An Evaluation of Experimental Requirements for Seismic Qualification of Substation Components and Recommendations for New Edition of Test Standard

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SUMMARY:
In the past and recent earthquakes, high voltage substation components have suffered damage and this damage has led to disruption in power distribution. As a result, electrical utilities have suffered financial losses and the lag in restoring power, has caused delays in restoring essential services and in post-earthquake recovery. The IEEE 693 (Recommended Practice for Seismic Design of Substations) Working Group was formed in part to address the seismic vulnerability of the high voltage equipment and to formulate procedures for seismic qualification of such equipment. The standard requires shake table testing for large substation equipment of higher voltage classes. As currently written, the standard provides significant latitude to users (utilities, manufacturers and researchers) with respect to the conduct of certain aspects of the test program. This choice was motivated in part to allow testing at as many facilities as possible, given the limitations of such facilities at the time of development of the standard. Although applicable at the time of its inception, many shake tables have been constructed in recent years that would now allow for a tighter test requirements. For example, many more facilities are now able to test to high performance level, conduct triaxial testing, and use more sophisticated array of instrumented and data collection. A review of the current test methodology was conducted and shortcomings were identified. Multiple test programs conducted at PEER, UC Berkeley dealing with seismic qualification of disconnect switches were considered as examples for this purpose. The recommendations follow the main idea of the IEEE693 standard aiming at ensuring adequate seismic resistance of sub-station equipment by including utilities, manufacturers, researchers and practioners in the development of the standard. Recommendations for development of a more robust experimental procedure were formulated. Examples of the application of such revisions to the test standard were then evaluated and found to provide a more comprehensive mean of characterizing the equipment response.

Keywords: Lifeline systems, electrical substation equipment, seismic qualification, IEEE693, shake table testing

1. INTRODUCTION

In the past and recent earthquakes, high voltage substation components have suffered damage and this damage has led to disruption in power distribution (Fujisaki, 2009). As a result, electrical utilities have suffered financial losses and the lag in restoring power, has caused delays in restoring essential services and in post-earthquake recovery. The recent earthquakes in New Zealand and Japan serve as representative examples of such failures as well as the challenges of the recovery efforts. The IEEE693 Working Group was formed in part to address the seismic vulnerability of such high voltage equipment and to formulate procedures for seismic qualification of such equipment in the standard.

The current version of the IEEE standard covering the seismic qualification of substation equipment was published in 2006 (IEEE, 2006). The standard requires that equipment and components of higher voltage classes must be seismically qualified by multi-axial testing on earthquake simulators (shake tables). In general, equipment requiring shake table testing possesses vulnerable characteristics, such as massive tall insulators or other components that have historically performed poorly in earthquakes.

The IEEE693 Working Group is developing the next version of the standard and bases its requirements on the feedback received from open discussions with academia, utility companies, consulting engineers, and equipment manufacturers. The involvement of all such interested parties in the development process of the standard has been proven to be very beneficial. One of the representative examples of the close relationship with academia is the development of a prescribed time history for seismic qualification testing of substation equipment (Takhirov et al, 2005a). Active participation of all interested parties (Takhirov, 2009) and Gilani et al (2001) are always supported by the IEEE693 Working Group.

As a result the IEE693-2005 standard represents a consistent, up-to-date, and self-contained document. The standard initially gained acceptance among North American utilities, but due to its continuous development and its quality, it has become a popular document used worldwide. The main objective of this paper is - as a part of this continuous development process - to review of the current state of seismic qualification testing of substation equipment and identify the areas of the standard that needed to be addressed. The review is based on more than fifteen years of testing and test witnessing experience by the authors of this paper, which have conducted and participated in tests at many laboratories worldwide.

2. AMPLIFICATION OF SUPPORT STRUCTURE

In many cases, substation components consist of equipment installed on a support structure to provide structural integrity as well as achieve electrical clearance from the ground. Examples include: a disconnect switch on a support structure, bushings on top of a transformer, a circuit breaker on a supporting structure and many others. Since all equipment/components are required to be tested full-scale in as-installed configuration, the feasibility of seismic qualification by testing can be limited by capacity of a test laboratory. These limitations can include the clearance above the shake table, the footprint of the support structure and the equipment itself. The allowed payload of a shake table, displacement and velocity limits are also big factors to consider. Utilities may often use support structures of their own design, and certain types of equipment may be installed with widely varying support configurations depending on functional needs.

