of the standard as compared to the 1997 version.

Comment: The requirements for qualifying transformer and their bushings are largely unrelated.

2.1 Transformer Requirements

2.1.1 Transformers will be undamaged and function <u>immediately</u> after an earthquake that has response spectra that are as large as the High Required Response Spectra.

Comment: Empirical data on transformer performance suggests that there may be catastrophic effects that present themselves months after an earthquake. The new requirements for documenting load paths in transformers may have address one of these issues, but the explosion of bushings, if related to earthquakes, is still not addressed.

2.1.2 Tank, core and anchorage shall be qualified by static analysis. This analysis will include an evaluation of the load path of the core, coils, tank and base to the anchorage. The design shall assure that load path components are sufficiently rigid that parts do not shift. Load path components will be identified.

Note: The standard does not address the stiffness of the anchorage. Research discussed below suggests that transformer case frequency may be important and that anchorage stiffness can influence the natural frequency of the transformer body.

Note: The standard notes the importance of the stiffness of the load path for core and coils, but there is no consideration of the stiffness for the bushing support.

2.1.3 Radiators, conservators and control cabinets will be qualified by static analysis.

2.1.4 Transformers shall be welded to plates or beams embedded in the foundation pad.

2.2 Bushing Requirements

2.2.1 Bushings are to be qualified by shake-table time-history testing to the performance level (twice the High Required Response Spectra (RRS)).

2.2.2 For shake-table testing, the bushings shall be mounted on a rigid stand and the bushing flange shall be subjected to the performance level excitation (twice the RRS) as if it were at the top of the transformer. It is assumed that the amplification of the transformer is 2, so that the stand will be subjected to 4 times the RRS.

Comment: There is no provision for the effect of the flexibility of the top of the transformer, to which the bushing is attached, the edge distance (which affects the as-installed bushing frequency), or the presence of a turret between the top of the transformer and the bushing flange. The factor of 2 reflects the peak in the transfer function between the ground and the top of the transformer where the bushing or turret would be mounted. The factor of 2 must account for the amplification of the motion of the body of the transformer, and this can be due to flexibility of the transformer case, flexibility of the anchorage, and motion of the transformer and its foundation pad caused by soil-structure interaction. The amplification factor is discussed further below.

Note: In an IEEE 693 meeting there was a discussion of research (I think conducted in Europe) that justified the transformer amplification factor of 2. I could not find this paper so that I have not commented on it.

2.2.3 For center-clamped, non-cemented bushings (they depend on axial clamping forces applied to the central conductor to hold them together) the affect of changes in temperature and relative coefficients of thermal expansion of bushing components must be considered. This will generally require that the clamping force used during the testing be reduced from its nominal setting at ambient temperature.

Note: This is a new requirement for the 2005 version of the standard.

Comment: It seems to me that the test report should require documenting the normal and test clamping forces.

Comment: The standard only requires the clamping force to be reduced for bushings where resistance to lateral loads is provided by the clamping force. The clamping force also resists rocking at the flange and thus reduces the loads that must be resisted by a cemented flange. It seems to me that all center-clamped bushings should have clamping loads reduced for temperature effects.

2.2.4 Bushings and other equipment are to be qualified with a weight attached to the conductor terminal pad. For 230 kV equipment the weight should be 15#, and for 500 kV equipment it should be 25#. This is to account for the weight of the conductor terminal hardware and does not include a significant amount of the conductor weight, the possible affects of the dynamic response of the conductor, or interaction loads due to inadequate slack in the conductor connection to adjacent equipment.

Note: Other parts of the standard address the slack interaction loads.

Note: This is a new requirement for the 2005 version of the standard.

2.2.5 There shall be no slippage, visible oil leaks, or broken support flanges.

Comment 1: There is a requirement to monitor peak stress in the flange and this will be onerous or impossible because strain gages cannot be positioned at corners.

Comment 2: I feel that it is important to determine if there can be slip at the interface without an oil leak to lubricate the interface. If this can be demonstrated, this would be one condition for limiting testing to only a pull test where leaking would be observed. The other condition would be that there could be no gasket extrusion without leakage.

2.2.6 There are requirements for surge arresters in Annex D.

Comment: Annex K, for surge arresters, does not have any requirements relative to standoffs. Depending on standoff design, they can double the chances of the surge arrester falling from its support.

3. Observations on Transformer and Bushing Earthquake Performance

The observations and comments on earthquake performance are primarily based on my observations (including the study of photographs) starting with the 1971 San Fernando, California, and subsequent major United States earthquakes. In addition to observations made at United States substations, investigations have been made in Japan, Chile, Taiwan, Mexico, Philippine, and Turkey. Essentially none of the equipment observed has been qualified to IEEE 693, although some California utilities have done qualification shake-table tests similar to those contained in the IEEE 693 Standard. It is not known if any qualified bushings failed.

Because very few, composite transformer bushings are included in the database, good or bad performance is not documented. The performance in qualification tests using the existing, flawed standard have been good. Relatively few bushings have been observed of the center-clamped, cemented type, or clamped type, but the limited observations are noted.

3.1 Bushing Damage and Failure Modes

3.1.1 Temporary Oil Leakage Between Flange and Lower Porcelain on Center-Clamped, Non-Cemented Bushings

This is a common bushing problem and refers to an oil leak during the earthquake. Some of these leaks probably are missed because they can be detected only if there is sufficient oil to run down the side of the transformer case (access to the top of the transformer is not possible). The bushing would generally not be changed out as a result of this problem.

Note: Center-clamped, non-cemented bushings have been the most common type of bushing observed in post-earthquake investigations in the United States.

3.1.2 Slipping between the Flange and Lower Porcelain Element on Center Clamped, Non-Cemented Bushings

This is a frequently observed problem. When there is an offset between the flange and the lower porcelain, there may or may not be a permanent oil leak. A permanent oils leak will require the bushing to be changed out. Even without a permanent oil leak, if the offset is 1/4" or more the bushing is changed out, although the criterion varies between utilities.

3.1.3 Gasket Worked its Way Out of Flange-Porcelain Interface

This is common and frequently results in a permanent oil leak. There is often, but not always, an offset at the interface. The mechanism of this failure is not understood and will be discussed below. The bushing will be changed out.

Note: In some cases when there is a slow oil leak at the interface, an effort is made to temporarily stop the leak so that the transformer can remain in service.

3.1.4 Cracked Porcelain on Center-Clamped Bushing Oil leak

This is relatively rare. It is speculated that the extrusion of the gasket from between the flange and the porcelain allowed flange-porcelain contact when the bushing rocks, and this initiates the crack. In one case there was a hairline crack along the length of the bushing that was only discovered when dust gathered on oil at the crack. The replaced bushing cracked in the same way in an after shock. The station had not been put back into service when the first crack was found.

3.1.5 Cracked Porcelain – Clamped, Cemented Bushing and Clamped Bushing

Few of these bushings have been seen in the United States. In one earthquake outside of the United States, in which a strong-motion seismograph located in the switchyard recorded a peak acceleration of 0.38g, six of twenty-nine 400 kV bushings failed. While center-clamped, non-cemented bushings are vulnerable to slipping, they can be rebuilt. The porcelain in clamped, cemented bushings fractures and the bushing must be replaced.

