Issues and Research Related to the Qualification of the Transformer-Bushing System

by

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Executive Summary

Experience from laboratory tests and earthquake damage indicates that the procedures for seismic qualifying transformer bushings (center-clamp, non-cemented) in IEEE 693 are not valid. The added amplification introduced in the IEEE 693 qualification procedure to account for not mounting the bushing on the transformer for qualification has not adequately captured the affect of the transformer on the bushing's response. Several research tasks are identified to address various issues related to the earthquake performance of bushings, but the most important is developing a valid procedure to be used in IEEE 693 to qualify the transformer-bushing system. Other topics are to evaluate composite and cemented-type bushings using the proposed protocols, explore methods to enhance bushing performance, evaluate bushing failure modes, and assess conductor interaction issues. Other concerns related to standard development are discussed, such as the need to tailor the protocol to the type of bushing. It is noted that interaction with transformer manufacturers should be sought in developing the bushing test procedures. Comments and suggestions or other thoughts are being sought and these should be forwarded to schiff@stanford.edu

1 Background

Numerous failure modes of transformer bushings have been observed after earthquakes. These include offset of porcelain relative to flange without permanent oil leak (clearance issue for large offset), offset with permanent oil leak (common), gasket extrusion with permanent oil leak (common), cracked porcelain (rare), and temporary oil leak (common). All but the last require remedial action or that the transformer be taken out of service. In the Northridge earthquake about 45 bushings in one utility experienced these problems, so the impact on service disruptions can be serious.

Research funds will be available to investigate transformer bushings. This report is being prepared to provide background, identify issues that might be addressed in a proposed research program, and suggest options and identify priorities for the issues to be addressed. While other transformer earthquake failures have been observed, requirements in the standard have addressed these issues.

This document is put forward to serve as a basis of discussion rather than a proposal even though suggestions are made. This document reflects my personal views and I am sure that other valid alternatives could be presented. This report is a revision of an earlier version and reflects discussion at the IEEE 693 meeting held on 2/2/06 and the review of a limited number of manufacturers. I am formulating this document in an informal setting by not citing references.

2 IEEE 693 Transformer Bushing Qualification Procedure

In general, the IEEE 693 Standard strongly recommends that equipment be qualified on the support structure that will be used at the substation. For transformer bushings this was not possible for two reasons. First, a given bushing can be sold to different transformer manufacturers for use on different transformer models. Secondly, typical power transformers are too large, heavy and costly to be used for tested bushings. In lieu of mounting the bushing on a transformer tank, the procedure specified in IEEE 693 requires the bushing to be mounted on a stiff support structure. An amplification factor of two, to account for the amplification between the base of the transformer to the flange of the bushing, is imposed on the bushing support structure via the input spectra. While the wording is different in the 1997 and 2005 versions of the Standard,

the procedure is the same. in addition to the amplification factor of two, the bushing must be tested with the input twice the motion specified by the Required Response Spectrum (RRS). The standard specifies the qualification excitation through the RRS. There are two qualification levels, the 0.25g RRS (Moderate Seismic Level) and the 0.5g RRS (High Seismic Level). Thus, the input to the structure supporting the bushing must be four time the RRS. In general, the bushing is mounted at 20 degrees from the vertical.

Transformer bushing tests (as well as analysis), like all other substation equipment, do not consider conductor interaction loads. Research has shown that conductors connecting equipment can generate significant dynamic loads. IEEE 693-2005 does require that weight equivalent to conductor connection hardware be added to the conductor terminal pad.

3 Tests and Earthquake Performance of Transformer Bushings

3.1 CERL Tests and Hecter Mine Earthquake

The author witnessed and participating in tests of a 500 kV GE Type U bushing at CERL (US Army Corps of Engineers test facility). This bushing was supported on a stiff support structure in which the bushing was positioned15 degrees from the vertical. It was subjected to test response spectra with a shape that conformed to IEEE 693-1997. The bushing started to leak when the spectrum amplitude was adjusted to between 0.25g RRS and 0.33g RRS. Figure 1 shows test configuration.

In October 1999 the 7.1 Hecter Mine earthquake subjected the Victorville substation to short-duration ground shaking of about 0.11g peak acceleration. One of four 500 kV bushings developed a permanent oil leak at the flange-porcelain interface from this excitation. This leak developed at ground motions less than supposedly more severe shake-table tests.