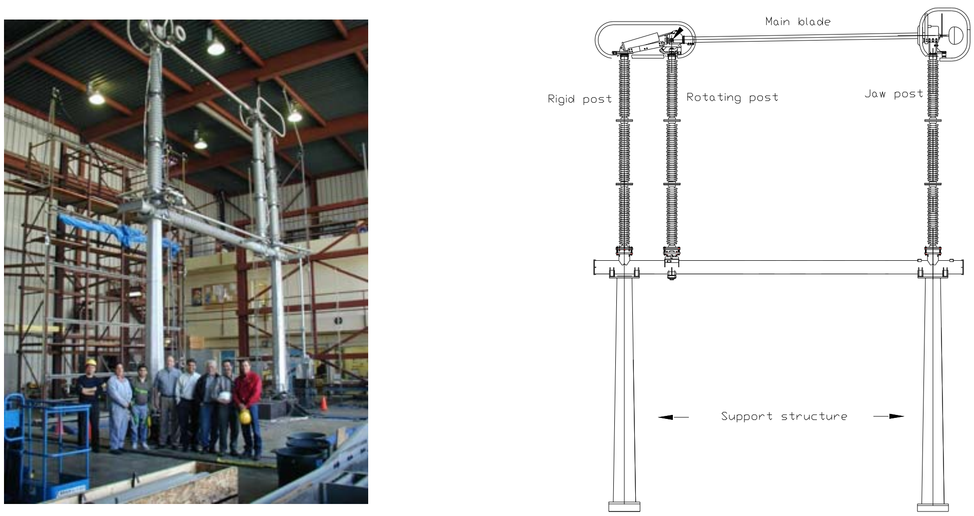
To address these issues, the standard allows the testing of electrical equipment without a support structure under amplified strong motion that accounts for the effects of a support structure. The shortcomings of this approach are discussed in this paper and are based on the extensive research program conducted on the 550-kV vertical break disconnect switch at the University of California, Berkeley as part of the Lifelines Program (Takhirov et al, 2005b). The switch was tested using many configurations, including the two major ones: main blade closed and main blade open. The latter configuration was tested with amplified strong motion obtained from the top of the support structure.

2.1. Support Structure Unknown

The current version of the standard (IEEE, 693) allows seismic qualifications testing when an actual support structure is not yet known, by imposing an amplification factor to required response spectra (RRS). A number of test results show that the amplification factor of 2.5 set by the standard for seismic qualification tests without a support structure may be not un-conservative in some cases and cannot alone account for the complex 6D motion (3 translations and 3 rotations) of the attachment points of the equipment to the support structure.

A representative example of this can be seen in test results of 550-kV switch tested at High

Performance Level (PL, defined by a standard spectral shape anchored to 1.0g in IEEE693) at the University of California, Berkeley (Takhirov et al, 2005b). Spectral accelerations of the table and support structure computed for High PL run are presented in Figure 2a, which show that the spectral accelerations on top of the support structure were amplified in a wide range of frequencies with some significant amplification in the vicinity of the first and second mode frequencies of the system. This plot is typical for all three directions of testing and only the X direction of shaking is shown in this figure. Ratios of spectral accelerations on top of the support structure to that of the table have a similar trend for all three directions of testing, as shown in Figure 2b. Spectral amplifications in both horizontal directions significantly exceeded the standard's factor of 2.5, with the most amplification seen in the X axis (direction of the switch with lower stiffness, perpendicular to the switch base). The latter amplification is more than two time greater than the 2.5 factor with the largest amplification is as high as 5.5.

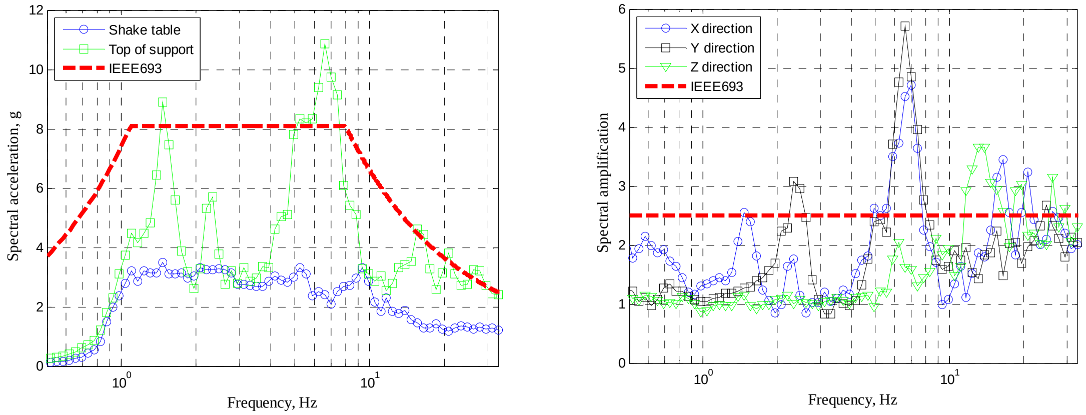


(a) (b)