3.1.6 Damage Due to Conductor Interaction

If conductor slack between the bushing and the adjacent independently supported piece of equipment is inadequate, the earthquake-induced relative deflections can impose loads on the bushing and cause one of the problems discussed in Sections 3.1.1 to 3.1.4. Rigid bus can cause these problems and some utilities are installing flexible connections between the bus and the bushing. In addition to interaction loads related to a lack of slack, the dynamic response of the conductor may also cause loads on the bushing and contribute to the damage, but this had not been documented in earthquakes (can not distinguish bushing inertial loads from induced conductor dynamic loads).

3.1.7 Post-Earthquake Explosions of Bushings

There have been three reported cases in which a bushing exploded two weeks to three months after an earthquake starting a fire and destroying the transformer. Inspection of the bushing showed that in two cases an arc had passed from the conductor to the flange through the capacitor, and this was the source of the bushing failure. Although it was inferred because of the timing that these failures were related to damage from the earthquake, no definitive cause has been identified.

It is my understanding that the grading capacitor is wound around the bushing conductor and it does not touch the inside shell of the bushing. There are also two electrical contacts near the flange, a ground to the outside of the capacitor and a lead to the voltage tap. The conductor is supported at each end and in some cases it may also be restrained near the flange. It is possible that the conductor goes into its own modal response and if not restrained at the flange could damage the electrical contacts at the flange or impact the flange (smallest clearance is thought the flange). This damage could over time eventually cause a catastrophic failure.

Comment: It may be appropriate for bushings in seismic areas operating at 161 kV and above to have restraints between the flange and the capacitor to reduce relative motion and the chances of damage. Assuming that the two failures noted were due to the motion of the capacitor, this is a relatively rare event. However, the total loss of a transformer is a very expensive consequence.

3.1.8 Cracked Flange

There is one case in which a center-clamped, non-cemented bushing slipped at the flange. The flange casting also fractured.

3.1.9 Damaged Porcelain Drains Conservator

In one case porcelain cracked and fell away from the bushings around the entire circumference near the flange. As a result, the bushing conductor and stub dropped. This opened the seal between the top of the stub and the bottom of the flange and allowed the oil in the conservator to drain through the cracked bushing.

3.1.10 Side-Mounted Turrets

Some bushings are mounted on a turret that is attached to the side of the transformer and the flange of the bushing is at about the same level as the top of the transformer. Thus, the stiffness of the top of the transformer case will have little impact on the bushing response compared to a bushing supported on the top of the transformer. This will eliminate several of the uncertainties associated with a bushing installation, although some installations have a traditional turret supporting the bushing on top of the larger side-mounted turret. It is interesting to note that one of the only bushings to have a porcelain failure was on a side-mounted turret that was topped by a short, smaller diameter turret.

3.2 Transformers and their Attachments

3.2.1* Surge Arresters

Surge arresters operating between 115 kV and 230 kV are one of the most seismically vulnerable items in switchyard. These units are typically supported on booms off the transformer case. It is speculated that the flexibility of the support contributes to their failure. They can be supported on standoffs. If standoffs of the non-through-bolt designs are used, the chances of the surge arrester falling are about doubled because of the failure of the standoff.

There are several wiring options, but if a conductor is directly connected between the surge arrester and the bushing, the failed surge arrester will tend to swing into the bushing and has the potential of damaging the bushing. Broken bushing sheds have been observed. There is one case in which the pull on the conductor from the falling surge arrester bent the stud at the top of the bushing. The recommended practice is to support the surge arrester on its own support column.

3.2.2 Anchorage

At one time it was common practice to install transformers on elevated rails with inadequate restraints, or install them on slabs at grade with inadequate or no anchorage. Elevated transformer would roll off the end of the tracks and topple, damaging bushings, surge arresters and radiators. Units on grade would slide and cause bushings and/or surge arrests to fail due to conductor loading. Control cables connected to the transformer and the slab would also be damaged.

Many utilities in areas of seismic risk have retrofitted their transformer anchorage. Retrofits are usually done without moving the transformer and typically bolt the transformer to the pad. While such anchorage is usually strong enough to prevent the transformer from sliding or tipping, issues of stiffness are not addressed or are difficult to implement economically as a retrofit.

The anchorage on new installations is typically welding to embedments, as specified in the standard. While most transformers are welded to the base plate adjacent to the transformer wall, so that the anchorage is stiff, others are welded to extension plates that increase the flexibility of the anchorage. There have been cases where the embedded plate was not adequately anchored to the foundation slab and have partially pulled out, reducing the stiffness of the anchorage.

The concern about anchorage stiffness is that a flexible anchorage may lower the rocking frequency of the transformer case so that it is near the as-installed bushing frequency. Detailed computed evaluations, which are discussed below, show that when the natural frequency of the as-installed bushing and the transformer case are close, a very large bushing response and load can be generated.

There are some issues related to bolted anchorage. The first is that the bolts pass though a tab, and if gussets are not used the result will be a flexible anchorage. There has been a case in which the bolts were used to hold a clip, and all of the lateral load must then be born by half of the bolts. There have been cases in the United States and Japan where conservative bolted anchors were severely damaged or bolts failed. The failure mechanism is not clear, but it is speculated that clearance in the holes was such that not all bolts were loaded at once and bolts are subjected to shear with little flexibility so that some bolts could be sheared off before other bolts could resist the load. There is also the possibility of impact associated with the clearance provided.

Over the years I have often been presented with the argument that by leaving the transformer unanchored, which is a form of base isolation, the loads on bushings would be reduced. There is one case in which three transformers adjacent to each other were unanchored and one slid. While one anecdote makes an unpersuasive case, the only bushing to fail was the one on the transformer that slipped. It only moved a few inches so that conductor interaction loading was not an issue.

3.2.3* Radiators

Most radiator problems are associated with the method used to attach the radiator to the transformer. The most common damage is to the top connection of a manifold-type radiator. The bottom connection is usually a structural connection independent of the piping, because the oil-circulating pump inserted between the radiator and transformer case does not provide the needed strength. The upper support, frequently provided by the pipe circulating the oil, can have a flange deform or pipe cracks causing a leak. A pipe connection on a large single element radiator has cracked and leaked. Radiators need stiff lateral restraints at the top and bottom.

In a couple of installations the radiators had their own supports and relative motion between the radiator and the transformer case caused a Dresser coupling to pull apart.

3.2.4* Conservators

Four failure modes related to conservators have been observed. Bolts holding the frame that supported the conservator failed. The conservator fell and become jammed between the transformer and an adjacent firewall. A metal pedestal supporting one end of the conservator cracked and failed, but the conservator did not fall. A weld connecting the support bracket to the conservator tank cracked and allowed oil to leak from the tank. The fourth type of failure observed was failure of a pipe connecting the conservator to the transformer body. The pipe failed because of the large flexibility of the conservator support imposed large loads on the stiff pipe connection. The broken pipe drained the conservator.

3.2.5 Transformer Case

I only know of one oil leak associated with the transformer case, other than where a radiator connected to the case. There was a reduction in the size of the case at about 3-1/2 feet off the ground. A weld in this corner cracked and created a small oil leak. It is interesting that no leaks have been observed at welds to the case used to anchor the transformer.

It is interesting to note that the box construction of a transformer case is not as rigid as I had expected. A transformer case was welded to embedments in the slab at 4 locations along the sides near each corner. The welds at one end failed and that end of the transformer slid about 14”. In addition, the transformer case apparently lifted off the pad so that a mop was able to slide under the transformer. Yet the welds at the other end of the transformer did not fail.

