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NEW IEEE 693 GUIDELINES FOR ELECTRICAL SUBSTATION EQUIPMENT WITH PROTECTIVE SYSTEMS

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Abstract

A major update to the 2005 edition of the IEEE Standard 693, Recommended Practice for Seismic Design of Substations, which has been used extensively worldwide, was published in early 2019 as IEEE Std 693-2018. This new edition includes major revisions to the provisions for the use of seismic protective systems for substation equipment. The paper describes the key aspects of these new provisions of IEEE 693 that provide specific and detailed requirements for the application of seismic protective systems technologies to the broad variety of substation electrical equipment.

While IEEE Std 693-2005 recognized that seismic isolation or energy dissipation devices might possibly be applied to substation equipment, the standard contained limited discussion of the technologies and provided no specific direction or requirements on how the technologies should be applied. The update of IEEE Std 693-2005 was in all a more than seven-year effort and included task groups focused on a number of different specific technical areas. The Seismic Protective Devices Task Group developed a comprehensive set of new requirements, to be contained in a new section of the standard, Annex W, Equipment with Seismic Protective Devices, that now provide specific guidance to designers, equipment and device manufacturers, utilities and end-users.

It is envisaged that the new IEEE Std 693-2018 Annex W will contribute to a more consistent design and implementation approach for the use of protective systems technologies, help facilitate a wider use of the technologies and ultimately result in more essential, lifeline substation equipment being provided with the highest possible levels of seismic protection.

Keywords: electrical equipment, substations, protective systems, seismic isolation, energy dissipation

1. Introduction

Since the publication of the 2005 edition of IEEE Standard 693 [1], there has been significant worldwide growth in the seismic technology fields of seismic isolation and energy dissipation. With the increasing application of these technologies for the enhanced seismic protection of many different types of structures, including high-voltage electrical substation equipment [2, 3, 4, 5, 6, 7], it was recognized that an update of the existing, rather limited, provisions for these technologies in IEEE 693-2005 was necessary.

A concerted, multi-year effort by the IEEE Seismic Design of Substations Working Group, from 2010 to 2018 has produced a major revision of IEEE Std 693, which was officially published in early 2019 as IEEE Std 693-2018. This new and expanded edition of the IEEE 693 standard includes three entirely new annexes related to: DC voltage equipment, seismic strength criteria for insulators, and, the subject of this paper, Annex W Equipment with seismic protective devices.

The basic objective in the development of Annex W was to define a seismic qualification framework for electrical substation equipment with seismic protective devices that was consistent with the overall qualification approach of IEEE Std 693 (which is, as much as possible, based upon direct testing of equipment) and which would be consistent with the standard in terms of seismic qualification levels and qualification acceptance criteria. The annex recognizes that testing of equipment is not always possible and thus provides alternative approaches which combine testing (of equipment, wherever possible, and also of the protective devices) with analysis to achieve the qualification objective.

The characteristics and behavior of the seismic protective devices are recognized to be of utmost importance, and emphasis is placed on the importance of device testing to confirm properties. The experience with seismic protective devices in other civil and structural sectors (for buildings, ASCE/SEI 7-10 [8], and for bridges, AASHTO 2014 [9]) was considered in the development of the new annex, and the general requirements adopted for device testing are similar to those in these other codes, but with adaptation and consideration of the specific differences associated with high-voltage electrical equipment. In particular, the (relatively) low mass of the equipment, the wide variation in structural configuration and flexibility of such equipment and the wide variation of protective systems that may be utilized.

The following sections 2 – 7 of the paper briefly describe the philosophy, main features and requirements of the new Annex W.

2. Types of Seismic Protective Devices

Seismic protective devices for substation equipment may be classified into three general groups:

(a) *seismic isolation devices* – used to create an “isolated” horizontal response with a frequency lower than the natural frequency of the equipment itself; examples include elastomeric and sliding isolation bearings.

(b) *rocking seismic isolation devices* – used to uncouple the supported equipment and create a primarily rigid-body, rocking mode of response; examples include wire rope isolators and spring isolators.