Figure 1. 550-kV vertical disconnect switch on 4.6 m tall support structure in closed configuration (a) and schematic drawing of the switch and its major parts – closed configuration is shown (b).

Similar large spectral amplifications in a wide frequency of ranges were observed in other tests as well. One example of seismic qualifications that had a similar outcome was the test program conducted on three-phase disconnect switch with a voltage rating of 245-kV, tested at the University of California at Berkeley (Takhirov, 2008). Even though it is somewhat expected that the spectral amplification will be larger for the 550-kV switch mounted on a tall and flexible structure, it was surprising to discover a somewhat similar amplification in the case of a relatively rigid frame supporting the 230-kV switches, as shown in Figure 3 (vertical break switch is shown).

Based on the discussion above, the amplification factor of 2.5 for unknown support structures can be un-conservative in some cases. For equipment qualified by the generic 2.5 amplification factor, IEEE693 requires that the equipment be installed on a support structure designed such that the amplification factor delivered is less than 2.25. Currently, analytical parametric research and a detailed analysis of the test results accumulated from fifteen years of seismic qualification testing at the University of California at Berkeley are currently in progress. These studies are expected to provide data on the extent of coverage provided by the currently specified amplification factor, and whether changes are needed.



(a) (b)

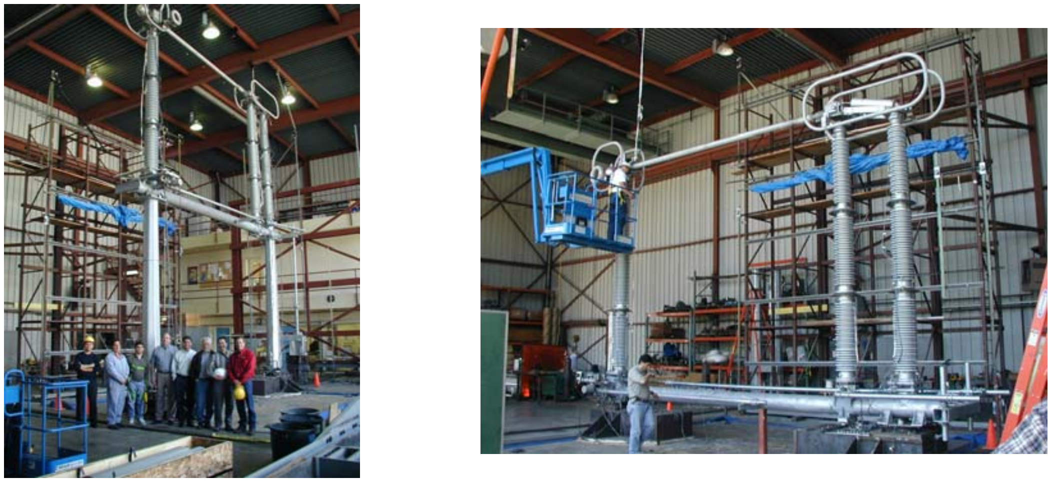
Figure 2. Spectral accelerations (a) and spectral ratios (b) of shake table and top of support structure

(a) (b)

Figure 3. Large spectral amplifications were also observed in 230-kV switch tests: main blade closed configuration (a) and main blade open configuration (b)