3.2.6. Internal Shifting of Parts

Unconfirmed reports have been made of possible internal corona in transformers after earthquake. It is speculated that shifting of internal parts caused a change in spacing and an increase in potentials that initiated corona.

The basis of this was from oil analysis within two years after an earthquake. The new load path requirements in the standard should address this issue, if indeed it did occur,

4. Possible Short Comings of Bushing Qualification Practices

4.1 Manufacturers have different methods for pre-loading when setting the clamping force that holds the bushing together. This can result in different clamping after the units are assembled. In one case the bushing is pre-loaded from top to bottom in compression and the tension nuts on the conductor is set. Note that the springs on the top are typically designed so that they are limited as to the extent that they can be overloaded (they bottom out). After the nut loading the bushing assembly is drawn tight, the pre-load is removed. The other method is to apply the pre-load by pulling on the conductor to apply the load. In this case the conductor is also pre-loaded (in the former case it was not). There are indications that use of the former method will result in the final pre-load being less that its rated value after external constraints are removed.

4.2 If a bushing is refurbished by a utility's bushing shop, preload may not be set correctly, for various reasons. It is expected that this would not generally be an issue, as bushings are not normally serviced in this way over the life of the transformer or the bushing.

4.3 In Sections 6.2 and 6.3, below, comparisons between tests and observed bushing performance in earthquakes indicate that the standard has not captured important aspects in the transformer-bushing interaction in the qualification process. That is, bushings (center-clamped, non-cemented) mounted on transfers failed at excitation levels below the value to which they were qualified.

4.4 Bushings are qualified, as is all other substation equipment, without power cable connections to adjacent equipment. The effect of the weight of the conductor is not considered. Since the acceleration at the top of a bushing on a rigid support structure can be over 6g, seemingly small conductor weight can add significant loads to the bushing. Also, the possible effect of the resonant response of the cable on the top of the bushing is not considered. Interaction loads, should not come into play if the practices specified in the standard are followed, however they may influence observed earthquake performance.

Note: The standard does now require that weight be added to the terminal pads, but this probably does not fully account for the mass loading at the top of the bushing.

4.5 Qualification practices do not take into account differences in design and vulnerability of different types of bushings. IEEE 693 has tailored equipment qualification methods to specific classes of equipment and this may be appropriate for bushings.

4.6 The bottom of the stub of the bushing is not restrained in qualification, but may be within the transformer. This is discussed further in Section 5.5

5. Effects of Bushing Construction on Performance

5.1 Center-Clamped, Non-Cemented Bushing

5.1.1 Flange with a Gasket Groove

There are several issues related to the design and failure mode of these bushing. Based on one GE Type-U bushing that I have seen disassembled, the porcelain surface facing the flange is ground flat and is very smooth. The flange has a turned groove in it that has a rectangular cross section. The ring-shaped rubber-like gasket that fits in the groove also has a rectangular cross section that is narrower than the width of the groove and thicker than the depth of the groove. When assembled, the gasket is compressed so that it fills the groove and tends to be squeezed out into the gap that is left between the top of the flange and the bottom surface of the porcelain. When compressed to its rated pre-load, there is still a gap between the flange and the porcelain so that they do not come in contact. It is my understanding that the gasket is not bonded to the porcelain or the flange.

The failure modes are not well understood and I will provide possible explanations of what may be going on. During an earthquake lateral force on the bushing, due to inertial forces and/or conductor loads could cause the bushing to tip at the flange-porcelain interface. As the bushing tips the gap between the flange and the porcelain will start to increase on one side of the flange-porcelain interface. The pre-load on part of the gasket will be reduced, and the gasket will expand to prevent oil from leaking out. Eventually, a gap will open so that the oil can escape the bushing. If severe shaking stops just after this occurs the bushing would probably reseal itself, and this would account for one of the failure modes described above.

Once oil starts to leak, the interface becomes lubricated, so this may account for the slipping of the porcelain relative to the flange. It is possible that there is slipping before a leak develops. There is another explanation for what appears to be slipping. When the bushing is tipped over, most of the contact load is on one edge of the bushing. Since earthquakes are three dimensional, if when the bushing is tipped up there is a transverse acceleration the bushing could rotate around the “point” contact, and when it drops back down it would appear to have slipped, when it actually “walked”. Thus, the source of all offsets is not clear. If the offset is large enough, there will be a permanent oil leak.

The extrusion of the gasket is more puzzling: it is hard to understand how it gets out of the groove that it sits in. Pressure inside the bushing may blow it out when the bushing tips over reducing the pressure on one side of the gasket.

Alternatively, during an earthquake the bushing not only rocks back and forth in a vertical plane, but probably rocks so that the top of the bushing relative to its base makes an orbital motion. This will have the effect of the high-pressure porcelain-flange contact point rotating around the outer edge, which I will call precessing. As it precesses, it may squeeze the gasket out in front, like a rolling pin and pie dough. This may push the gasket out of the groove and out of the gap between the flange and the porcelain. Once the gasket gets squeezed out enough, there will be a permanent oil leak. I have observed situations where there is little or no slipping between the flange and the porcelain, Figure 1, but the gasket has been displaced. It is possible that internal pressure in the bushing blows the gasket out when it is unloaded as the porcelain tips.

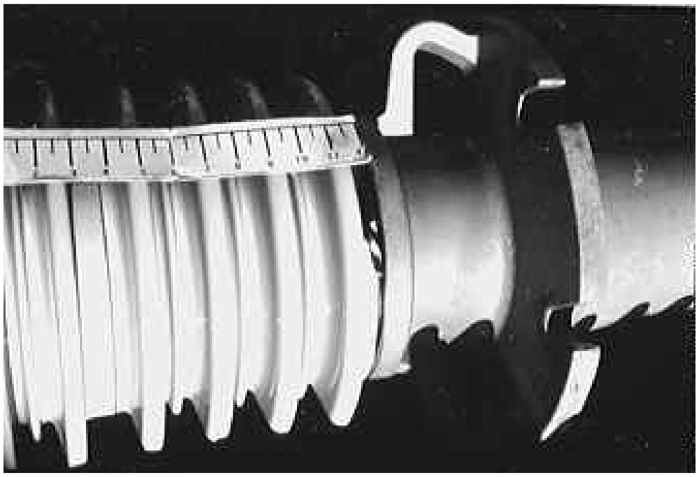

Figure 1

Comment: In one research project the bushing was modeled and the effect of the flexibility of the gasket was included in estimating the dynamic response of the bushing. This model used a spring rate for the gasket based on an unconstrained compression test of the rubber. It is my view that this greatly underestimated the spring rate of the gasket so that the validity of the results is questionable. When the gasket is confined in the groove its spring rate will approach the bulk modulus rate, and this is indicated in the test data that was used to estimate the spring rate of the gasket material.

5.1.2 Gasket with No Groove

The configuration is similar to the previous description, except that there is no groove in the flange and the gasket is bonded to the flange and/or the porcelain.

5.1.3 Dual Gaskets

The configuration is similar to the previous description, but there are two gaskets. The largest diameter gasket is made of a stiff material and serves to support the load between the flange and the porcelain. The inner gasket is made of rubber-like material and serves as a seal to retain the oil within the bushing.

5.2 Center-Clamped, Cemented Bushing

This is configured similar to the gasket described in Section 5.1.2, but the flange forms a cup that extends up the sides of the porcelain, and cement fills the gap between the inside of the cup and the outside of porcelain. The bushing is still center clamped.