(c) *damping (or energy dissipation) devices* – used to add supplemental damping to equipment, may also cause some change in equipment response frequency, but this is not the primary feature; examples include viscous dampers, metallic hysteretic dampers and friction dampers.

3. Seismic Qualification Methods

One of the basic objectives of IEEE Std 693 is to provide a framework for the seismic qualification of electrical substation equipment, and a large portion of the document is focused on this purpose. Further, qualification of equipment by testing, rather than analysis, is the preferred approach taken in the standard. Accordingly, Annex W is structured around qualification methods, and specifically the use of testing wherever possible and practical as the primary basis for qualification. The annex recognizes that qualification by test can be practically challenging, in terms of both equipment size, shape and weight and also equipment dynamic properties. When isolation (frequency shortening) is included, the dynamic characteristics of the seismically protected equipment may make testing unfeasible, and thus it was necessary that the annex requirements also address this scenario.

The qualification method to be used is determined by the following equipment classifications:

(i) *Category 1* equipment is that for which the standard allows qualification by analysis. This includes equipment of voltage ratings less than 170 kV and equipment that is too large and/or heavy to allow for shake table testing.

(ii) *Category 2* equipment is that for which the standard requires qualification by shake table testing, and for which testing is possible considering the seismic protective system characteristics and shake table performance limits.

(iii) *Category 3* equipment is that for which the standard requires qualification by shake table testing, but which is not able to be tested considering the seismic protective system characteristics and shake table performance limits.

The annex provides analysis and/or testing requirements for each of these three categories of equipment with seismic protective devices and also testing requirements for the seismic protective devices themselves.

For the testing of equipment protected with damping devices, shake table performance limits are generally not a limitation, and therefore when only damping devices are used for equipment, the qualification requirements of the applicable equipment annex, including any shake table testing requirements, shall apply.

3.1 Category 1 equipment

The seismic qualification method required for Category 1 equipment is a combination of dynamic analysis of the complete seismically protected equipment and testing of the seismic protective devices. The devices shall satisfy the prototype and production (routine) testing requirements, and the test results shall confirm the device properties used in the dynamic analysis and that the devices have the required displacement and force capacities determined from the analysis.

Equipment and seismic protective device qualification acceptance criteria are as follows: the equipment design level acceptance criteria defined in the relevant equipment annex shall be satisfied; evaluation of equipment forces or stresses, including appendages and their connections to transformers and liquid-filled reactors, shall be made for the demands from the analysis at the design level of the equipment including the seismic protective system; equipment displacements (and thus the demands on the protective devices) shall be those obtained from a performance level analysis; the seismic protective device tests shall satisfy the prototype and production testing acceptance criteria (see 4.1 and 4.2 below).

3.2 Category 2 equipment

The seismic qualification method required for Category 2 equipment is shake table testing per the requirements of IEEE Std 693-2018 Annex A, and the complete equipment, including the seismic protective system shall be tested, and the shake table testing shall be at the performance level. In addition, the seismic protective devices shall satisfy the prototype and production testing requirements.

Equipment and seismic protective device qualification acceptance criteria are as follows: the equipment acceptance criteria defined in the relevant equipment annex shall be satisfied, and Annex A of the standard defines specific criteria for the performance level; the seismic protective device tests shall satisfy the prototype and production testing acceptance criteria (see 4.1 and 4.2 below).

3.3 Category 3 equipment

The seismic qualification method required for Category 3 equipment is a combination of equipment shake table testing, seismic protective device testing, and dynamic analysis of the seismically protected equipment. This method is included in the standard to allow the implementation of seismic protective systems for equipment when it is not possible to perform shake table tests (which would normally be required) due to shake table performance limitations. For example, in the case of protected equipment with a fundamental frequency such that it is not possible for the shake table to satisfy the test input frequency requirements defined in the standard. It is recognized that application of this qualification method is complex, and thus the annex allows that the specific details of application of the method shall be at the discretion of the end user (which is typically a utility).

The general approach for Category 3 equipment qualification is intended as follows:

(a) Conduct shake table testing of the equipment not including the seismic protective devices and qualify the equipment to a chosen ZPA level using the well-established procedure defined in Annex A of the standard. The ZPA level need not correspond to a specific IEEE Std 693 qualification level (i.e., moderate or high).