2.2. Support Structure Known and Well-defined

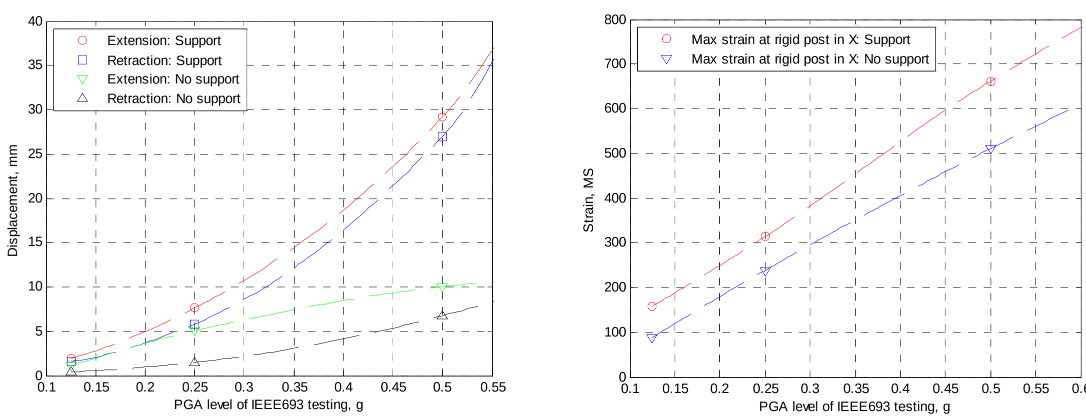
The current version of IEEE693 standard specifies the following procedure for seismic qualification of substation equipment when the structure is known and well-defined. The equipment and the support structure shall be accurately modelled and a non-stationary analysis shall be performed on the model. The amplified spectral accelerations shall be delivered from the analysis and these spectral accelerations comprise target response spectra to be met or exceeded by the shake table. Except for a 1.1 factor on the calculated amplification, the current version of the standard does not specify any other means to account for uncertainties associated with modelling and many assumptions done in the model. To implement this approach, the 550-kV switch was tested in closed configuration with and without support structure (Takhirov et al, 2005b) as shown in Figure 4.



(a) (b)

Figure 4. 550-kV vertical disconnect switch on 4.6 m tall support structure in closed configuration (a) and in closed configuration attached directly to a shake table platform (b).

This case represents a case when the model is perfectly defined: properties of the “switch’s model” and the “support structure’s model” perfectly reflect the actual ones. Three levels of tests with amplified excitation at 0.125g, 0.25g and 0.5g were performed. The test results were compared to test data recorded for the switch with support structure. The differential displacement between the tips of so called Jaw post insulator (located at the opening side of the main blade) and Rotating post insulator (located under the hinge fixture coupling two posts together) was monitored during the tests. In addition, strains were monitored in all insulator posts including Rigid post where the strains had a tendency to peak at much higher values than at other posts. The comparison of these two measurements for the switch on the support structure and without it is shown in Figure 5. Based on the plots, the differential displacement between the Jaw and Rotating posts differ by about 300%. Therefore, the no-support configuration tested with an amplified motion severely underestimates the amplitude of this motion and behaves differently compared to the case with support. Frequency content of the displacement records was different also which is not shown here due to limitation of the paper’s size. The strains in Rigid insulator post - which was the most overstressed post - were underestimated in the no-support configuration by about 30% in transverse direction.



(a) (b)

Figure 5. Change in distance between Rotating and Jaw posts (a) and strain at bottom section of Rigid post insulator – the most overstressed post (b)

Based on the plots provided above the following can be concluded. Even in this case of ideal match between physical components and finite element models the latter fail to fully represent complexity of actual equipment with a support structure. For the case discussed in this paper, the effects of top-of-support rotation are very difficult to address adequately. In many seismic qualification programs done commercially, modelling is done without any component tests taken into account and in many cases no calibration of the model is performed which raises a strong concern about validity of the final model. Even in the perfect match situation the performance of the equipment can differ significantly when support structure's effect is substituted by an amplified motion.

This approach needs to be reconsidered and re-evaluated to achieve consistency in testing and seismic qualification. A new reliable and conservative enough approach needs to be developed to assess structural performance of the equipment and its support as a coupled system with complex and nonlinear properties.