Comment: In this bushing, the form of the flange prevents lateral slipping of the bushing relative to the bushing. The clamping force still serves to resist rocking. The standard does not require the pre-load to be reduced for this bushing associated with temperature effects. However, the reduced clamping force will allow the bushing to experience larger binding forces and stresses at the cemented connection. I feel that all center-clamped bushings should have pre-load reduced associated with temperature effects.

5.3 Bushing with Flange with an Internal Raised Retainer Ring

I have heard this description, but do not know if or how frequently it is used. The flange has a raised rim that fits inside of the center hole of the porcelain. I do not know the configuration of the gasket. The internal rim on the flange prevents slipping between the flange and the porcelain.

5.4 Clamped Bushing

In this type of bushing, the base of the porcelain flares out to a larger diameter. Dogs are bolted to the flange to secure the bushing to the flange. I have not seen this type of bushing in the U.S. I understand that it may not be manufactured currently. I have seen a 400 kV bushing of this type fail (cracked porcelain at base) in an earthquake.

5.5 Relative Motion between the Conductor/Capacitor and Bushing Housing

Earthquake induced vibration of the conductor/capacitor may cause problems. This was discussed in Section 3.1.7.

5.5 Cable Restraint in the Transformer Below the Bushing

Two knowledgeable representatives from bushing manufacturers have discussed with me the issue of the effect of bracing the conductor just below the stub of the bushing. Inside of the transformer This is done to reduce the effect of short circuit induced deflection of the cable within the transformer. I have seen a picture of this bracing and it appears to be stiff and the conductor was similar to that used for transmission lines. Short lengths of this material tend to be rather stiff. Thus, this restraint may affect the dynamic response and seismic performance of the bushing and it is not taken into account during qualification.

In some cases braded conductor, which is relatively flexible, is used to make the connection to the bushing, so that bracing the end of the cable away from the bushing should have little effect of the bushing response. Second, even if a stiff connection is used to the bushing, adequate flexibility has to be provided so that when a vacuum is drawn, deflection in to the top plate (rocking of the bushing) of the transformer and by implication at the end of the stub of the bushing must be accommodated. There have been cases where stiff bracing of the cable has cause the bushing to fail when a vacuum was drawn.

I have had discussions about earthquake performance of bushings on bulk-oil dead-tank circuit breakers. In some cases the transformer and circuit breaker bushings have similar or the same ratings and construction. In the United States there is no record of a bulk-oil circuit breaker bushing failing. At one time this was the predominant type of circuit breaker at the 230 kV level and many have been subjected to severe earthquake motions. There can be two explanations. I have been told that these bushings have relatively stiff connections near the stub. Also, the tops of circuit breaker enclosures have a relatively small diameter compared to transformers and may be domed so that they are structurally stiffer. It is interesting to note that in Japan there have been several slipping bushing failures on their bulk-oil circuit breakers. However, their breakers were very large, with tanks almost 20 feet tall and are much larger in diameter. Thus, they may have behaved more like U.S. transformers. I am not sure of the design of the bushings used in Japan, but they report that they do not have transformer-bushing failures.

The advisory committee may be able to resolve the issue of internal restraints on bushing conductors and if this should be considered during qualification.

5.6 Composite Bushing

My understanding is that these bushings are constructed like other hollow-core composite insulators. A wound, fiberglass tube is shrink fit and bonded into a pocket in a flange. As in porcelain bushings the conductor is under tension to hold the bushing together. Silicon rubber sheds are added. Although reports of results of seismic qualification testing of hollow-core composites have generally been good, a consortium of utilities formed to qualify substation equipment reported marginal results. The IEEE 693-2005 standard was modified based on these results. To my knowledge, no composites have yet been qualified using the new qualification procedures. Composite bushings on dead-tank circuit breakers have been exposed to earthquakes and have performed well to my knowledge. It is my understanding that the shells of composite circuit breaker and transformer bushings are the same. I am not aware of composite transformer bushings being exposed to severe earthquakes.

Note: IEEE 693-2005 does not increase the loading on the bushing, but does have different acceptance criteria.

6. Review of Selected Research on Transformers and Bushings

Three projects will be briefly described.

6.1 Seismic Response of High Voltage Electrical Transformer-Bushing Systems

A paper in the Journal of Structural Engineering of ASCE in February 2006 and authored by Andre Filiatrault and Howard Matt describes a numerical and experimental project dealing with transformers. In this project detailed FEM were developed for four power transformers (one 230 kV and three 500 kV) that included constructions details. The transformer in one of the models was full scale tested (without oil, coils or core) to validate the modeling. Such an endeavor requires many assumptions and approximations and two of these will be discussed below. The findings that are related to this effort are the following.

6.1.1 Transformers cases have different transverse and longitudinal frequencies. The ratio of the fundamental transverse to longitudinal frequencies vary from about 45% to 75%. The transverse frequencies are 8.4, 14.2, 11.1, and 10.5 Hz.

6.1.2 The bushings used in the study were similar to those described in Section 7.1. The ratio of the as-installed bushing frequency to the rigidly-mounted bushing frequency are 3.1, 2.7, 2.1, and 2.6. These frequencies reflect stiffness of the bushing support that is controlled by the thickness of the top of the transformer, stiffeners, and the edge distance. Note that all of the as-installed frequencies are 1/2 to 1/3 of the rigidly-mounted bushing. The bushings were supported on turrets or mounting flange, and most were relatively short.

6.1.3 The models used 2% damping and they were linear so that the response to the earthquake (RRS compatible) was probably larger than would be observed in an earthquake, where damping would probably be larger at these shaking levels.

6.1.4 In the 230 kV, 3-phase transformer the transverse spectral amplification was very high (about 17) and this was attributed to the fact that the as-installed bushing frequency was near that of the transformer. What surprised me was that the bushings had sufficient weight to drive the transformer case (no units had coils or cores), but the bushing modal mass participation was 75% of that of the case. In general, spectral amplifications of the transformers were 2.5 to 10. Plots of the spectral amplification of the transformers are shown in Figure 2.

Comment: It is my recollection that a paper discussed in an IEEE 693 meeting justified the transformer amplification of 2 that is used in the standard. While this is also generally true in the current study, it used a different method. The amplification is based on the amplification at the as-installed bushing frequency and not of the transformer independent of frequency. The computer models have amplifications greater than 2.

6.1.5 Two methods were used to calculate the amplification between the input and the response. In the first method a collection of scaled real time-histories was applied to the transformer base and the response at the top of the transformer was observed. Plots in Figure 2 show the spectral amplifications - ratios of response spectra output to input. In the transverse (narrow) direction, average amplifications at the bushing frequencies are 1.6, 1.1, 17.1, and 2.3. Two of these values are below the factor to 2 used in IEEE 693, one is close, and one is very large. The large value is due to the transverse frequency of the transformer case being close to that of the bushing and the large modal mass participation of the three bushings. The spectral amplifications of the transformers were all well above 2.

Comment 1: The modal mass participation for the bushings on the three-phase transformer approached that of the tank, while for the single-phase transformer it was relatively small. Thus, the bushing on the single-phase transformer does not drive the response of the tank as they did on the three-phase transformer. The bushing frequencies were also more widely separated from that of the tank. Thus, the large amplification in Transformer C is due to two factors: 1) the frequencies of the bushings are close to that of the tank, and 2) the bushings have a significant modal mass relative to the tank. It is not clear if the closeness of the bushing and tank frequencies will have the same affect for a single-phase transformer.