3.2 Consortium Tests at PEER and Northridge Earthquake

A consortium of utilities organized by the author conducted tests to evaluate the performance of a method to retrofit transformer bushings to improve serviceability after an earthquake. Tests were conducted on 230 kV GE Type U bushings mounted on a stiff support structure with the bushing positioned 20 degrees from the vertical. Tests were performed at the PEER test facility in Richmond. A bushing was subjected to an IEEE 693 compatible test response spectrum adjusted to increased amplitudes. The bushing was tested to about 250% of the High Seismic Level (2.5g RRS), the capacity of the table, and did not fail.

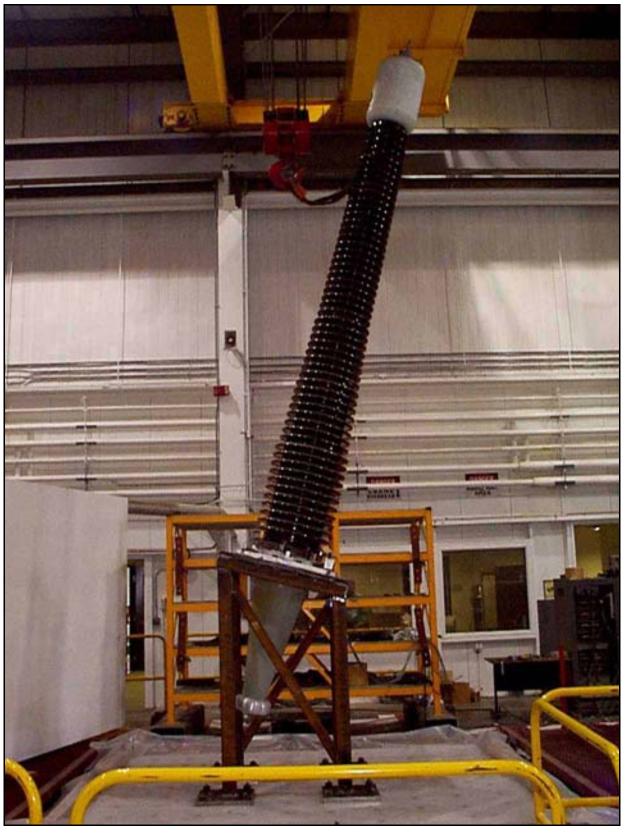

Figure 1 Bushing on stiff support for qualification test

Subsequent to the above test, the bushing was mounted on a 5' square, 1/2" thick plate (a simulation of a transformer top) and did develop a leak at excitation level below the high seismic level.

In the Northridge earthquake about twenty-five 230 kV bushings of a similar type developed permanent oil leaks at the flange-porcelain interface at shaking levels substantially below those experienced in the PEER tests. Thus, the performance of these 230 kV bushings during the shake-table tests was much better than similar bushings on transformers during earthquakes.

3 Bushing Frequencies and Earthquake Performance

Stiffly mounted 230 kV porcelain bushings have been observed to have frequencies in the 14 Hz to 20 Hz range and 500 kV porcelain bushings have from 6-1/2 to 8-1/2 Hz range. As-installed bushing frequencies have been observed to have dropped to 1/2 or less of the stiff support frequency. This change in frequency is attributed to the flexibility of the transformer cover and may be one factor contributing to the difference between test and earthquake bushing performance.

4 Conclusions Drawn from Observations

The conclusion of these observations is that the test procedures given in IEEE 693 for qualifying transformer bushings have not adequately captured the as-installed configuration of bushings on transformers. The qualification procedures are un-conservative and bushings will fail at ground acceleration levels 30% to over 50% below the level to which they were qualified. Adding an amplification factor of 2 to account for eliminating the transformer in testing did not adequately account for its affect on bushing performance. Other factors of the installation may affect the response beyond just elevating the severity of the excitation. There is a need better understand the affect that the transformer has on bushing performance and use this information to develop valid qualification procedures for IEEE 693.

5 Research Needs

At least five areas of investigation can be identified relative to bushings. Each of these topics is discussed in the following sections.

5.1 Develop A Valid Method for IEEE 693 to Qualify Transformer Bushings

The highest priority task is to develop valid method(s) for bushing qualification in IEEE 693. Transformers and their bushings are not only the most costly item in a substation, but their loss of service can have the largest impact in both extent and duration on customer disruption. The power community has suspected that the existing procedures in IEEE 693 are flawed and the availability of research funds are an opportunity to address this critical deficiency.