3. PROJECTED PERFORMANCE OF QUALIFIED EQUIPMENT

Another common approach of seismic qualification testing permitted by the standard is extrapolation of the results of half-level of testing to full PL. Equipment qualification by test is often conducted at half of the PL (e.g., spectrum anchored to 0.5g pga for the High level). The equipment is projected to be capable of withstanding seismic loading at the full PL (e.g., spectrum anchored to 1.0g pga for the High level), provided that the measured stresses are within acceptable limits. This concept is based upon the assumption that the equipment behaviour will remain linear up to the PL level of testing. In many cases this is not a reasonable assumption, especially for the electrical equipment composed of bearings, spring cans, stops or bumpers and other mechanical devices that may exhibit nonlinear behaviour. In addition, although electrical function is verified following testing at the half-PL, there is no demonstration of electrical function at the full PL when using this approach. For example, substation equipment can be tested at half-High PL while the strains are monitored at critical locations throughout the test article. For critical parts with complex geometry or where strains cannot be measured, or cannot be expected to indicate acceptability of the part, the shake table test is required to be supplemented by static testing in which the parts are subjected to estimated PL loading. Functionality of the equipment is then confirmed after these tests. If the strains are below or at the allowable values, the results of supplemental static testing are acceptable, and electrical functionality is confirmed, the equipment is considered to be qualified, and its performance can be projected to the full High PL. This approach was introduced in earlier versions of the standard to address the following: (1) limited number of shake tables was available that could deliver the required motions, (2) available shake table facilities had limited payload capacities, and (3) risk of financial loss during testing of expensive equipment, (4) safety concerns with testing large, brittle porcelain components, some of them subjected to high internal gas pressures at shaking levels close to structural failure, (5) uncertainty regarding the seismic capability of equipment that could actually pass full PL testing. After introduction of the standard, several brand new shake table facilities have come on line and several old tables have been upgraded to achieve adequate payload capacities. In recent years, a number of full High PL qualification tests of high voltage equipment have been successfully completed.

A typical example that shows shortcomings of the approach is provided herein. In a vertical break disconnect switch its main blade shall remain inside of the contacts when the switch is in closed configuration. In many cases the blade has additional electrical shielding components in the vicinity of the jaw contact clip which limits the allowable relative motion between the switch blade and the jaw clip. Depending on level of excitation, travel of the blade can exceed the allowable causing an impact like loading which is not anticipated. In addition to that, the switch can perform nonlinearly and it usually does making prediction of its travel based on low level testing almost impossible. A change in distance between Rotating and Jaw posts in the 550-kV switch tests (Takhirov et al, 2005b) is discussed here. The displacement between Rotating and Jaw post was monitored directly by a position transducer. Five levels of seismic qualification testing were performed with IEEE693 RRS anchored at 0.125g, 0.25g, 0.5g, 0.75g and 1.0g (High PL). As shown in Figure 6 peak displacement changed nonlinearly and it was not possible to extrapolate performance at High PL from that at half-High PL.

For instance, from half-High PL seismic qualification testing it would be assumed that: travel of the blade's contacts will not exceed 60 mm (30 mm times two) in both retraction and extension the contacts on Jaw side will never reach the stopper on the blade (in retraction). In reality, the switch's performance was nonlinear that lead to significant increase in the relative displacement. As a result, the blade's contacts were forced to travel more than 105 mm in extension; the travel of blade's contacts in retraction was close to 80 mm at which displacement it was restrained by the blade shielding component. The latter can lead to impact loading of Jaw post and should be avoided if at all possible. To address this issue the limiting component was relocated further away as part of the Research and Development (R&D) effort by the switch manufacturer. A necessity of this simple improvement of the switch's blade would be completely missed in half-scale test.

The following conclusion remarks can be drawn from this discussion. First, seismic performance of substation components is nonlinear and can lead to under-testing of the equipment and faulty conclusion about its performance. Second, functionality of the equipment is not possible to predict and extrapolate from half-scale to full-scale PL testing. It is recommended that the use of half-PL testing as a basis of qualification either be removed from the standard, or limitations added regarding its use.

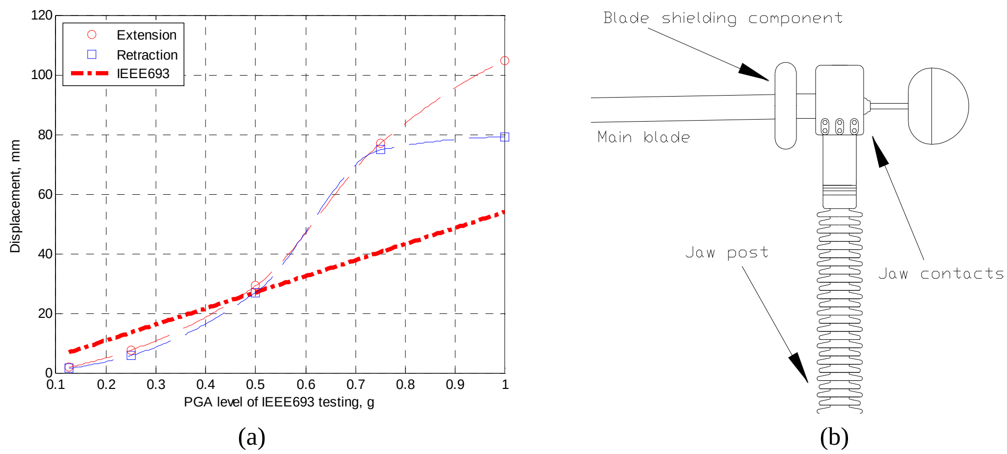


Figure 6. Change in distance between Rotating and Jaw posts (a) and schematic drawing of blade shielding component (b)