Comment 2: These transformers had relatively short turrets. The effect of taller turrets using this approach would reduce the as-installed bushing frequency. Because of the rocking motion of the turret and bushing the amplification at the bushing flange would be larger. The standard does not account for this effect.

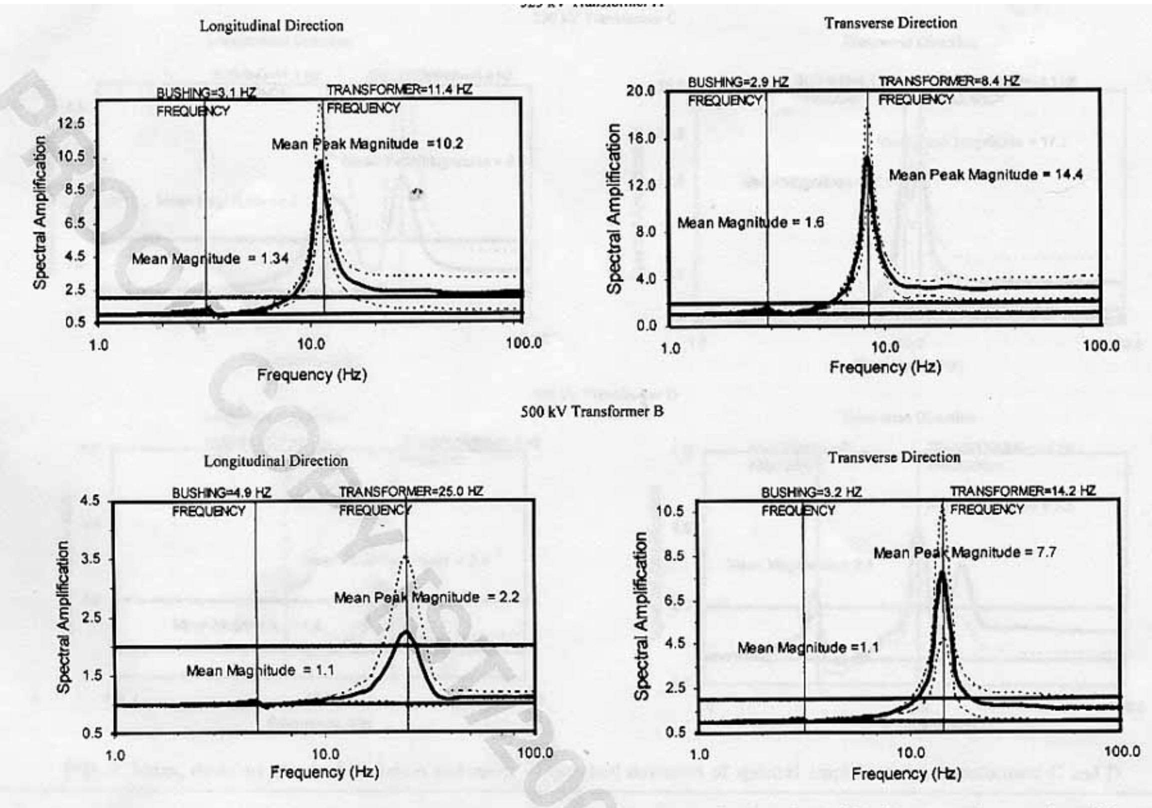

Fig. 2. Mean, mean +1 standard deviation and mean −1 standard deviation of spectral amplifications, transformers A and B

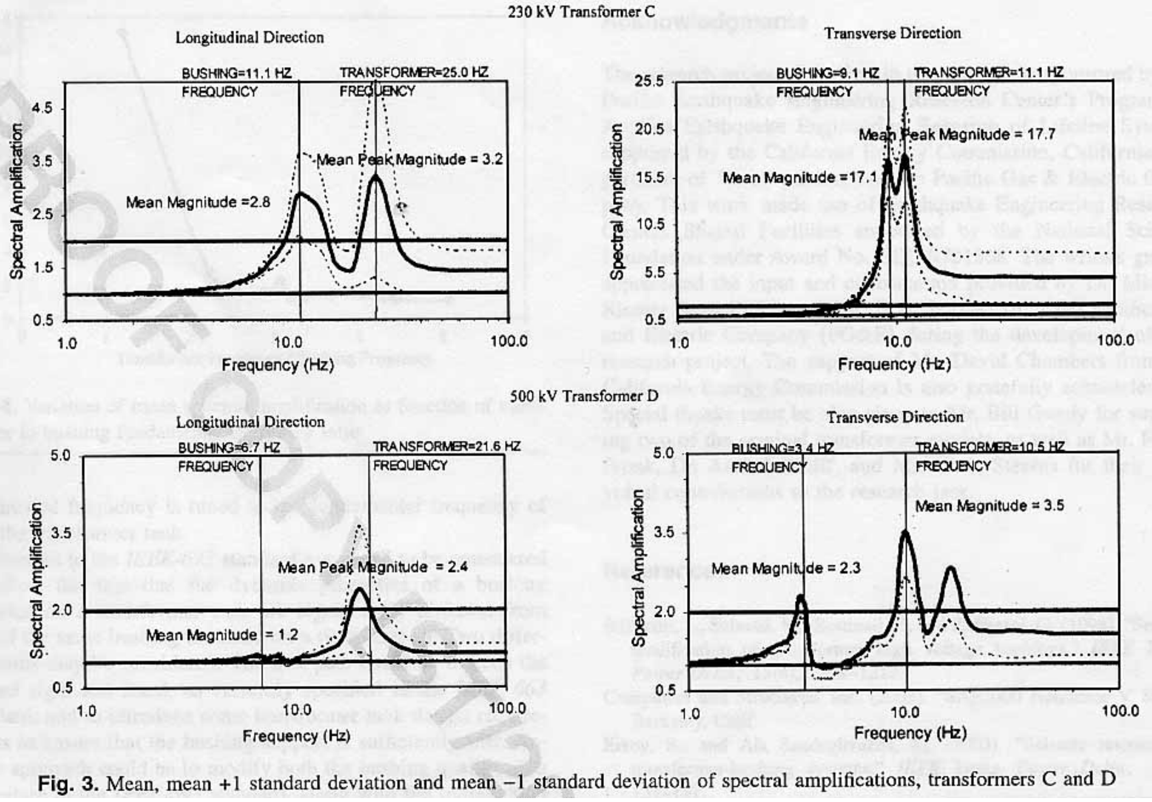

Fig. 3. Mean, mean +1 standard deviation and mean −1 standard deviation of spectral amplifications, transformers C and D

Figure 2

The second method compared the moment at the base of the bushing, when the bushings is mounted on a rigid support, to the moment when it is mounted on the transformer and subjected to an IEEE 693 compatible earthquake. In this case the responses were compared for three transformers and the amplifications were 1.1, 1.7, and 7.9. The high value corresponds to the case where the as-installed frequency was close to the transformer frequency.

One conclusion of this work is that transformer amplification and modal frequency relative to as-installed bushing frequency is important.

Comment 3: There is a need to get a representative sample of transformer case frequencies, if this information is available from manufacturers, so that the importance of the as-installed bushing frequency can be determined.

Comment 4: There is a need to get information on the range of turret heights used by manufacturers, and the technical basis for height selection.