The necessity for testing labs to be able to implement the procedures given in IEEE 693 and the cost of qualification places many constraints on the testing procedure. While more innovative methods may ultimately be developed, I envision a support structure in which the bushing is supported on a flexible plate. The results from the tests described (in section 3.2) suggest that the flexible plate reduces the seismic capacity of the bushing that was tested. If this is true, it seems that it would desirable to make the plate as stiff as possible. This is limited by the ability of transformer manufacturers to economically (and electrically) stiffen bushing supports. This clearly demonstrates the need for transformer manufacturers to actively participate in the process to develop the testing procedures. Assuming that a bushing support structure(s) is developed that captures the important effects introduced by the transformer, the scaling of the ground motions will have to be reconsidered so that the protocol adequately represents the bushing on the transformer when subjected to earthquakes. This may require a lowering of the input excitation.

There are several other things that may influence characteristics of the test procedures.

5.1.1 Qualification Procedure Based on Operating Voltage of Bushing

A 230 kV bushing is often found on a 500 kV transformer (the low voltage bushing) and on a 230 kV transformer (the high voltage bushing). It is my understanding that the thickness of the transformer cover is uniform so that the support of the 230 kV bushing on a 500 kV transformer may be stiffer than when it is installed on a 230 kV transformer. Transformer cover thickness may be controlled by the physical dimensions of the transformer rather than the operating voltage or by the bracing system used to accommodate the loads introduced when a vacuum is applied to the transformer. Again, input from the manufacturers is needed. Based on what is discovered about transformer design, it may be appropriate to have different support structures for different operating voltage bushings in the range from 161 kV and 500 kV bushing. Technically, 765 kV bushings should also be included, but historically these have not been the subject of much discussion. In light of the fact that we can not qualify some 500 kV bushings using the current standard it is not clear what the prospects are for the 765 kV bushing. I am not aware of seismic qualification of this class of bushing.

5.1.2 Turret Heights can vary and can Influence as-Installed Frequency

A review of pictures taken at earthquake investigations shows that there are large variations in turret height. There are cases where the height of the turret exceeds that of the bushing (above the flange). It is expected that taller turrets will decrease the seismic capacity of the bushings (Lower installed frequency and amplified transverse motions at flange). It would be desirable to have the research develop a degradation factor associated with turret height so that testing can be simplified and it would be an incentive for transformer manufacturers to control turret height. For turrets above a given height a turret bracing system may be needed to accommodate taller turrets without reducing bushing seismic performance.

5.1.3 Effect of Bushing Tilt

In general, tall turrets are used with vertical bushings, although there are exceptions. It would be desirable to have the research develop a degradation factor associated with bushing tilt angle so that tests could be simplified. It is interesting to note that in one series of tests of a 500 kV bushing, the bushing appeared to leak first at the lower part of the flange where the static moment would add compressive loads and reduce the change of leaking. This may have been a flaw in the observation during the test.

5.1.4 Orientation of Bushing Support Surface in Tests

In all of the test fixtures that I have seen (PEER, CERL, Germany) the stiff support structure was tilted. Generally, the transformer's covers are horizontal, so that it may by desirable to design the support structure with a horizontal flexible plate. If the bushing is to be mounted at an angle, it could be done with a short turret at the flange, as is typically the case in practice.

5.1.5 Bushing Location Relative to Transformer Cover Edge

There is an issue of distance of the bushing from the edge of the transformer case (or the testing support). It is my feeling that this primarily controls the frequency of the as-installed bushing. Thus, this may be part of the frequency control (plate thickness, size, and boundary conditions) rather than an independent parameter that has to be controlled. Tests or analysis should verify that edge distance primarily only effects as-installed frequency and not other characteristics of the motion. Input from the manufacturers would be helpful here.

5.1.6 Turret Footprint can be Important

The size of the turret footprint also has a large effect on as-installed frequency, other factors being fixed. Transformers observed in the Mexico earthquake investigation show that large conical "turrets" can be used. In some cases the "turret" extended to the sides of the case so that the transformer cover was cone shaped. This is expected to have a significant impact on the as-installed frequency of the bushing. It is my view that the "qualification of transformer bushings" is an inappropriate statement of problem. I feel that the transformer-bushing system needs to be considered in the qualified process. This presents challenges because the manufacture of bushings are typically done by a different company than the transformer manufacturer. This may require that the standard impose some requirements on the stiffness of the transformer cover near the bushing support. When the problem is stated in this way, the transformer manufacturers are stakeholders in the qualification of bushings and they need to be active participants in the standard development process. I suggest that in the future that we address this issue as the qualification of transformer-bushing systems to emphasize this interdependence.