4. OPTION OF REPLACING TEST ARTICLE WITH A BRAND NEW ITEM IN PL TESTS

The current version of the standard does discuss the replacement of a test article or its parts with brand new items between test runs with different configurations. As an example, a disconnect switch with ground switch would be required to be tested in three configurations: main blade closed and grounding blade open (C-O), main blade open and grounding blade open (O-O), main blade open and grounding blade closed (O-C). When PL testing is conducted, the qualification test program would require that the test article be subjected to at least three very large earthquakes, in which the equipment may be stressed at levels approaching failure. The current standard specifies that at the Performance Level, ductile parts may undergo minor yielding, and some permanent deformation is allowed without fracture of any part, provided that the functionality is maintained. It would seem unreasonable for the equipment to be expected to survive more than one large earthquake. Although aftershocks are a consideration, the demand loading from such events is generally substantially lower than the main shock.

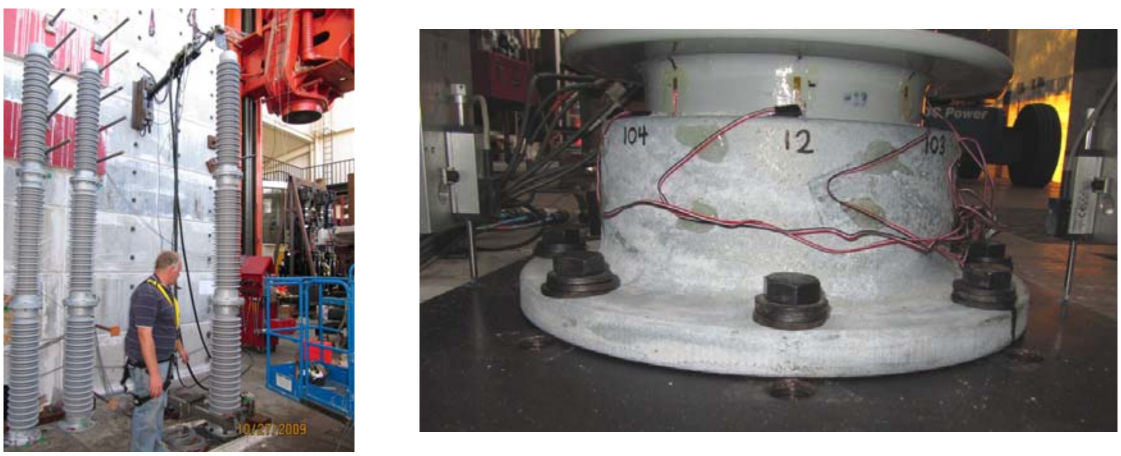
The primary objective for the most if not all utilities is to maintain or provide for rapid restoration of electric service following a large earthquake. Beyond this performance goal is the desire to limit damage to substation during the earthquake, but at reasonable cost; these competing goals will continue to require a balancing act for utilities and manufacturers. The IEEE693 Working Group is currently considering proposals to permit in the next version of the standard, replacement of parts or even the entire test article (of the same design) between different PL tests. The authors support this approach based upon the foregoing discussion.

5. MEASUREMENT TECHNIQUES

During seismic qualification tests many parameters of the equipment's performance are monitored. A list of commonly used instrumentation includes accelerometers, position transducers, and strain gages. Displacement of the terminals to which power cables are going to be attached shall be monitored and peak displacement relative to the shake table shall be reported. Current version of the standard allows using strain gage data to estimate displacements. This section addresses this issue.

5.1. Static Calibration of Strain Gages Prior to Seismic Qualification

To have some estimate of dynamic forces acting on porcelain and polymer insulators a static calibration tests are conducted prior to seismic qualification tests. The insulators are instrumented with strain gages which allow monitoring bending moments in two principal directions. The strain gage reading is correlated to a cantilever load at the top of insulator applied statically as shown in Figure 7a. Insulator is usually firmly attached to a strong floor at the bottom and actuator is attached to the top of the insulator to apply a bending force. A research team of the University California at Berkeley usually takes one extra step in this calibration procedure and introduces two position transducers at the bottom of the insulator to account for flexibility of the attachment point in direction of loading (if any), as shown in Fig. 7b.