(b) Perform dynamic analysis of the equipment not including the seismic protective devices to the chosen ZPA level achieved in the shake table testing. The shake table test results are used to validate the numerical model of the equipment, and the annex requires that the method of validation and the adequacy of the model be subject to design review (see 7 below).

(c) Dynamic analysis of the equipment model with the seismic protective devices included is undertaken to assess the seismic response at the desired IEEE Std 693 qualification level.

(d) The equipment with the seismic protective devices is qualified to the desired qualification level if the key equipment responses (displacements, forces, stresses, accelerations, reactions, etc.) resulting from the dynamic analysis are not greater than the corresponding responses that were previously shown to be acceptable by the equipment shake table testing of (a) above.

As with the Category 1 and 2 qualification methods, the seismic protective devices shall satisfy the prototype and production (routine) testing requirements.

4. Requirements for Testing of Seismic Protective Devices

The seismic protective devices shall be subjected to two types of test: prototype and production (routine) tests. This general approach is conceptually the same as the requirements for seismic protective device tests in ASCE/SEI 7-10 [8] and AASHTO 2014 [9]. Prototype tests are performed to identify properties and confirm the capacity of the device to resist the required design forces and displacements. Similarity provisions are defined, which if satisfied, allow for the consideration of data from previous tests to satisfy the prototype test requirements, subject to the approval of the end user. Production tests shall be performed on all devices to be used in the construction.

Prototype and production tests are defined in terms of increments of the performance level displacement, D_{PL}, which is the maximum seismic protective device displacement determined from the shake table tests, or analyses, depending on the applicable equipment category.

4.1 Prototype tests

The annex requires that prototype tests be performed separately on two full-size specimens of each type and size of device utilized in the equipment seismic protective system. The protective system components to be tested shall include any provided in the system to resist wind loads. Prototype test specimens are not permitted to be used in the construction unless accepted by both the equipment and protective system designer and the end user.

The following sequence of tests shall be performed:

(a) Five fully-reversed cycles of loading at each of the following increments of the performance level displacement, D_{PL}, — 0.25, 0.5 and 1.0.

(b) Five fully-reversed cycles of loading at 1.1 times D_{PL}.

(c) Fifteen fully-reversed cycles of loading at 0.75 times D_{PL}.

(d) If a seismic protective device is also a vertical-load-carrying element, then one fully-reversed cycle of loading at 1.1 times D_{PL} and with a vertical load of 1.0 times the vertical load including the effects of seismic overturning, where the vertical load is the maximum for all devices of a common type and size.

(e) If the specified wind load on the equipment results in movement of the seismic protective device, twenty fully-reversed cycles of loading at a lateral force corresponding to the specified wind load.

It is required that tests (a) to (c) be performed dynamically, at the fundamental mode frequency of the protective system. In the case of damping devices, the testing frequency should be the predominant response frequency of the equipment including the devices. If the force-deflection properties of the devices are not dependent on the rate of loading, then tests (a) to (c) need not be dynamic.

If the device is a vertical-load-carrying element, then test (a) shall be performed at the average dead load on all devices of a common type and size, as well as at the maximum and minimum vertical loads including the effects of overturning.

If the device properties are sensitive to the direction of loading, then tests (a) to (c) shall be performed in the primary directions of sensitivity to appropriately characterize the device properties.

Acceptance criteria – The annex defines explicit acceptance criteria for all of the above tests, evaluating device performance in terms of effective (secant) stiffness, energy dissipated per cycle and stability. The details are not elaborated here, but in general, it is required that the device properties exhibited by testing shall be within 15 or 20 percent of the values used in the design.

Additional test requirements – Prototype tests shall be performed by, and reported on, by an independent testing facility, or if performed by the device manufacturer then the tests should be observed by an independent third-party who shall also verify the accuracy of the test report.

4.2 Similarity

Prototype tests are not required if the seismic protective device, when compared to another tested device, satisfies all of the following criteria:

- The device is not more than 15 percent larger nor more than 30 percent smaller than the previously tested prototype, in terms of governing device dimensions.
- Is of the same type and materials.
- Has an energy dissipated per cycle that is not less than 85 percent of the previously tested device.
- Is fabricated by the same manufacturer using the same, or more stringent, documented manufacturing and quality control procedures.

