ABSTRACT: 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 IEEE693 (Recommended Practice for Seismic Design of Substations) Working Group was formed in part to address the seismic vulnerability of 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 tighter test requirements. For example, many more facilities are now able to test to the High Performance Level, conduct triaxial testing, and use more sophisticated arrays of instruments for 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 acceptable seismic performance of substation equipment by including utilities, manufacturers, researchers and practicing engineers 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.

KEY WORDS: Lifeline systems, electrical substation equipment, seismic qualification, IEEE693, shake table testing.

1 INTRODUCTION

In past and recent earthquakes, high voltage substation components have suffered damage leading to disruption in power distribution [1]. As a result, electric utilities have suffered financial losses and the lag in restoring power delayed the restoration of essential services and post-earthquake recovery. Lengthy power outages may potentially inflict significant economic damage on affected communities or whole regions. 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 [2]. 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 [3]. Active participation of all interested parties [4] is always supported by the IEEE693 Working Group.

As a result the IEEE693-2005 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

Substation components or entire equipment assemblies are often installed on a supporting 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 requiring shake table testing must be tested full-
scale (preferably in the as-installed configuration), the feasibility of seismic qualification by testing can be limited by the capacity of a test laboratory. These limitations may 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 significant 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 [5]. 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 is Unknown

The current version of the standard (IEEE, 693) allows seismic qualifications testing when an actual 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 [5]. 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.

The top-of-support spectra plotted in Figure 2 represents the translational component of the coupled switch/support system. Since the switch has a significant mass compared to the support, these spectra only apply to the specific assembly being supported. A further complication is that the rotational response at the top of support is not captured by applying a simple scale factor to the ground input motion.

![Figure 2. Spectral accelerations of table, top of support structure and current IEEE693 amplified spectra for unknown structure.](image)

Spectral accelerations of the table and support structure computed for High PL run are presented in Figure 2, 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 3. 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 times greater than the 2.5 factor with the largest amplification is as high as 5.5.

![Figure 3. Spectral ratios of shake table and top of support structure.](image)

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 [6]. 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 phases of 245-kV switch, as shown in Figure 4 (the switch in closed configuration is shown).

![Figure 4](image)

Figure 4. Large spectral amplifications were also observed in 245-kV switch tests with relatively stiffer frame

Based on the discussion above, the amplification factor of 2.5 for unknown support structures may 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.

2.2 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 and assumptions associated with modelling. To implement this approach, the 550-kV switch was tested in closed configuration (configuration shown in Figure 1) and without support structure [5] as shown in Figure 5.

![Figure 5](image)

Figure 5. 550-kV vertical disconnect switch attached directly to shake table platform

In addition, strains were monitored in all insulator posts including the Rigid post (stationary post on the hinge end of the switch) 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 6 and Figure 7.

![Figure 6](image)

Figure 6. Change in distance between Rotating and Jaw posts

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.
with complex geometry or where strains cannot be measured, critical locations throughout the test article. For critical parts tested at half-High PL while the strains are monitored at this approach. For example, substation equipment can be demonstrated of electrical function at the full PL when using function is verified following testing at the half-PL, there is no exhibit nonlinear behavior. In addition, although electrical stops or bumpers and other mechanical devices that may the electrical equipment composed of bearings, spring cans, many cases this is not a reasonable assumption, especially for 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 effect is substituted by an amplified motion.

Based on the discussions 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, as well as many cases encountered in practice, 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 concerns about the validity of the final model. Even in the perfect (albeit ignoring the support rotation effects) 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 behavior 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 behavior. 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 must 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 as shown in Figure 8.
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, and the contacts on the Jaw end will never reach the stopper on the blade (in retraction). In reality, the switch’s performance was nonlinear, leading 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 the 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 on the 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 a half-PL test.

The following conclusions can be drawn from this discussion. First, seismic performance of substation components may be nonlinear and can lead to under-testing of the equipment and un-conservative conclusions 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.