5.1.7 Gasket between the Bushing Flange and Turret

Tests that have been done suggest that the gasket between the bushing flange and the turret do not influence the response or performance.

5.1.8 Develop a Design Envelop of Control Parameters

Several of the above sections discuss design parameters that influence the as-installed bushing frequency. I suggest that an element of the research explore the development of a parameter design envelop (or parameter design space), as most of these parameters appear to primarily control the as-installed frequency. This would avoid an overly prescriptive (fixed transformer cover thickness, insulator edge space, etc.) standard and give the manufacture the option of varying parameters, such as cover thickness, bracing and bushing edge distance, cover bracing, turret height, turret footprint and still meet the overall design objective.

5.1.9 Effect of Transformer Case Frequency

Research has shown that the lowest transformer case natural frequency can have a large impact on bushing performance if its frequency is near the as-installed bushing frequency. By case frequency I refer to the body of the case rather than frequencies associated with transformer cover deformations. This research, conducted by Andre Filiatrault, modeled the transformer in more detailed than is done by some manufacturers. For the small sample of transformers studied (four), one relatively small size (physical size) transformer case, had a case frequency that was close to the as-installed natural frequency of the bushing. For this situation there was a resonance (case frequency) on resonance (as-installed bushing frequency) and the bushing experienced very large response. Fortunately, this size transformer case was not typical of those found at substations. For typical size transformer cases the overall case natural frequency was removed from the as-installed bushing frequency. It should be noted that in the models referred to above, the case was modeled with the perimeter of the case fixed to the foundation, rather than anchored at specific anchor points as is found in practice. The anchorage used in the models would be much stiffness than what is actually found in practice so that the issue of transformer case frequency should be evaluated with realistic anchorage details. In addition, guidance is needed to determine when transformer case frequency is an issue that should be considered, however, if clear guidance can not be provided, the standard may have to require that transformer case frequencies be determined by the manufacturer.

Above (Section 5.1) it was noted that it would be desirable to have the bushing support stiffness on a transformer as stiff as possible. In light of the case frequency issue, a rational approach is needed that considers actual frequencies rather than simple design rules, such as having the bushing installed frequency be 1/2 that of stiff support frequency. A 230 kV bushing can have a stiff support frequency as high as 22 Hz. Cutting this in half gives a 11 Hz as-installed frequency which may, in some commonly encountered situations, bring it close to the transformer case frequency.

If after evaluating the effect of anchorage details on transformer case frequency it is found that typical transformers will have case frequencies removed from typical as-installed bushing frequencies, I suggest that unusual transformer configurations be addressed separately and that the qualification procedure deal with common situations. I feel that the bushing qualification procedure will be complex enough as it is without trying to make a general procedure that encompasses unusual design configurations into the normal qualification procedure. While all reasonable situations should be covered by the standard, the standard may require that less common situation be given special analysis.

5.1.10 Difference in Porcelain and Composite Bushings may Require Different Test Protocols

The weight of a composite bushing is typically about half that of the equivalent porcelain bushing. The frequencies of the bushings on stiff supports are very different. The limited data that I have suggests that a 230 kV composite bushing will have a frequency 1/4 to 1/3 of porcelain and for a 500 kV bushing the composite is about half that of porcelain. The loads on the bushing that contribute to failure may also be different. For the composite and grouted bushings it is speculated that the moment at the base may control structural failure while for central-clamped porcelain bushing may also be affected by base shear (this may affect offset). The different bushings may have different implications on the stiffness of the transformer case at the bushing support, which may complicate transformer design as the design may have to include the type of bushing that is to be used.

5.1.11 Internal Bushing Conductor Connection and Bushing Response

At the recent IEEE 693 meeting I had an opportunity to discuss transformers with Keith Ellis and look at a picture of an internal conductor connection to a 500 kV transformer bushing. This insulated conductor appeared to be structurally substantial (for aluminum, 3000 amp service would require a cross section area of about 3 square inches although the copper lead would be smaller), was about a foot long between the lower bushing terminal pad and what appeared to be a stiff restraint on the conductor. At 230 kV some bushing have a 6000 amp rating and would have an even larger conductor. There is a need to evaluate the affect of this connection on bushing response. This may also be a method to modify and improve the seismic performance of bushings. Clearly, many designs, such as draw-lead bushings, would not provide this restrain. One encouraging aspect of a lower restrain is that this is a feature currently used by transformer manufacturers. This is another instance where input from transformer manufacturers would be useful.