The prototype testing similarity exemption shall be approved by the end user and the design review.

4.3 Production tests

All seismic protective devices used in the construction shall undergo a production test program prior to installation. The objective of the production test program is to evaluate and confirm the properties of the devices used in the construction with those properties assumed in the design. The production test program may be incorporated into the device manufacturer’s quality control program. Unless otherwise approved, at a minimum, the production test program shall comprise three fully-reversed cycles of load at 1.0 times the performance level displacement, D_{PL}. The tests shall be dynamic, unless the device properties are not dependent on the rate of loading, in which case slow speed tests may be performed. The production test results of each device shall be within 15 percent of the values assumed in the design. For devices with characteristics based upon metallic yielding it is recognized that it may not be appropriate to apply the above tests to the devices to be used in the construction and alternative procedures should be defined.

4.4 Other types of devices

The annex recognizes that other types of seismic protective devices may exist for which the prescribed prototype and production tests may not be appropriate due to the characteristics of their behavior. For such devices, alternative prototype and production tests may be proposed by the manufacturer, and subject to the approval by the end user and the design review.

5. Dynamic Analysis

Given that the behavior of many protective systems is dependent on load history and/or rate of loading, a dynamic analysis method is prescribed for equipment with seismic protective devices. This contrasts with the IEEE Std 693 in general which in most cases allows the use of static analysis methods for most types of equipment. In general, time-history analysis is required, with response spectrum analysis permitted for some equipment and device configurations. The following summarizes considerations and requirements for analysis.

5.1 Response spectrum analysis

Response spectrum analysis, in accordance with the requirements of Annex A of the standard, may be used when all of the following conditions are satisfied:

(a) The force-deformation characteristics of the seismic protective devices are amenable to modeling by equivalent linearization.

(b) The equipment is regular in configuration, and geometric nonlinearities associated with large deformations (such as P-delta effects and others) are not expected.

(c) In the case of isolation-type protective systems, the maximum seismic response does not develop tension or uplift forces that cause separation at the devices or equipment supports.

(d) The use of response spectrum analysis is approved by the end user and the design review.

(e) The combined damping of the equipment and protective devices in the important modes of response does not exceed 20 percent.

5.2 Time-history analysis

As required for Category 1 and 3 equipment, time-history analysis of the equipment with the seismic protective devices shall be performed in accordance with the requirements of Annex A. Analyses are required at both the design and performance levels.

5.3 Modelling

The equipment may be modelled as linear if analysis shows that the equipment remains elastic. If the behavior of any components of the equipment is expected to be in the inelastic range, then such components shall be modelled as nonlinear.

The seismic protective devices shall be modelled considering their force-deformation and force-velocity characteristics as determined from the device testing. When response spectrum analysis is allowed, appropriate equivalent linear device properties should be used, linearized to be consistent with the level of expected device deformation under seismic loading.

5.4 Damping

The annex specifically considers damping: for time-history analysis, an inherent damping of two percent shall be used (unless a different value can be substantiated, as allowed elsewhere in the standard) for the equipment, not including the seismic protective devices. For response spectrum analysis, equipment modal damping shall be established from the results of the device tests.

5.5 Bounding analysis

To account for variations in the seismic protective device properties due to effects such as manufacturing variability, environmental and ageing effects and property variability due to loading frequency, temperature and other phenomena, the annex requires that bounding analyses be performed. Variations in device properties such as stiffness and damping shall be determined from manufacturer's test data. Bounding analyses shall be performed for appropriate values of expected upper and lower bound values of the device properties, and the resulting maximum response values, as applicable, shall be used for the design of the equipment, seismic protective devices and the connections between the devices and the equipment and foundation. The annex defines minimum limits on the bounds: the lower bound value of the device property should not be greater than 85 percent of the nominal value and the upper bound should not be less than 120 percent of the nominal value (where the nominal value of any device property is the manufacturer's recommended, standard design value, or the mean value obtained from device prototype tests).