The implications of two underlying assumptions should be assessed. It has been assumed that the sides of the transformer case are independent of the core and coil. In the limited number of core-type transformers that I have seen open, this was the case. This would probably not be the case for shell –type transformers, but I am not sure how prevalent this design is for new units.

In the models and experiments, the transformer cases were secured to the foundation around the their entire perimeters. In practice, transformers are anchored at a few points, typically 4 to 8 locations. This type of anchorage will be less stiff than those used in the model so that the estimated transformer frequencies in the study will be higher than real transformers. This means that in practice, the transformer frequencies will be closer to the as-installed bushing frequency.

Comment 5: The implications of this project are the following. A) The stiffening of the bushing support to raise its frequency may not be beneficial. More important is the relation between the as-installed bushing frequency and the lateral transformer frequency. The knowledge of the exact difference in frequencies is not important as long as the separation is above a threshold value. It is not clear if the modeling that is done by transformer companies can get accurate enough estimates of the transformer frequencies. B) It would appear that turret height does play an important role in the seismic exposure of the bushing.

6.2 Tests Following the Hector Mine Earthquake and Tests at CERL

The strong-motion record recorded at a substation indicated the peak acceleration was 0.11g. A 500 kV bushing slipped in this event causing a permanent oil leak. Tests conducted at the site, on the same type of bushing on another identical transformer, indicated that the as-installed frequency of the bushings was about 5 Hz. The edge distance for this installation was relatively small. Based on similar bushings, the rigidly-mounted bushing would have a frequency between 6-1/2 Hz and 8-1/2 Hz.

Comment 1: Tests have been done on 500 kV GE Type U bushings and frequencies have ranged between 6-1/2 and 8-1/2 Hz. This is a big percentage shift for the same bushing. It would be desirable to have an explanation for this difference.

In tests conducted at CERL, a 500 kV bushing of the same type described above was tested on a rigid support structure and it developed a leak between 0.25g RRS and 0.33g RRS. This is an indication that the procedures used in IEEE 693 may not provide a valid qualification level.

Comment 2: The bushing failed in the earthquake at 44% to 30% of the level to which it was qualified. It should be noted that Hector Mine earthquake had a very short duration.

6.3 Tests at PEER and results from the Northridge Earthquake

Tests on 230 kV center-clamped, non-cemented bushings were conducted to evaluate a bushing retrofit method. The natural frequencies of the bushing were found to be 18 Hz and 20 Hz with the higher frequency aligned with the lifting lugs. The bushing was tested to 25% above the high performance qualification level on a rigid support structure and did not fail. When installed on a 1/2” thick 5’ by 5’ plate it did develop a leak below the high performance level.

Over 25 of the same type of bushing failed in the Northridge earthquake at lower ground motions. This is another example indicating that there were problems with the IEEE 693 qualification procedures. When installed on the flexible plate the as-installed bushing frequency dropped to 7.4 Hz. While this installation will introduce a rocking component to the response, the main effect of the plate is the shift in frequency to a different, more energetic part of the test response spectrum. The spectral amplification on the 2% damped RRS changed from .75 to 1.625, over a two-fold increase. It is not clear what affect the rocking motion of the bushing introduced by the flexible plate has on the bushings performance. From the theoretical perspective of qualification relative to the RRS, the as-installed frequency of the bushings is probably not critical, as most bushings will have a frequency between 1.1 Hz and 8 Hz, the flat part of the RRS. In an actual earthquake, and to a lesser degree during testing, the response spectrum will have peaks and valleys in this frequency interval and it is a matter of chance how a peak will match up with the bushing’s frequency.

Comment 1: Experimental and earthquake data shows that seismic withstand capacity is over-estimated for center-clamped, non-cemented bushings using IEEE 693 methods. While the test data was for center-clamped, non-cemented bushings, the shift in frequency to the more energetic part of the RRS caused by the flexibility of the top of the transformer, should have the same effect on any type of bushing.

When installed on the flexible plate, the bushing was tested with and without a gasket between the flange and the plate. Without the gasket the frequency was 7.4 Hz and with the gasket it was 6.4 Hz. The damping also increased from 2% to 4% with the gasket.

Comment 2: Since bushings are installed with gaskets, it seems appropriate that they be qualified with gaskets. Based on the data above, this will lower their frequency slightly, and significantly increase the damping. In other tests the gasket did not appear to change the bushings frequency and this difference should be resolved.

7. Impact of Bushing Installation

7.1 Dynamic Properties of Bushings

From reliable data that I have seen for rigidly supported 230 kV bushings, one had a natural frequency of about 14 Hz (I do not recall if the frequencies were different in different directions) and another had frequencies of 18 and 20 Hz (the 20 Hz frequency was aligned with the lifting lugs that appears to have stiffened the bushing).

I am familiar with several 500 kV porcelain bushings tests. In one bushing the natural frequencies were 5.66 Hz and 6.35 Hz (in direction of lifting lugs). The other bushings (three tested at the lab) had natural frequencies of 8.2 Hz and 7.9 Hz, 8.0 Hz and 8.2 Hz, and 8.0 Hz and 7.8 Hz. I do not have explicit information of the orientation of the lifting lugs.

I do not have frequency data on composite bushings, but I have heard that their frequencies are about 1/2 of the equivalent porcelain bushing.

7.2 Affect of Installation

Many bushings are mounted to the top of the transformer case. From my investigations it appears that transformers have internal or external stiffeners to accommodate the effects of the vacuum that a transformer is subjected to, but they do not have braces to stiffen the top specifically to support the bushing.

The natural frequency of the bushing, as installed on the transformer, can be reduced to 1/2 or 1/3 of its rigid-mounted natural frequency. Several factors will affect the bushing's as-installed natural frequency. Several of these factors interact.

Comment: I have seen reports for GE-Type U bushings with frequencies of 6-1/2 to 8-1/2, a relatively large percentage difference for supposedly identical bushings.

7.2.1 Flexibility of Transformer Top

The flexibility of the transformer top affects the bushing in two ways: it lowers the as-installed frequency and it introduced a rocking motion. In lab tests the rigid-mounted frequency of a 230 kV bushing was about 19 Hz and when mounted on a 1/2" by 5' square plate it dropped to about 7 Hz. The spectral acceleration of the RRS for these two frequencies is about .75 for 19 Hz and 1.625 for 7 Hz, so that the transformer installed bushing experiences a spectral acceleration over twice that of the rigid-mounted bushing. It is not clear what the effect of the rocking motion (pure rotational motion) will have on bushing performance. However, if there is a turret, the lateral acceleration due to rocking will be increased at the bushing flange and center of gravity. From the perspective of seismic qualification, shifts below 8 Hz have less consequence since the spectral amplification is constant over the 1.1 Hz to 8 Hz interval.

7.2.2 Edge Distance

By edge distance I mean the distance from the outer edge of the bushing flange (or the base of the turret that supports the bushing) to the edge of the transformer case. Edge distances vary widely and I have observed distances as small as a few inches. Small edge distance controls the as-install bushing frequency more than the thickness of the top plate of the transformer, as the edge of the transformer case serves as a stiffener. A corner installation provides a stiffer support.

7.2.3 Turret Height

The turret height raises the center of gravity of the bushings, and all other things held constant, this will lower the as-installed bushing frequency. Because of the rocking action the lateral acceleration at the busing flange increases relative to the acceleration on top of the transformer.