An interesting issues is rated to bulk-oil circuit breakers. Bulk-oil circuit breakers have bushings that are similar to transformer bushings, but due to the large mechanical service loads when a circuit breaker trips, the bushings are secured near their lower conductor connections. In the US I have never observed a leak or offset of this type of bushing in a circuit breaker. The circuit breaker cases are much smaller and the small diameter of the tank would make their top surface that supports the bushing much stiffer. However, this suggests that lower restrain on a transformer bushing may improve seismic performance. It should be noted that in Japan there have been leaks on bulk-oil circuit breakers, but these were unusually large units (height about 20').

5.2 Evaluate Various Bushings Using Proposed Qualification Method

I feel that as part of the research effort there should be an evaluation of composite and grouted as well as center-clamped bushings using the proposed new qualification methods.

The most serious problems with bushings observed after U.S. earthquakes has been continuing leaks that required the transformer to be taken out of service (for bushing replacement) or the application of extraordinary measures to temporarily stop the leak. While there are no firm statistics, it has been my observation that extruded gaskets were more prevalent than large relative displacements between the bushing and the flange that contributed to continuing leaks. Over the years, bushing manufacturer sales representatives has approached me touting grouted bushings, as they will not have these problems. The January, 2003 Colima, Mexico earthquake (Mw=7.8) provided performance data of grouted bushings. It is my recollection that the site had 29 grouted or clamped 400 kV transformer bushings (all were of this design rather than the center-clamped design). One clamped bushing failed (cracked porcelain) and 4 or 5 grouted bushings failed (cracked porcelain). The ground motion obtained from a seismograph in the switchyard had a peak ground acceleration of 0.38g. It is interesting that six of seven 230 kV center-clamped bushings developed leaks, but did not crack. Since grouted porcelain bushings, to my experience, are relative rare in the U.S. it may be difficult to get a surplus one to tests. I suggest that we contact Mexico to see if they can participate in this project. Should we go with this route, I have some contacts.

With the issue of IEEE 693-2005, new methods of qualifying composites will be instituted. In a limited number of tests of composite CVTs it was observed that using the methods in IEEE 693-1997, damage to the composite member actually gave the appearance that the units was performing better. It would be informative to reevaluate composite bushing(s) using the new support structure and composite procedures. There are indications that performance is design specific, so that general observations about composites can not be based on the evaluation of a single design. Getting a composite bushing of any design to evaluate may be difficult, but if possible it would be desirable to select one of the type that exhibited seismic vulnerability.

5.3 Evaluate Methods to Enhance Bushing Performance

Using existing qualification methods there are 500 kV bushings that can not be qualified. It is my view that a new valid qualification method will lower the rated capacity of bushings further. It would be desirable to explore methods to enhance bushing performance. Several methods have been explored and I will not review them here. Most of these address the gross performance of the bushing without exploring the failure mores although practical implementation may be problematic.

At least one method uses a mitigation procedure that is based on the observed failure modes even though their genesis is not understood. This is the use of a retainer ring at the flange-porcelain interface. On a 230 kV bushing this prevented significant slipping between the porcelain and the flange and also prevented the gasket from extending beyond the porcelain-flange interface so that after shaking stopped, leaking also stopped. This method should be evaluated with a new improved retainer ring on a 500 kV bushing to verify that there are no unanticipated consequences. One advantage to this method is that it can be applied to existing transformer bushings while they are in the transformer at relatively low cost and minimum service disruption.

5.4 Evaluate Failure Modes of Bushings

As a researcher I have been interested in understanding the failure modes of bushings. While there have been research efforts directed at this problem, they have not been successful. I feel that this pursuit goes beyond academic curiosity, as a better understanding of failure modes could lead to improved designs and performance. While some of this may get into proprietary issues, the result would be a benefit to the power industry through better performance.

It is my feeling that an understanding of the failure modes is not required to develop a valid qualification method for qualifying transformer bushings.

5.5 Conductor Interaction Loads

Conductor interaction loads for bushings are another source of loading that can contribute to bushing failure. Conductor connections can also introduce damping and reduce response. Typically for a new installation that considers seismic design issues there is slack to accommodate relative deflections between the ends of the conductor, but conductor dynamics can load the bushing. While this is a fertile area for further research, my own feeling is that it is probably beyond the stage were conductor loading can be explicitly considered in bushing qualification tests.