5.6 Input motion

For response spectrum analysis, the response spectrum specified in Annex A of the standard for the intended qualification level should be used.

For time-history analysis, a minimum of three sets of triaxial earthquake ground motion records, determined in accordance with the requirements of Annex A, shall be used. It is recognized that ground motion time histories compatible with Annex A may not include shaking characteristics for special conditions such as very near-fault locations or long-duration, subduction-type events. For equipment installed in locations with special conditions it may be more appropriate to develop site-specific, time-history records which if done, should be subject to review and approval by the end user and the design review.

6. General Requirements for Seismic Protective Devices

Annex W includes a series of general requirements for the seismic protective devices including the explicit requirement that bounding of device behavior due to age, temperature and other environmental factors be considered. Some of the additional general requirements are described in the following sections:

6.1 Displacement capacity

The seismic protective devices shall have a displacement capacity (and velocity capacity, for velocity-dependent devices) of at least 1.1 times the performance level displacement, D_{PL}. The calculation of maximum displacement shall take account of the device property bounding.

6.2 Vertical stability

Seismic protective devices that carry equipment gravity loads shall have the means to accommodate any expected uplift, and to resist any increased vertical load, that may occur due to seismic overturning forces, without compromise to the device behavior.

6.3 Re-centering

The seismic protective system shall have sufficient restoring capability to return the equipment to its original position after a performance-level seismic event. Some residual displacement may be acceptable, but not more than 0.1 times D_{PL}, subject to review and approval by the end user and the design review.

6.4 Wind, fault and other loads

The seismic protective system shall be designed to resist specified wind, fault and other load conditions, and protective system displacement and movement of the equipment under the specified loads shall not exceed any specified limits.

6.5 Equipment interconnection and clearances

Conductors and other equipment interconnection shall be designed to accommodate at least 1.1 times D_{PL}. If equipment component flexibility contributes to interconnection demands the additional displacement due to component flexibility shall also be accommodated.

6.6 Long-term variation of device properties

The variation of the seismic protective device stiffness and damping properties over the life of the equipment shall be accounted for in the bounding analysis of section 5.5.

6.7 Variation of device properties due to temperature and other environmental factors

Variation of device properties considered in the bounding analysis shall include seasonal temperature effects for the equipment installation location, as defined by the user or the user's agent. As defined by the user or the user's agent, the devices shall have proper protection from moisture, rain, snow, ice and other environmental factors if their properties may be affected by these factors. If the environmental protection cannot be provided, the variation of the device properties shall be accounted for in the bounding analysis.

6.8 Installation quality assurance

The manufacturer shall provide a manual that describes all requirements for installation of the seismic protective devices, including any requirements for alignment and/or adjustment at the time of installation. The devices should not require long-term adjustment after initial installation.

6.9 Maintenance

The seismic protective devices shall be designed for the expected life of the equipment, which shall be 30 years unless otherwise defined by the end user. Maintenance requirements shall be considered by the designer and clearly defined to the end user. The device manufacturer shall provide a periodic inspection and maintenance manual to the end user, which should include any special requirements for post-earthquake inspection.

7. Designer Qualifications and Review

Annex W requires that the designer of the seismic protective system for the equipment (who may be different from the equipment designer) shall have expertise in the use of seismic protective devices and systems and the seismic design and analysis of electrical substation equipment.

In consideration of the complexity of much substation equipment and the application of seismic protective devices thereto, the annex highly recommends that a third-party review of the design of the seismic protective system be undertaken. The review should be performed by an expert in the use of seismic protective devices who is independent of the manufacturer(s) of the equipment and the seismic protective system, and who is selected by the end user. The scope of the review should include the modeling of the devices and analysis, the results of the testing of the seismic protective devices, the results of shake table testing of the equipment if performed, and the general suitability for use of the seismic protective system considering site-specific conditions such as site response and input motion.

8. Conclusions

The new provisions in Annex W of IEEE Std 693-2018 are expected to contribute to a more consistent design and implementation approach for the use of protective systems technologies, and to help facilitate a wider use of the technologies and ultimately result in more essential, lifeline substation equipment being provided with the highest possible level of seismic protection.

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