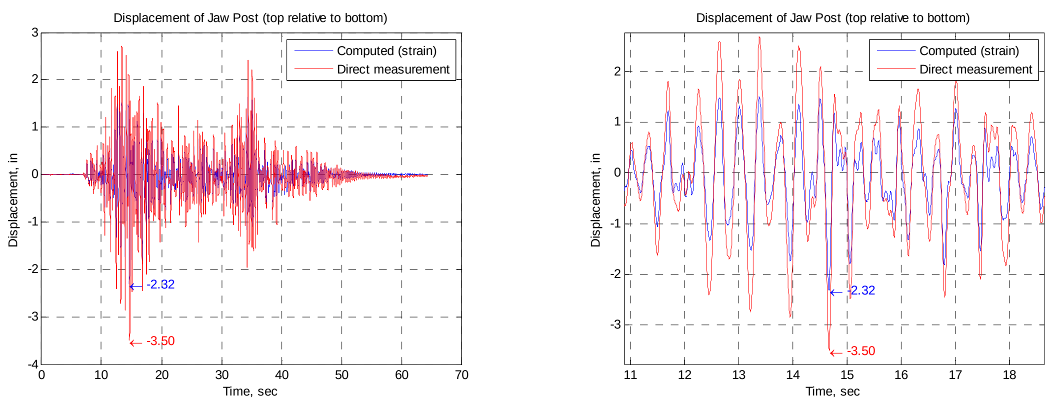
(a) (b)

Figure 7. Setup for strain gage calibration (a) and zoomed view of the bottom part with two position transducers accounting for flexibility of the attachment if any (b)

As a result of the calibration procedure the strain is correlated to a moment at the bottom of the insulator which is controlled by a concentrated load applied on the top in this calibration setup. The correlation is done to estimate so called "equivalent cantilever load" during dynamic testing. This strain can be correlated to the displacement of the insulator's top which is valid only: (1) for this case of concentrated load and (2) represents a relative displacement of top versus bottom.

5.2. Interpretation of Strain Gages Data during Seismic Qualification

During dynamic seismic qualification testing the inertia forces are distributed along the height of the insulator and as such the strain gage correlation obtained from static cantilever test fails to represent the tip's displacement. Test data from a test program of 550-kV vertical break disconnect switch conducted at the University of California, Berkeley (Takhirov, 2011) are discussed here. The displacements of the support structure, base of the insulators and their tops were directly measured during the tests. To increase accuracy of displacement measurements a triangulation technique was utilized. Typical test results for Jaw post in switch closed configuration are presented in Figure 8. The plots compares displacement estimated from strain data and the values monitored directly. The figures demonstrate that the strain gage data produces displacement estimates lower than the ones obtained by the direct measurements. It worthy to note that the dominant vibration mode of the insulator was the first mode that explains the fact that the strain gage and displacement data are almost in phase with some higher mode effects. It is not the case for the polymer insulators due to their increased flexibility relative to the stiff porcelain insulators. In case of the polymer insulators the phase and the frequency of the data is expected to be much more different than the one shown in Figure 8.



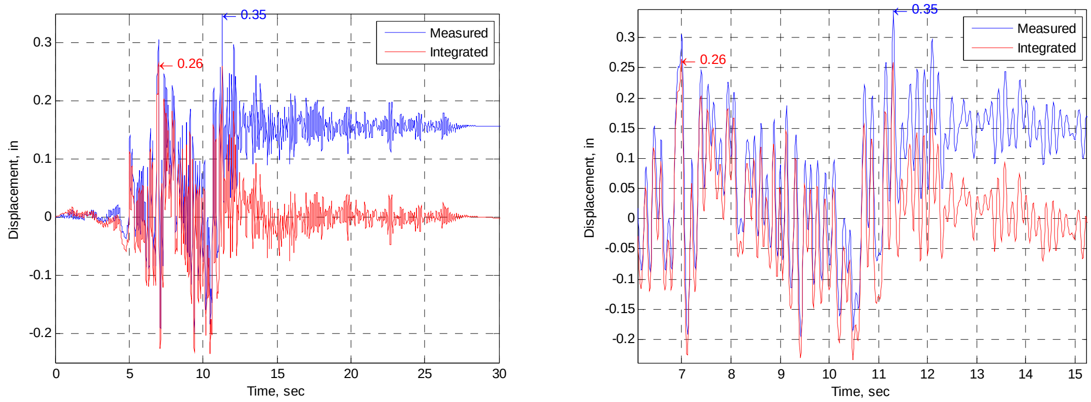
(a) (b)