7.2.4 Turret Diameter and Construction

Turret construction can have several effects on the bushing response. A larger diameter footprint on the top of the transformer will increase the effective stiffness of the transformer top. It will also reduce the edge distance and each of these factors will increase the as-install frequency of the bushing. As the diameter at the top of the turret increases beyond the diameter of the bushing flange, the top plate of the turret can contribute to the stiffness of the mount and change the as-install bushing frequency. This is clearly influenced by the thickness of the top of the turret.

Some turrets have the shape of a truncated cone, so that the footprint is increased. In extreme cases, which have been observed in the field, the “turret” forms the entire top of the transformer case. This design would provide a very stiff installation.

7.2.5 Gaskets

Rubber-like gaskets will often be found at two locations in the installation of bushings. One gasket is located between the bushing flange and the member to which it is bolted. There may be a second gasket between the adopter plate or turret and the transformer top. As noted above, one research effort indicated about a 14% reduction in the bushing frequency and an increase in damping due to the gasket. In another project, this effect was not observed.

7.2.6 Orientation

Bushings can be installed with their longitudinal axis vertical or tilted to the vertical by about 20 degrees. The standard recognizes this by requiring that the bushing be tested at its in-service slope. The standard also suggests that it be tested at 20 degrees so that it will then be qualified for broader range of installations.

Comment: In the test described in Section 6.3, the 500 kV porcelain bushings appeared, from visual observation, to develop a leak first on the “down hill” side of the bushing, where the gasket would be under compression due to the effect of gravity, rather than on the tension side of the bushing. This my have been due to the fact that fluid leaking from the bushing, water in this case, run down around the bushing and was observed at the compression side.

8. Summary and Interpretation of the above Findings and their Implications

From the above information I have summarized findings and have made recommendations that relate to the testing program and to changes to be considered to the standard.

8.1 Issues Related to the Testing Program

There are several issues that are interrelated, so clearly identifying and understanding each issue is challenging.

8.1.1 Experimental and earthquake data shows that seismic withstand capacity is over estimated for center-clamped, non-cemented bushings using IEEE 693 methods. I feel that this is also true for other types of bushings. This is illustrated by the fact that there is an increase in the spectral amplification in the RRS between the frequency of a rigid-mounted bushing used in qualification to that when it is installed on a transformer.

8.1.2 The testing lab will have to have the capability to adjust the pre-load on bushings to meet the requirements of the standard since the bushings that we will be testing are largely stock bushings.

8.1.3 The standard treats the qualification of transformers and bushings independently.

8.1.4 It is not clear to me at this time if the qualification of bushings can be done without also determining some characteristics of the transformer. Before I started this paper I thought that it would be necessary to place some minimum stiffness for the transformer case near where the bushing is supported. This may not be needed, but it may be necessary to know more about the natural fundamental natural frequencies of the transformer case to determine the seismic withstand capacity of a bushing that is to be installed on a transformer. This is due to possible dynamic interaction between the bushing and the transformer case.

8.1.5 Issues related to the as-installed frequency of a bushing

8.1.5.1. Shifting of the bushing’s as-installed frequency to the 1.1 to 8 Hz range places it in the high-energy part of the RRS. One can assume that all 500 kV bushings will fall in this range and that 230 kV bushings will be in this range or close to it. There is little chance that they will fall below the 1.1 Hz frequency.

8.1.5.2. A bushing installed on a transformer will experience rocking motions. Independent of the change in frequency and assuming the height of the turret is very small, it is not clear if the rocking motion, on its own account, contributes to bushing failure.

8.1.5.3. The turret will raise the C.G. of the bushing-turret assembly and this will lower the as-installed frequency. As noted above, this will not have a large impact, as installing the bushing on the transformer with or without a turret will place it in the 1.1 to 8 Hz range, where the spectral acceleration of the RRS is constant. The second effect is that the rocking motion will increase the lateral acceleration of the bushing flange and C.G. Note that the frequency of the vibration and the horizontal acceleration due to rocking are related, and at this time I have not evaluated the affect of increasing the height of the C.G. on net effect on lateral accelerations.

8.1.5.4. The limited analysis of data on transformer-bushing interaction suggests that interaction is more significant for 3-phase transformers because of the larger modal mass of the bushings relative to the case. This allows the bushing to drive the case and the resonance on resonance affect is much more severe.

8.1.5.5. The gasket under the bushing flange may change frequency and increase damping. This should be validated.

8.1.5.6. Relative deflection parallel to the interface between the flange and porcelain can be due to shear deformation in gasket (which would not be a problem) or due to actual slip (which would be a problem). There could be slipping during shaking, but no net slip at the end of the test. One key issue would be to determine if there can be slip without an oil leak to lubricate the interface. If it can be demonstrated that an oil leak is needed for slipping, this would be one condition for limiting testing to just a pull test where leaking would be observed. The other condition would be that there could be no gasket extrusion without leakage. There is a need for high resolution monitoring of relative displacement at the interface.

Thoughts relative to these issues

8.1.5.A. The research should determine if bushing rocking has negative impact on seismic performance.

8.1.5.B. Determine the effect of turret height on seismic performance.

8.1.5.C. Determine the effect of a gasket under the bushing flange with respect to frequency, but primarily on damping.

8.1.5.D. As a result of reviewing the data for this paper, I question the need for a general rule that as-installed bushing frequency should be raised. Thus, in general, it is not clear that the stiffness of the transformer case that supports the bushing should be increased. Raising the as-installed bushing frequency may aggravate the resonance on resonance problem.

8.1.5.E. I have a concern that on a three-phase transformer, coupling may increase the seismic exposure. During the earthquake, energy will be imparted to all three bushings. The end and center bushings will have slightly different as-installed frequencies because of difference in the edge distances. The bushings will probably be loosely coupled through the deformation of the transformer top plate to which they are mounted. It may be possible that there will be energy coupling between the bushings and the response will be larger that expected.

8.1.6 Can the Qualification of Bushings be done with a Simple Pull Test

Can the research be formulated so that the initiation of failure is identified and the more complex aspects of the response that occur at larger excitation levels after a leak develops need not be considered? If this can be done, it may be possible to qualify a bushing with a simple pull test that identifies the level when failure starts.

I feel that there are three issues.

8.1.6.1. I will designate a gap-type leak as a leak that is due to the tipping of the porcelain relative to the flange so that a gap opens and oil is allowed to leak.

8.1.6.2. Is sliding of the porcelain relative to the flange without an oil leak possible, or is a gap-type oil leak required for lubrication before slipping occurs? In the few tests that I have observed, leaks have occurred before significant slipping.

8.1.6.3. Can the gasket be worked out from between the flange-porcelain interface without there first being a gap-type oil leak, or can precision below the gap-type leak level cause gasket migration?

The views that I am about to express are based on my impression of how things might work rather than actual data.

8.1.6.A. I feel that the interface has to be lubricated before slipping occurs. If the “slipping” is really due to walking, then what appears to be slipping may occur without there being an oil leak.

8.1.6.B. I have a feeling that gaskets can work there way out without the gap opening up to an extent that there would be a gap-type oil leak. If this can occur, there could be an oil leak due to gasket extrusion. Thus, there could be an oil leak at rocking less than that required to cause a gap-type oil leak.

8.1.6.C. If there can be the appearance of slipping without a gap-type oil leak or if the gasket can work its way out without there being a gap-type oil leak, shake table test will be required. If a gap-type oil leak is required for slipping and gasket extrusion, then it may be possible to qualify the bushing by using a simple pull test.