4 OPTION OF REPLACING TEST ARTICLE WITH 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 EQUIPMENT WITH PASSIVE SEISMIC PROTECTION

Passive seismic protection systems have found limited use in electric substation equipment due to the general lack of experience possessed by manufacturers and utilities, life cycle/ maintenance concerns, and development/ installation costs compared to conventional approaches. In addition, conductor slack issues associated with increased (electrical) terminal displacements in such systems have discouraged their use. Large scale disasters highlighting the vulnerability of lifeline systems and the recent developments in improving seismic resilience of substation equipment via isolation/ damping technologies [8] reveal a compelling need for more definitive guidance for qualification of HV equipment with seismic protection. High-voltage DC and ultra-high voltage AC equipment may have tall, massive porcelain insulators and other fragile components such that passive seismic protection may provide one of the few feasible means for achieving good seismic performance.

Little guidance for qualification of electric substation equipment using seismic protection technologies can be found in IEEE 693 and its counterparts from other standard-making bodies. A framework for such qualification may include the following features.

Depending on feasibility of a shake table testing of this type of equipment, the seismic qualification may be conducted via detailed finite element analysis or by means of shake table tests of full-scale as-installed configurations. The seismic protection of the HV equipment can include a seismic isolation system supporting the equipment and its support structure, damping devices increasing effective damping of the system, and many others. To address issues of proper modelling, component testing is needed. The component testing is also needed to demonstrate that the protection system is reliable with repeatable properties. The issue of the protection device’s aging/decaying during years of outdoor installation while exposed to all environmental challenges needs to be addressed. Maintenance issues are also a significant concern for utilities.

5.1 Seismic Qualification by Analysis

If the seismically protected system cannot be tested in full-scale as-installed configuration it may be qualified by analysis as currently allowed by the standard for transformers and other oversized equipment.
**FE analysis: isolation system or damping device component testing.** To develop a FE model that closely represents the isolation system, component testing on the isolation system is needed. The results of these tests would be used for calibration of the non-linear force versus displacement relationship assumed in the analysis. This testing would also be used to verify that the isolation system has the required displacement/force capacity determined from the analysis of the coupled equipment-isolation system (with an appropriate factor of safety). The tests are recommended to be conducted in a cyclic setting with incrementally increasing amplitude up to displacement level expected at High PL.

**FE analysis: bounding analysis.** To account in variations in the damper/isolator properties, a bounding analysis should be conducted. The lower bound should equal the value obtained from the component tests but not greater than 85% of nominal value and the upper bound should equal the value obtained from the component tests but not smaller than 120% of nominal value. The components and connections in the equipment and its anchorage should be designed from the worst case results obtained from the bounding analysis.

**FE analysis: dynamic analysis of seismically protected system.** To qualify the equipment to certain seismic qualification level, a dynamic analysis of the equipment-isolation system needs to be performed. The equipment and its support structure could be modelled as linear if analysis shows that the components of the equipment remain elastic. The isolation system needs to be modelled as nonlinear component based on the results of the component tests. Alternatively, for velocity- and frequency-independent devices, it would be permitted to perform linear analysis using equivalent properties of the isolation/damping system at the target displacement.

**FE analysis: seismic qualification level.** For either moderate or high qualification levels, the acceleration spectrum anchored to the performance level (Moderate or High PL) should be used.

5.2 **Seismic Qualification by Means of Shake Table Testing**

If the seismically protected system cannot be tested in full-scale as-installed configuration it may be qualified by analysis as currently allowed by the standard for transformers and other oversized equipment.

In many cases the HV substation equipment is relatively light weight, with limited footprint and height, and as such it can be semi-actively evaluated by means of shake table testing.

**Shake table testing: component tests and bounding analysis.** Similar to the requirements of the seismic qualification by analysis, the isolation system and/or damping devices should be subjected to component testing prior to the shake table testing and bounding analysis performed.

**Shake table testing: resonance search tests.** Sine sweep testing should be conducted independently in three directions. For seismically isolated equipment, both the isolation system and equipment frequencies and damping should be identified.

For isolated equipment and damping devices that are displacement-dependent, a minimum of four sweeps with amplitudes ranging from 0.05g to 0.25g are proposed to be conducted. The sine sweeps may be replaced by equivalent white noise excitations at multiple levels to estimate the frequency dependency on the level of excitation. The required response spectra should envelop the lowest resonant frequency obtained in the resonant search tests.

**Shake table testing: time history testing.** Only triaxial full-scale testing is permitted. The seismic qualification method for equipment with seismic protective devices should be by shake-table response histories testing. An option of using a site-specific spectrum as specified by the utility may be used for evaluation.