Figure 8. Displacement data estimated from strain versus direct measurements (a) and zoomed view of displacements in vicinity of the peak values (b)

In the case of the 550-kV switch discussed herein the strain gage data were underestimating peak relative displacement by about 34%. This error is quite large and cannot produce satisfactory estimates of the total displacement. In addition to this possibility of introduction of a large error the following actions are needed to estimate the total displacement of the terminal: displacement of the insulator's bottom needs to be monitored, polarity of the displacements needs to be checked to avoid misuse the signs of the records, rotation of the insulator's bottom needs to be monitored to account for rigid body motions of the insulators. Even in case of small rotations this approach introduces a large error and requires more resources to achieve the same goal: 4 data acquisition channels (X and Y support displacements and X and Y strains in insulator post) vs. 2 channels (direct measurement of X and Y displacements of the terminal). To streamline the process of measurements and deliver reliable results, this option of displacement estimates based on strain data is proposed to be removed from the standard. Only direct measurements of displacements should be used.

5.3. Interpretation of Displacement Based on Acceleration

The standard allows usage of acceleration data for displacement estimates in reporting for the seismic qualification testing. An example showing this can lead to introduction of a significant error is provided here. A theoretical displacement obtained from a finite element analysis of a non-linear system is presented in Figure 9. This displacement has a number of peaks and residual deformation due to plastic deformation or permanent deflection. The displacement was double differentiated to produce acceleration. This acceleration represents a "measured" acceleration and the original displacement represents "direct measurement of the acceleration". The acceleration was double integrated (as it would be done in seismic qualification testing) to produce the displacement time history (red line in Figure 9). As seen in Figure 9, the displacement computed from the acceleration (1) underestimates the peak displacement by 25% and (2) misses residual displacement. To streamline the process of measurements and deliver reliable results, the estimate of displacement based on acceleration data is proposed to be removed and only direct measurements of displacements be used.



(a) (b)

Figure 9. Displacement estimated from double integrated acceleration versus "directly measured" (a) and zoomed view of displacements in vicinity of the peak values (b)

To streamline the process of measurements and deliver reliable results, this option of displacement estimates based on acceleration data is proposed to be removed from the standard. The standard should be revised to require that only direct measurement of displacements be used.

5. CONCLUSIONS

More rigorous testing has led to the manufacture of improved equipment. The results of the testing presented in this paper show that there is a need to improve in areas of IEEE693 such as first support amplification, qualification without known support structure, projected performance from half-scale tests, correlation between finite element models and actual equipment/components and measurement techniques.

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REFERENCES

IEEE (2006). IEEE693: IEEE Recommended Practice for Seismic Design of Substations.

Fujisaki, E. (2009). Seismic Performance of Electric Transmission Systems, *Presentation at PEER Annual Meeting*, San Francisco, California.

Gilani, A., Whittaker, A., and Fenves, G, (2001) Seismic Evaluation and Retrofit of 230-kV Porcelain Transformer Bushings, Earthquake Spectra, Volumne 17, Issue 4, Pages 597-616.

Takhirov, S., Fenves, G., Fujisaki, E., and Clyde, D. (2005a) Ground Motions for Earthquake Simulator Qualification of Electrical Equipment. *Pacific Earthquake Engineering Research Center, University of California at Berkeley, PEER 2004/07*.

Takhirov, S., Fenves, G., and Fujisaki, E. (2005b). Seismic Qualification and Fragility Study of Line Break 550-kV Disconnect Switches, *Pacific Earthquake Engineering Research Center, University of California at Berkeley, PEER 2004/08*.

Takhirov, S. (2008). Seismic Qualification Report on EC-1, P and EV-1 Types of 245-kV Disconnect Switches with EVG-1 Grounding Switch Installed. *Report No. SS-SCE-2008, Earthquake Engineering Research Center, University of California, Berkeley*.

Takhirov, S. and Gilani, A. (2009). Earthquake performance of high voltage electric components and new standards for seismic qualification. *Proceedings of TCLEE-2009*, Oakland, California: June 28-July 1.

Takhirov, S. (2011). Seismic Qualification Study of 550-kV Vertical Break Disconnect Switch. *Report No. PEER – STI/2011-02, Pacific Earthquake Engineering Research Center University of California, Berkeley*, September 2011.