8.1.6.D. It may be difficult to resolve the above questions in the lab because each failure requires that the bushing be rebuilt. It is not clear that we know and can control all critical variables for conducting the test.

8.1.7 Do cable restraints at base of bushing inside of the transformer significantly affect the bushing seismic response and should they be considered in the qualification process?

8.1.8 There is a need for more information on representative characteristics of transformer case frequencies. In particular, is the strong interaction observed between the bushings and the transformer case in the 3-phase 230 kV transformer typical or an anomaly?

8.1.9 There is a need to get information on the range of turret heights used by manufacturers and get a better understanding of the function that they serve.

8.1.10 I feel that it would be desirable as part of the project to evaluate a retainer ring on a 500 kV bushing. There are many vulnerable bushings currently in the field and they will be there for decades. A few hundred dollar fix that would improve the changes of the serviceability of the bushing following an earthquake would be a cost effective activity.

8.1.11 When a bushing is installed on an operating transformer, what internal pressure develops as a result on the increase in temperature. If there is a pressure build up, it may cause the gasket to be blown out when the upper part of the bushing rocks over. If there is an internal pressure, tests should be run with this pressure,

8.2 Issues to be Considered for Inclusion in the Standard

8.2.1 Should the standard be formulated so that the qualification procedure takes into account the characteristics of different methods of bushing construction. I feel that one of the important parts of the IEEE standard that makes is very effective and improves the earthquake performance of qualified equipment is that qualification methods are tailored to each class of equipment, so that procedures address critical issues of the class. It seems that this may also be appropriate for different bushing types.

8.2.2 It is my view that conductor interaction issues should not be considered in the testing of substation equipment. This is not to say that they are unimportant, rather they are too complex and variable. The sections of the standard that deal with providing adequate slack in conductors should be followed. I feel that there is still a need to determine the role played by dynamic response of conductors on terminal loads.

8.2.3 I feel that the standard committee should consider requiring bushings that require tests for qualification should also require that the motion of the bushing conductor-capacitor assembly be restrained at the flange. This may reduce the changes of damage and catastrophic failures.

8.2.4 Once a better understanding of transformer frequencies is obtained, the importance of the stiffness of anchorage can be assessed.

8.2.5 Since bushings are installed with gaskets, it seems appropriate that they be qualified with gaskets. This may lower their frequency slightly, and significantly increase the damping.

8.2.6 There is a requirement in the standard to monitor peak stress in the flange and this will be onerous or impossible, as there are corners and gussets were strain gages can not be positioned. It is difficult to predict the location of the peak strain, so many gages may be needed. The intent of this requirement is good, and I have observed a crack bushing flange, but I feel that there is a need for a more workable requirement. One possibility is to measure the strain at some defined location, and then change the acceptance criteria to add a knockdown factor to account for stress raisers. This will not be a solution for a poor design, as the knockdown factor will be based on reasonable design, rather than the specific design.

8.2.7 The standard should require the test report to document the normal and test bushing clamping forces.

8.2.8 It seems to me that center-clamped, cemented bushings and probably composite bushings should also have their clamping force reduced for temperature effects for testing.

9. Request for Information to help Formulate the Testing Program

I have formulated two groups of questions that will help us in the test design. One group deals with transformers and the other with bushings. I hope that members of the committee who are knowledgeable about the issues can respond. It is at this stage that the Bushing Advisory Committee can have the largest impact on the project and I look forward to your responses. I am seeking information that is related to testing rather than to changes in the standard.

Below I am asking rather specific questions the response to which I expect will be different for different transformer designs. I would appreciate your providing the most common values and the range of typical values. I would like to avoid the extreme values that are seldom encountered. You may want to break your response down separately for 230 kV transformers and 500 kV transformers. Feel free to qualify your response as appropriate. If you feel that I do not adequately grasp the situation and your want to reformulate the question, feel free to do so. Also, if there are other issues that I should have brought up, but did not, please add appropriate comments.

I will treat responses as being confidential and results will be aggregated and specific responses will not be attributed to the person or organization responding.

9.1 Issues Related to Transformers

9.1.1 We are starting to design a bushing support structure to try to get a reasonable characterization of the top of a transformer. The support structure, fabricated from standard structural forms will be stiff and provide clearance so the stub of the bushing can sit above the shake table. It will be a frame with diagonals for stiffness. A plate will sit on top of the frame and be bolted at its edges. The bushing will be attached to the plate. We are designing it so that we can locate the bushing at various positions relative to the edge of the support structure (to simulate the edge of the transformer case). Tentative plans call for a 3/4" thick plate. I would like your thought on the dimensions of the plate to characterize the top of a transformer between stiffeners. In an earlier test program conducted at a different institution we used a 5' by 5' plate. We were thinking of using a larger plate for these tests. What are your suggests as to the size and thickness of the plate?

9.1.2 In constructing the transformer case, is the case strengthened at locations that support the bushings for that purpose?

9.1.3 What are the range and typical values of edge distances (distance of the outer edge of the bushing flange or turret to the edge of the transformer case) for 230 kV and 500 kV transformers.

9.1.4 There are several issues related to turrets. I have seen turrets that are taller that the height of the bushing above the flange. What is the range of common turret heights? What factors determine the turret height?

9.1.5 I have observed transformers where to turret is supported off of the side of the transformer case. Is this currently a design that is used, and if so, is it common?

9.1.6 How are turrets attached to the transformer case – welded or bolted?

9.1.7 Numerical analysis has indicated that there can be strong interaction between bushings and transformers that puts very large seismic loads on the bushing. I would like to get information on natural frequencies of transformer cases. Does your company do analysis in which the frequencies of the transformer case are determined? Are measurements ever made to determine the fundamental frequency of the transformer case? Are you aware of transformer frequencies?

9.1.8 Are transformer anchorage designed to be welded to the base plate close to the transformer wall? Are welding tabs or plates provided to secure the trasformer?

9.1.9 In the construction of core-type transformers, are there structural connections between the core-coil assembly and the transformer case, other than at the base? Are large shell-type transformers currently being manufactured and sold?

9.2 Issues Related to Bushings

9.1.1 What is the range of frequencies for 230 kV and 500 kV composite bushings mounted to a stiff support structure and the weights of these bushings.

9.1.2 Do you think center-clamped, non-cemented bushings can slip in an earthquake at the flange-porcelain interface without an oil leak to lubricate the surface? I would value any other insights that you can provide.

9.1.3 Do you think center-clamped, non-cemented bushings can have gaskets extruded at the flange-porcelain interface without an oil leak in an earthquake? I would value any other insights that you can provide.

9.1.4 On center-clamped, non-cemented bushings, will there be a build up of internal pressure due to temperature raise and do you feel that this could cause a gasket to blow out when the flange-porcelain interface starts to open during an earthquake? I would value any other insights that you can provide.

9.1.5 In our tests of composite bushings, should we reduce the center-clamped force to account for temperature effects?

9.1.6 Do you feel that internal restraints on cables below the bushing stud have a significant effect of bushing earthquake response? Is it dependant on transformer design? Assuming that this restraint has a beneficial effect on earthquake performance, but it is dependent on transformer design, do you feel this effect should be part of the qualification process?

10. Acknowledgements

Over the years I have had assistance from utility people and manufacturers in expanding my understanding of how equipment is constructed and how it performs in earthquakes. Relative to this paper I would particularly like to acknowledge the help provided by Keith Ellis and Lonnie Elder. Let me note that any errors in my expressing how things work or interpretations of observations are my own doing.