6 **REQUIRED RESPONSE SPECTRUM**

As currently written, IEEE 693 requires most substation equipment to be qualified by means of numerical analysis or by full-scale shake table testing. The demand on the equipment is specified by required response spectra (RRS) of the strong motion imposed at the attachment points of the equipment. In case of numerical analysis, for complex structures with many modes in the seismic range, a detailed finite element model is required. The damping ratio is required to be measured directly or a conservatively low value (e.g., 2%) is permitted to be used. The lower frequencies of the mathematical model should, if possible, also be verified by simple-bump or other specified test methods. In case of full-scale testing by means shake table tests a resonance search test is required. The resonant frequency search test is for the determination of resonant frequencies and damping of equipment before and after each time history test. The data obtained from the test may be an essential part of an equipment qualification; however, the test does not constitute a seismic test qualification by itself.

Per the current version of IEEE693, a maximum damping value of 2% may be assumed on all equipment and structures and any claims of any damping beyond 2% must be substantiated by testing. Historically, the determination of damping of substation equipment has been focused on the damping associated with the horizontal response of equipment and with particular emphasis on the lower modes of vibration. In reality, structural and non-structural systems can have damping ratios other than 2%, depending on various factors such as structural types, construction materials, the level of ground motion excitations and many others. For instance, the effective damping of the equipment can change during the time history tests especially during high PL testing due to some plastic deformations expected during this severe motion. For seismically isolated equipment the variation in damping can be related to physical properties of the isolation system itself.

In most building codes and seismic design standards [9] the design spectra is provided at 5% damping ratio. If a structure has a damping ratio different from 5% a special damping scaling factor (DSF) is used to modify the design spectra to that particular damping value. A similar approach was used in the IEEE693 standard which specifies required response spectra at 2%, 5%, and other damping and provides DSF for other damping ratios. The 2%-damped spectrum is specified as the target for spectral matching when developing input motions for testing.

In recent research utilizing the updated, 2011 version of the NGA database of ground motions recorded in worldwide shallow crustal earthquakes in active tectonic regions (i.e., the NGA-West2 database), dependencies of the DSF on variables...
including damping ratio, spectral period, moment magnitude, source-to-site distance, duration, and local site conditions are examined [10].

The comparison between the IEEE93 required response spectra at 5% damping and the estimated RRS for other damping ratios utilizing results of [10] is provided in Figure 10.

The plots show that newly modified DSF closely matches the required response spectra specified in the current version of the standard. The updated spectra would have slightly higher demand in frequency range from 2Hz to 8Hz for 1%, 2%, and 10% damping ratios. Smaller spectral accelerations would be required for lightly damped systems with resonant frequency less than 1 Hz (see plot for 1% as an example). The latter will lead to lesser displacement demand, which is especially important and crucial for design of seismically isolated equipment.

Judging from the magnitude of the spectral differences in Figure 10, the modifications of the required response spectra are quite minor and most likely are not practical to introduce in the new version of the standard.

Figure 10. Required response spectra estimated from IEEE93 at 5% damping ratio by utilizing results of [10].

To achieve consistency in testing and numerical analysis of seismic qualification of substation equipment, IEEE93 standard provides two pre-approved three-component time histories satisfying certain requirements of the standard and enveloping the required response spectra at 2% damping ratio.

One of them is empirically based input motion that was derived from a real strong motion recorded during the Landers 1992 earthquake. The strong motion called TestQke4IEEE [3]. The spectrum of the shake table motion based on TestQke4IEEE would still envelope the updated spectra as shown in Figure 11 since test response spectra envelop the required response spectra with some margin that is usually much greater than the spectral improvements derived from [10].

This result supports the conclusion that the modifications of the required response spectra per [10] are most likely can be avoided (at least for 2% damping ratio).

Figure 11. Spectral accelerations of shake table motion based on TestQke4IEEE would still envelope the updated [10] RRS at 2%.

CONCLUSIONS

More rigorous testing has led to the development and manufacture of improved equipment. The results of the testing and analysis presented in this paper show that there is a need to improve in areas of IEEE93 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 issues related to required response spectra.

More research is needed on HV substation equipment with passive protection devices to develop improved guidance for the seismic qualification process of this type system. Development of supplemental damping devices or other means for dealing with excessive terminal displacements are needed.

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REFERENCES


